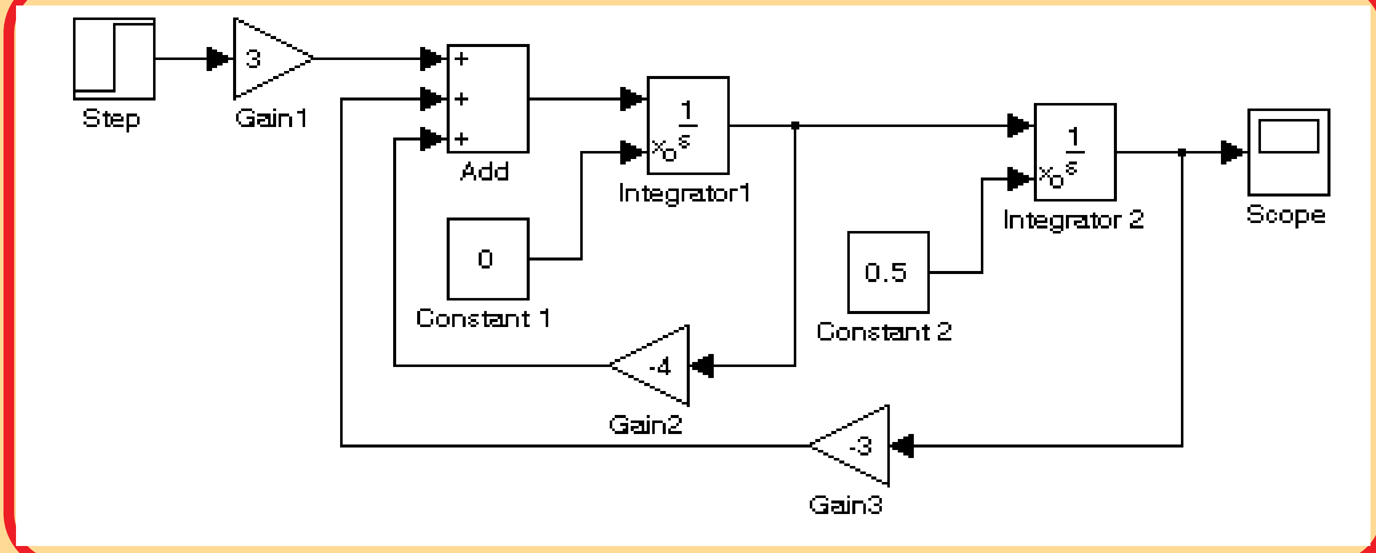
Introduction to Simulink with Engineering Applications

Second Edition

Steven T. Karris



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Disclaimer

Preface

This text is an introduction to Simulink ®, a companion application to MATLAB ®. It is written for students at the undergraduate and graduate programs, as well as for the working professional.

The author claims no originality of the content, and the description of the Simulink blocks is extracted from The MathWorks™ documentation without intent to infringe. The intent is to provide a complete reference text, and whenever necessary, the author refers the reader to The MathWorks™ documentation. Whenever there is a conflict between this text and The MathWorks™ documentation, the latter takes precedence.

Although some previous knowledge of MATLAB would be helpful, it is not absolutely necessary; Appendix A of this text is an introduction to MATLAB to enable the reader to begin learning both MATLAB and Simulink simultaneously, and to perform graphical computations and programming.

Chapters 2 through 19 describe the blocks in all Simulink Version 7.1 libraries. Their application is illustrated with Simulink models that contain the pertinent blocks, and some are supplemented with MATLAB functions, commands, and statements. Some background information is provided for lesser known definitions and topics. Chapters 1 and 20 contain several Simulink models to illustrate various applied math and engineering applications. Appendix B is an introduction to masked subsystems, and Appendix C introduces the reader to random generation procedures. Appendix D is an introduction to Weighted Moving Averages.

This text supplements our *Numerical Analysis Using MATLAB and Excel,* ISBN 978–1–934404–03–4. It is self-contained; the blocks of each library are described in an orderly fashion that is consistent with Simulink's documentation. This arrangement provides insight into how a model is used and how its parts interact with each another.

Like MATLAB, Simulink can be used with both linear and nonlinear systems, which can be modeled in continuous time, sample time, or a hybrid of these. Examples are provided in this text.

Most of the examples presented in this book can be implemented with the Student Versions of MATLAB and Simulink. A few may require the full versions of these outstanding packages, and these examples may be skipped. Some add–ons, known as Toolboxes and Blocksets can be obtained from The MathWorks,™ Inc., 3 Apple Hill Drive, Natick, MA, 01760-2098, USA, www.mathworks.com.

To get the most out of this outstanding application, it is highly recommended that this text is used in conjunction with the MATLAB and Simulink User's Guides. Other references are provided in the reference section of this text.

This is the second edition of this title, and although every effort was made to correct possible typographical errors and erroneous references to figures and tables, some may have been overlooked. Accordingly, the author will appreciate it very much if any such errors are brought to his attention so that corrections can be made for the next edition.

The author wishes to express his gratitude to the staff of The MathWorks™, the developers of MATLAB® and Simulink® for the encouragement and unlimited support they have provided me with during the production of this text.

Our heartfelt thanks also to Mr. Howard R. Hansen, and Dr. Niel Ransom, former CTO of Alcatel, for bringing some errors on the first print to our attention.

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Table of Contents

Chapter 1

Introduction to Simulink

This chapter is an introduction to Simulink. This author feels that it is best to introduce Simulink in this chapter with a few examples. Tools for simulation and model–based designs are presented in the subsequent chapters. Some familiarity with MATLAB is essential in understanding Simulink, and for this purpose, Appendix A is included as an introduction to MATLAB.

1.1 Simulink and its Relation to MATLAB

The MATLAB® and Simulink® environments are integrated into one entity, and thus we can analyze, simulate, and revise our models in either environment at any point. We invoke Simulink from within MATLAB. We begin with a few examples and we will discuss generalities in subsequent chapters. Throughout this text, a left justified horizontal bar will denote the beginning of an example, and a right justified horizontal bar will denote the end of the example. These bars will not be shown whenever an example begins at the top of a page or at the bottom of a page. Also, when one example follows immediately after a previous example, the right justified bar will be omitted.

Example 1.1

For the electric circuit of Figure 1.1, $u_0(t)$ [*]is the input and the initial conditions are $i_L(0^-) = 0$, and $v_c(0^-) = 0.5\ V$. We will compute $v_C(t)$.

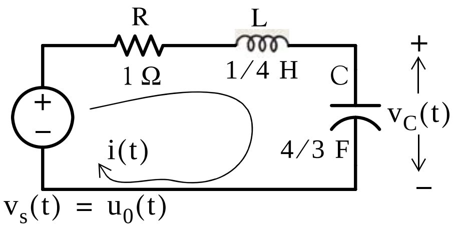


Figure 1.1. Circuit for Example 1.1

For this example,

$$i = i_L = i_C = C\frac{dv_C}{dt} \tag{1.1}$$

* *Throughout this text, the designation* $u_0(t)$ *will be used to denote the unit step function. We will use* $u(t)$ *to denote any other input to be consistent with the MATLAB and Simulink designations.*

and by Kirchoff's voltage law (KVL),

$$Ri_L + L\frac{di_L}{dt} + v_C = u_0(t) \tag{1.2}$$

Substitution of (1.1) into (1.2) yields

$$RC\frac{dv_C}{dt} + LC\frac{d^2v_C}{dt^2} + v_C = u_0(t) \tag{1.3}$$

Substituting the values of the circuit constants and rearranging we obtain:

$$\frac{1}{3}\frac{d^2v_C}{dt^2} + \frac{4}{3}\frac{dv_C}{dt} + v_C = u_0(t)$$

$$\frac{d^2v_C}{dt^2} + 4\frac{dv_C}{dt} + 3v_C = 3u_0(t) \tag{1.4}$$

$$\frac{d^2v_C}{dt^2} + 4\frac{dv_C}{dt} + 3v_C = 3 \qquad t > 0 \tag{1.5}$$

To appreciate Simulink's capabilities, for comparison, three different methods of obtaining the solution are presented, and the solution using Simulink follows.

First Method – Assumed Solution

Equation (1.5) is a second–order, non–homogeneous differential equation with constant coefficients, and thus the complete solution will consist of the sum of the forced response and the natural response. It is obvious that the solution of this equation cannot be a constant since the derivatives of a constant are zero and thus the equation is not satisfied. Also, the solution cannot contain sinusoidal functions (sine and cosine) since the derivatives of these are also sinusoids. However, decaying exponentials of the form ke^{-at} where *k* and *a* are constants, are possible candidates since their derivatives have the same form but alternate in sign.

It can be shown* that if $k_1e^{-s_1t}$ and $k_2e^{-s_2t}$ where k_1 and k_2 are constants and s_1 and s_2 are the roots of the characteristic equation of the homogeneous part of the given differential equation, the natural response is the sum of the terms $k_1e^{-s_1t}$ and $k_2e^{-s_2t}$. Therefore, the total solution will be

* *For a thorough discussion, please refer to Circuit Analysis II with MATLAB Applications, ISBN 0–9709511–5–9, Appendix B.*

$$v_c(t) = \text{natural response} + \text{forced response} = v_{cn}(t) + v_{cf}(t) = k_1 e^{-s_1 t} + k_2 e^{-s_2 t} + v_{cf}(t) \qquad (1.6)$$

The values of s_1 and s_2 are the roots of the characteristic equation

$$s^2 + 4s + 3 = 0 \qquad (1.7)$$

Solution of (1.7) yields of $s_1 = -1$ and $s_2 = -3$ and with these values (1.6) is written as

$$v_c(t) = k_1 e^{-t} + k_2 e^{-3t} + v_{cf}(t) \qquad (1.8)$$

The forced component $v_{cf}(t)$ is found from (1.5), i.e.,

$$\frac{d^2 v_C}{dt^2} + 4\frac{dv_C}{dt} + 3v_C = 3 \qquad t > 0 \qquad (1.9)$$

Since the right side of (1.9) is a constant, the forced response will also be a constant and we denote it as $v_{Cf} = k_3$. By substitution into (1.9) we obtain

$$0 + 0 + 3k_3 = 3$$

or

$$v_{Cf} = k_3 = 1 \qquad (1.10)$$

Substitution of this value into (1.8), yields the total solution as

$$v_C(t) = v_{Cn}(t) + v_{Cf} = k_1 e^{-t} + k_2 e^{-3t} + 1 \qquad (1.11)$$

The constants k_1 and k_2 will be evaluated from the initial conditions. First, using $v_C(0) = 0.5\ V$ and evaluating (1.11) at $t = 0$, we obtain

$$v_C(0) = k_1 e^0 + k_2 e^0 + 1 = 0.5$$

$$k_1 + k_2 = -0.5 \qquad (1.12)$$

Also,

$$i_L = i_C = C\frac{dv_C}{dt}, \quad \frac{dv_C}{dt} = \frac{i_L}{C}$$

and

$$\left.\frac{dv_C}{dt}\right|_{t=0} = \frac{i_L(0)}{C} = \frac{0}{C} = 0 \qquad (1.13)$$

Next, we differentiate (1.11), we evaluate it at $t = 0$, and equate it with (1.13). Thus,

$$\left.\frac{dv_C}{dt}\right|_{t=0} = -k_1 - 3k_2 \qquad (1.14)$$

Equating the right sides of (1.13) and (1.14) we obtain

$$-k_1 - 3k_2 = 0 \tag{1.15}$$

Simultaneous solution of (1.12) and (1.15), gives $k_1 = -0.75$ and $k_2 = 0.25$. By substitution into (1.8), we obtain the total solution as

$$\mathbf{v_C(t) = (-0.75e^{-t} + 0.25e^{-3t} + 1)u_0(t)} \tag{1.16}$$

Check with MATLAB:

```
syms t                                   % Define symbolic variable t
y0=–0.75*exp(–t)+0.25*exp(–3*t)+1;       % The total solution y(t), for our example, vc(t)
y1=diff(y0)                              % The first derivative of y(t)

y1 =
3/4*exp(-t)-3/4*exp(-3*t)

y2=diff(y0,2)                            % The second derivative of y(t)

y2 =
-3/4*exp(-t)+9/4*exp(-3*t)

y=y2+4*y1+3*y0                           % Summation of y and its derivatives

y =
3
```

Thus, the solution has been verified by MATLAB. Using the expression for $v_C(t)$ in (1.16), we find the expression for the current as

$$\mathbf{i = i_L = i_C = C\frac{dv_C}{dt} = \frac{4}{3}\left(\frac{3}{4}e^{-t} - \frac{3}{4}e^{-3t}\right) = e^{-t} - e^{-3t}\ A} \tag{1.17}$$

Second Method – Using the Laplace Transformation

The transformed circuit is shown in Figure 1.2.

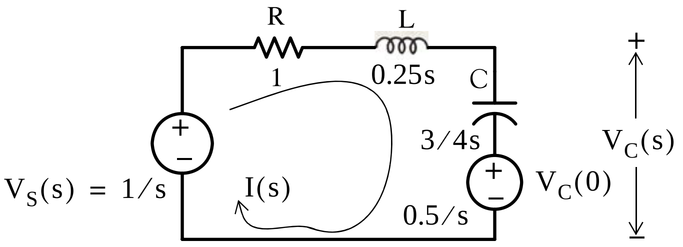


Figure 1.2. Transformed Circuit for Example 1.1

By the voltage division[*] expression,

$$V_C(s) = \frac{3/4s}{(1+0.25s+3/4s)} \cdot \left(\frac{1}{s} - \frac{0.5}{s}\right) + \frac{0.5}{s} = \frac{1.5}{s(s^2+4s+3)} + \frac{0.5}{s} = \frac{0.5s^2+2s+3}{s(s+1)(s+3)}$$

Using partial fraction expansion,[†] we let

$$\frac{0.5s^2+2s+3}{s(s+1)(s+3)} = \frac{r_1}{s} + \frac{r_2}{(s+1)} + \frac{r_3}{(s+3)} \tag{1.18}$$

$$r_1 = \left.\frac{0.5s^2+2s+3}{(s+1)(s+3)}\right|_{s=0} = 1$$

$$r_2 = \left.\frac{0.5s^2+2s+3}{s(s+3)}\right|_{s=-1} = -0.75$$

$$r_3 = \left.\frac{0.5s^2+2s+3}{s(s+1)}\right|_{s=-3} = 0.25$$

and by substitution into (1.18)

$$V_C(s) = \frac{0.5s^2+2s+3}{s(s+1)(s+3)} = \frac{1}{s} + \frac{-0.75}{(s+1)} + \frac{0.25}{(s+3)}$$

Taking the Inverse Laplace transform[‡] we find that

$$\mathbf{v_C(t) = 1 - 0.75e^{-t} + 0.25e^{-3t}}$$

Third Method – Using State Variables

$$Ri_L + L\frac{di_L}{dt} + v_C = u_0(t) \; ^{**}$$

By substitution of given values and rearranging, we obtain

* *For derivation of the voltage division and current division expressions, please refer to Circuit Analysis I with MATLAB Applications, ISBN 0–9709511–2–4.*

† *A thorough discussion of partial fraction expansion with MATLAB Applications is presented in Numerical Analysis Using MATLAB and Excel, ISBN 978–1–934404–03–4.*

‡ *For an introduction to Laplace Transform and Inverse Laplace Transform, please refer to Circuit Analysis II with MATLAB Applications, ISBN 0–9709511–5–9.*

** *Usually, in State–Space and State Variables Analysis,* $u(t)$ *denotes any input. For distinction, we will denote the Unit Step Function as* $u_0(t)$*. For a detailed discussion on State–Space and State Variables Analysis, please refer to Signals and Systems with MATLAB Computing and Simulink Modeling , ISBN 0–9744239–9–8.*

$$\frac{1}{4}\frac{di_L}{dt} = (-1)i_L - v_C + 1$$

or

$$\frac{di_L}{dt} = -4i_L - 4v_C + 4 \tag{1.19}$$

Next, we define the state variables $x_1 = i_L$ and $x_2 = v_C$. Then,

$$\dot{x}_1 = \frac{di_L}{dt}^{*} \tag{1.20}$$

and

$$\dot{x}_2 = \frac{dv_C}{dt} \tag{1.21}$$

Also,

$$i_L = C\frac{dv_C}{dt}$$

and thus,

$$x_1 = i_L = C\frac{dv_C}{dt} = C\dot{x}_2 = \frac{4}{3}\dot{x}_2$$

or

$$\dot{x}_2 = \frac{3}{4}x_1 \tag{1.22}$$

Therefore, from (1.19), (1.20), and (1.22), we obtain the state equations

$$\dot{x}_1 = -4x_1 - 4x_2 + 4$$

$$\dot{x}_2 = \frac{3}{4}x_1$$

and in matrix form,

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}-4 & -4\\ 3/4 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}4\\ 0\end{bmatrix}u_0(t) \tag{1.23}$$

Solution[†] of (1.23) yields

$$\begin{bmatrix}x_1\\ x_2\end{bmatrix} = \begin{bmatrix}e^{-t} - e^{-3t}\\ 1 - 0.75e^{-t} + 0.25e^{-3t}\end{bmatrix}$$

Then,

$$x_1 = i_L = e^{-t} - e^{-3t} \tag{1.24}$$

* *The notation* $\dot{x}$ *(x dot) is often used to denote the first derivative of the function* x, *that is,* $\dot{x} = dx/dt$.

† *The detailed solution of (1.23) is given in Signals and Systems with MATLAB Applications, ISBN 0–9744239–9–8, Chapter 5.*

and

$$x_2 = v_C = 1 - 0.75e^{-t} + 0.25e^{-3t} \tag{1.25}$$

Modeling the Differential Equation of Example 1.1 with Simulink

To run Simulink, we must first invoke MATLAB. Make sure that Simulink is installed in your system. At the MATLAB command prompt (>>), we type:

```
simulink
```

Alternately, we can click the Simulink icon shown in Figure 1.3. It appears on the top bar on the MATLAB Command Window.

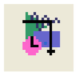


Figure 1.3. The Simulink icon

Upon execution of the Simulink command, the **Commonly Used Blocks are** shown in Figure 1.4.

In Figure 1.4, the left side is referred to as the **Tree Pane** and displays all Simulink libraries installed. The right side is referred to as the **Contents Pane** and displays the blocks that reside in the library currently selected in the Tree Pane.

Let us express the differential equation of Example 1.1 as

$$\frac{d^2 v_C}{dt^2} = -4\frac{dv_C}{dt} - 3v_C + 3u_0(t) \tag{1.26}$$

A block diagram representing (1.26) is shown in Figure 1.5. Now, we will use Simulink to draw a similar block diagram.

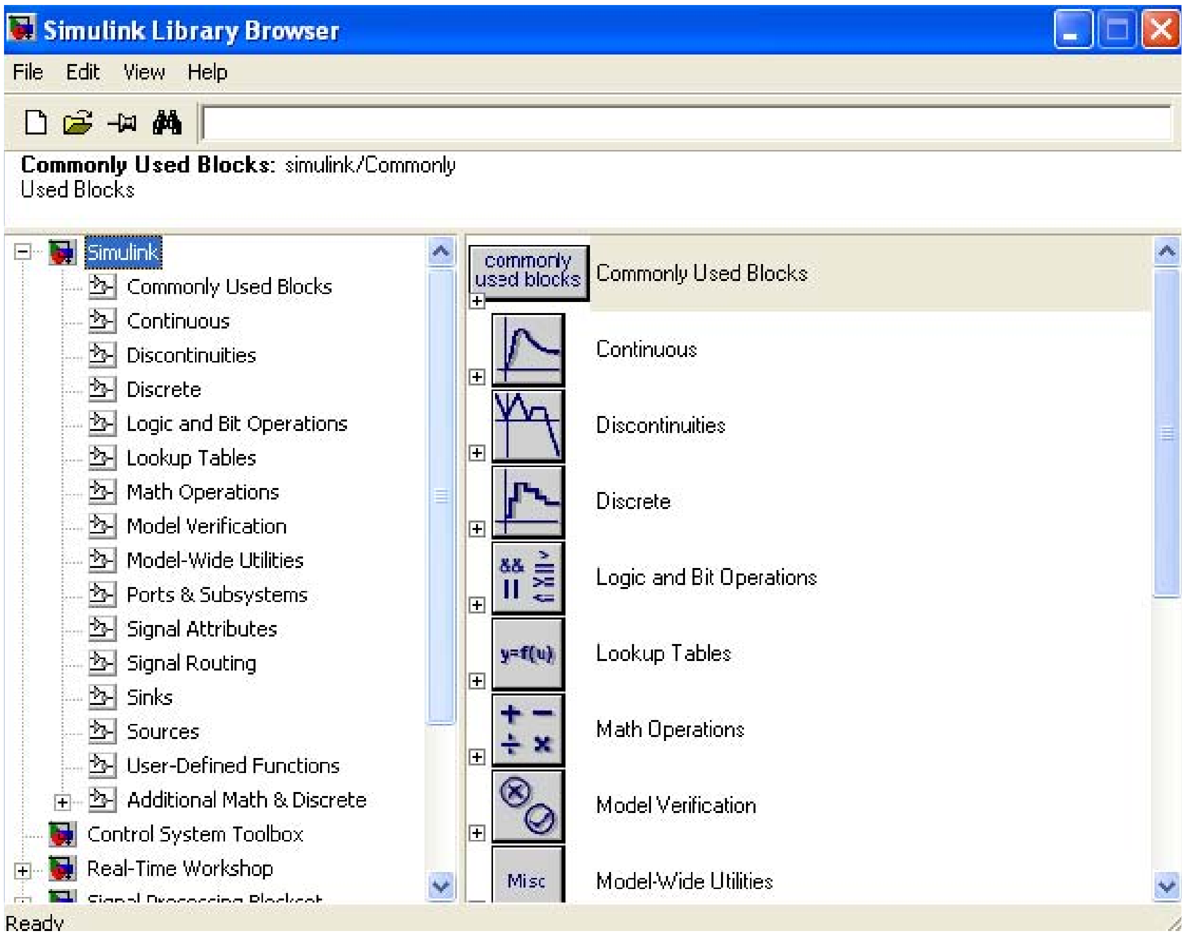


Figure 1.4. The Simulink Library Browser

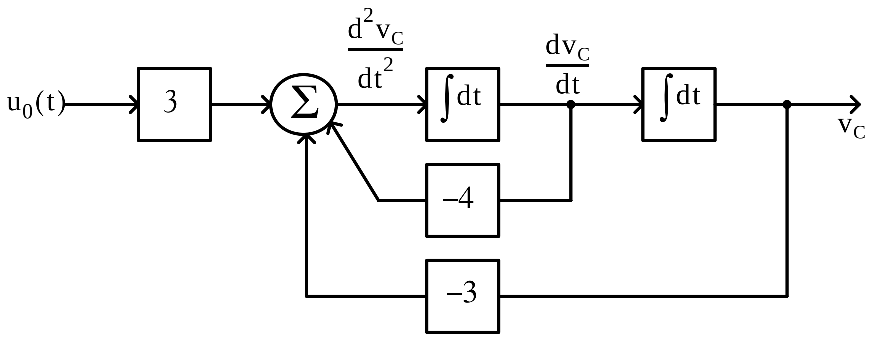


Figure 1.5. Block diagram for equation (1.26)

To model the differential equation (1.26) using Simulink, we perform the following steps:

1. On the **Simulink Library Browser**, we click the leftmost icon shown as a blank page on the top title bar. A new model window named **untitled** will appear as shown in Figure 1.6.

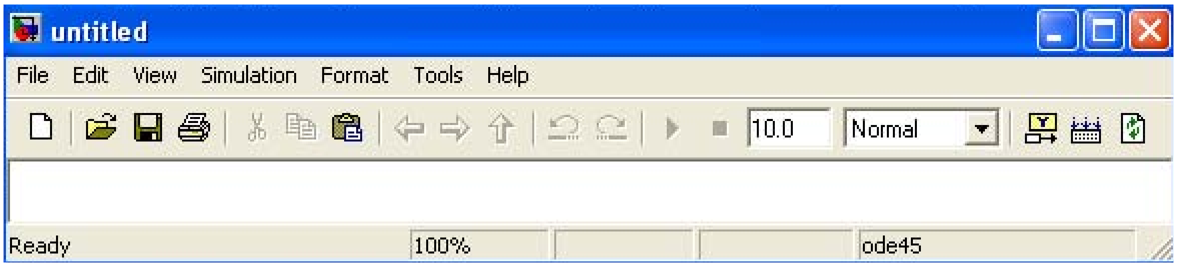


Figure 1.6. The Untitled model window in Simulink.

The window of Figure 1.6 is the model window where we enter our blocks to form a block diagram. We save this as model file name Equation_1_26. This is done from the **File** drop menu of Figure 1.6 where we choose **Save as** and name the file as Equation_1_26. Simulink will add the extension .mdl. The new model window will now be shown as **Equation_1_26**, and all saved files will have this appearance. See Figure 1.7.

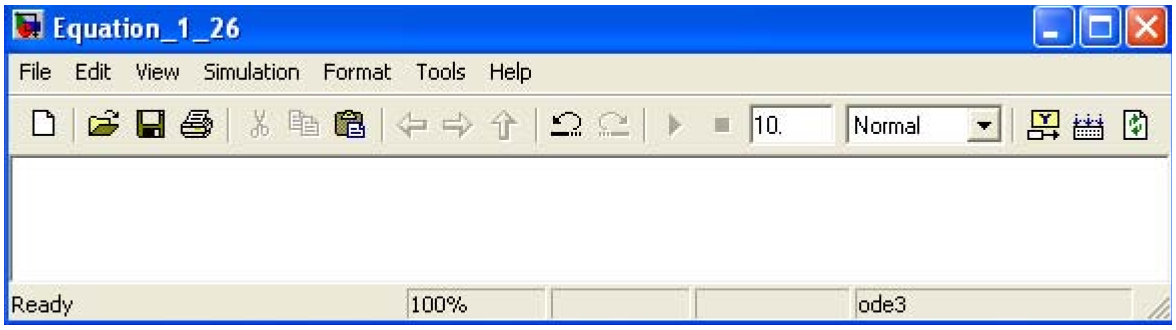


Figure 1.7. Model window for Equation_1_26.mdl file

2. With the **Equation_1_26** model window and the **Simulink Library Browser** both visible, we click the **Sources** appearing on the left side list, and on the right side we scroll down until we see the unit step function block shown as **Step** block. See Figure 1.8. We select it, and we drag it into the **Equation_1_26** model window which now appears as shown in Figure 1.8. We save file Equation_1_26 using the File drop menu on the **Equation_1_26** model window (right side of Figure 1.8).

3. With reference to block diagram of Figure 1.5, we observe that we need to connect an amplifier with Gain 3 to the unit step function block. The Gain block in Simulink is under **Commonly Used Blocks** (first item under Simulink on the **Simulink Library Browser**). See Figure 1.8. If the **Equation_1_26** model window is no longer visible, it can be recalled by clicking on the white page icon on the top bar of the **Simulink Library Browser**.

4. We choose the **Gain** block and we drag it to the right of the Step block (unit step function) as shown in Figure 1.9. The triangle on the right side of the unit step function block and the > symbols on the left and right sides of the gain block are connection points. We point the mouse close to the connection point of the unit step function until is shows as a cross hair, and draw a straight line to connect the two blocks. We double–click the **Gain** block and on the **Function Block Parameters**, we change the gain from unity to 3. See Figure 1.10.

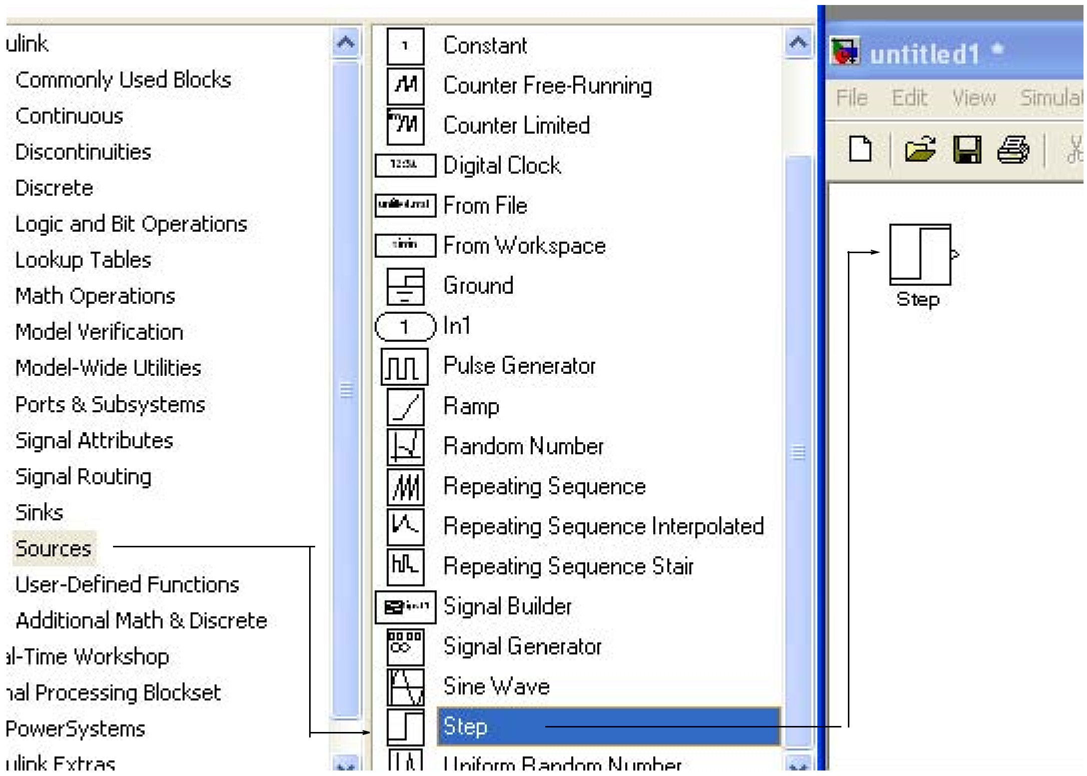


Figure 1.8. Dragging the unit step function into File Equation_1_26

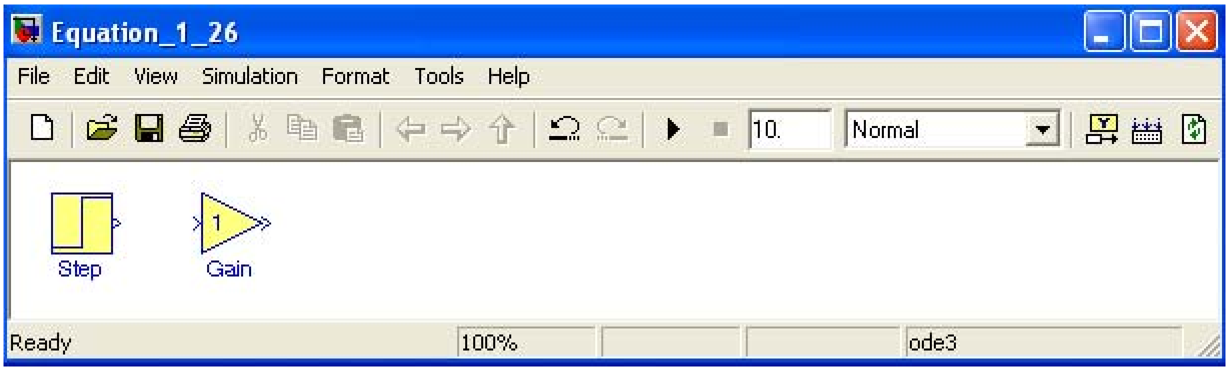
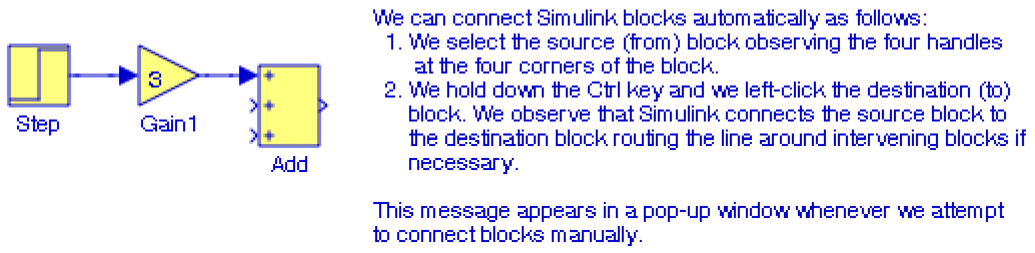


Figure 1.9. File Equation_1_26 with added Step and Gain blocks

5. Next, we need to add a thee–input adder. The adder block appears on the right side of the **Simulink Library Browser** under **Math Operations**. We select it, and we drag it into the Equation_1_26 model window. We double click it, and on the **Function Block Parameters** window which appears**,** we specify 3 inputs. We then connect the output of the **Step** block to the input of the **Gain** block, and the output of the of the **Gain** block to the first input of the **Add** block as shown in Figure 1.10.



We can connect Simulink blocks automatically as follows:
1. We select the source (from) block observing the four handles at the four corners of the block.
2. We hold down the Ctrl key and we left-click the destination (to) block. We observe that Simulink connects the source block to the destination block routing the line around intervening blocks if necessary.

This message appears in a pop-up window whenever we attempt to connect blocks manually.

Figure 1.10. File Equation_1_26 with added Add block and connections between the blocks

6. From the **Commonly Used Blocks** of the **Simulink Library Browser**, we choose the **Integrator** block, we drag it into the Equation_1_26 model window, and we connect it to the output of the **Add** block. We repeat this step and to add a second **Integrator** block. We click the text "Integrator" under the first integrator block, and we change it to Integrator 1. Then, we change the text "Integrator 1" under the second Integrator to "Integrator 2" as shown in Figure 1.11.

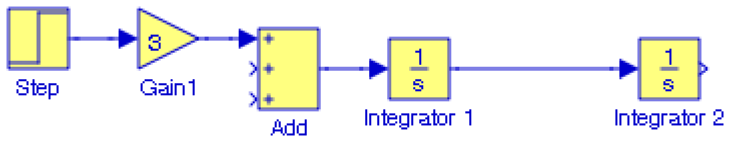


Figure 1.11. File Equation_1_26 with the addition of two integrators

7. To complete the model to represent the block diagram in Figure 1.5, we add the **Scope** block which is found in the **Commonly Used Blocks** on the **Simulink Library Browser**, we click the **Gain** block, and we copy and paste it twice. We flip the pasted **Gain** blocks by using the **Flip Block** command from the **Format** drop menu, and we label these as **Gain 2** and **Gain 3**. Finally, we double–click these gain blocks and in the **Function Block Parameters** dialog box, we change the gains in **Gain 2** and **Gain 3** blocks from unity to –4 and –3 as shown in Figure 1.12.

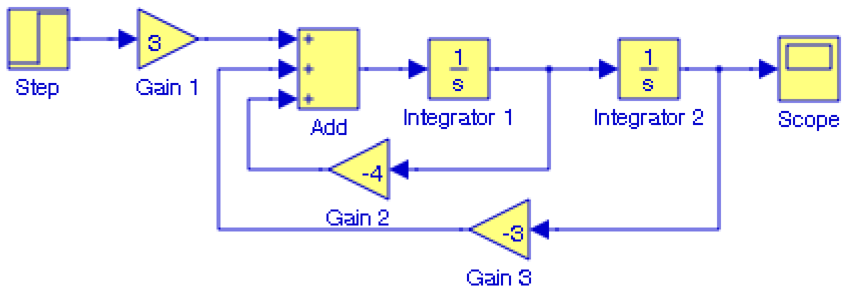


Figure 1.12. File Equation_1_26 complete block diagram

8. The initial conditions $i_L(0^-) = C\left.\frac{dv_C}{dt}\right|_{t=0} = 0$, and $v_c(0^-) = 0.5\ V$ are entered by double–clicking the **Integrator** blocks and entering the values 0 for the first integrator, and 0.5 for the second integrator. To obtain a true picture of the output (voltage across the capacitor), we

double–click the **Unit** block and in the **Source Block Parameters** window we change the **Step time** value from 1 to 0. We leave all other parameters in their default state. We also need to specify the simulation time. This is done by specifying the simulation time to be 10 seconds on the **Configuration Parameters** from the **Simulation** drop menu. We can start the simulation on **Start** from the **Simulation** drop menu or by clicking the ▶ icon.

9. To see the output waveform, we double click the **Scope** block, and then clicking on the Autoscale icon. Then we right–click near the vertical axis, we click on **Axes properties**, we specify **Y–min** =0, **Y–max** = 1.5, we click **OK**, and we obtain the waveform shown in Figure 1.13. Henceforth, we will use this procedure to scale the vertical axis in our subsequent **Scope** block displays.

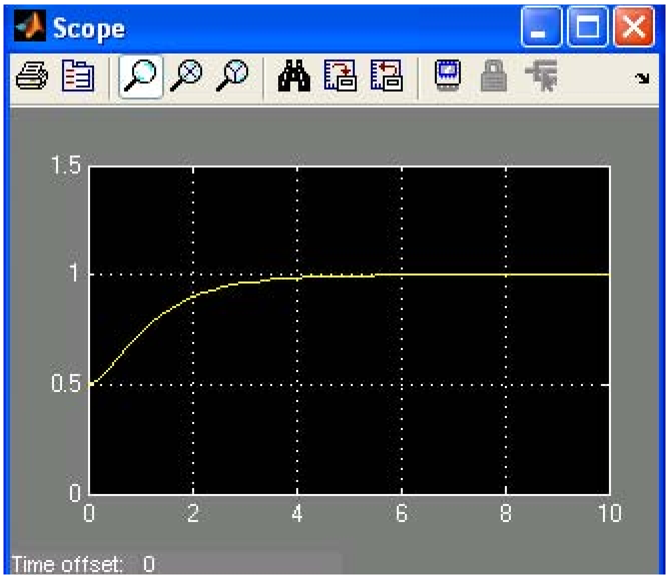
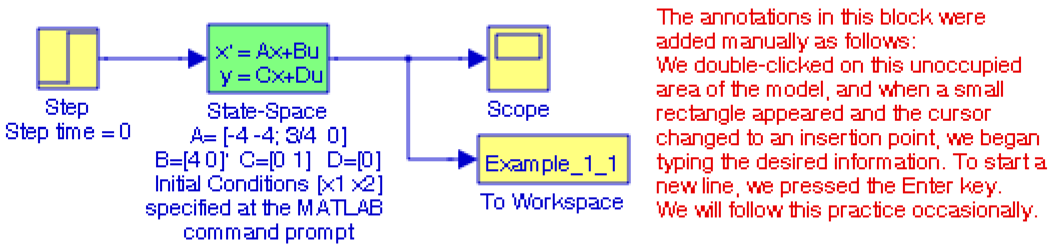


Figure 1.13. The waveform for the function $v_C(t)$ in Example 1.1

Another easier method to obtain and display the output $v_C(t)$ for Example 1.1, is to use **State–Space** block from **Continuous** in the Simulink Library Browser, as shown in Figure 1.14.



The annotations in this block were added manually as follows: We double-clicked on this unoccupied area of the model, and when a small rectangle appeared and the cursor changed to an insertion point, we began typing the desired information. To start a new line, we pressed the Enter key. We will follow this practice occasionally.

Figure 1.14. Obtaining the function $v_C(t)$ for Example 1.1 with the **State–Space** block.

The **simout To Workspace** block shown in Figure 1.14 writes its input to the workspace. In this example, we have assigned the name **Example_1_1** to it, and Simulink appends it with the **.mat** extension. As we know from our MATLAB studies, the data and variables created in the MATLAB Command window, reside in the MATLAB Workspace. This block writes its output to an array or structure that has the name specified by the block's Variable name parameter. It is highly recommended that this block is included in the saved model. This gives us the ability to delete or modify selected variables at a later time. To see what variables reside in the MATLAB Workspace, we issue the command who or whos.*

From Equation 1.23,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -4 & -4 \\ 3/4 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 4 \\ 0 \end{bmatrix} u_0(t)$$

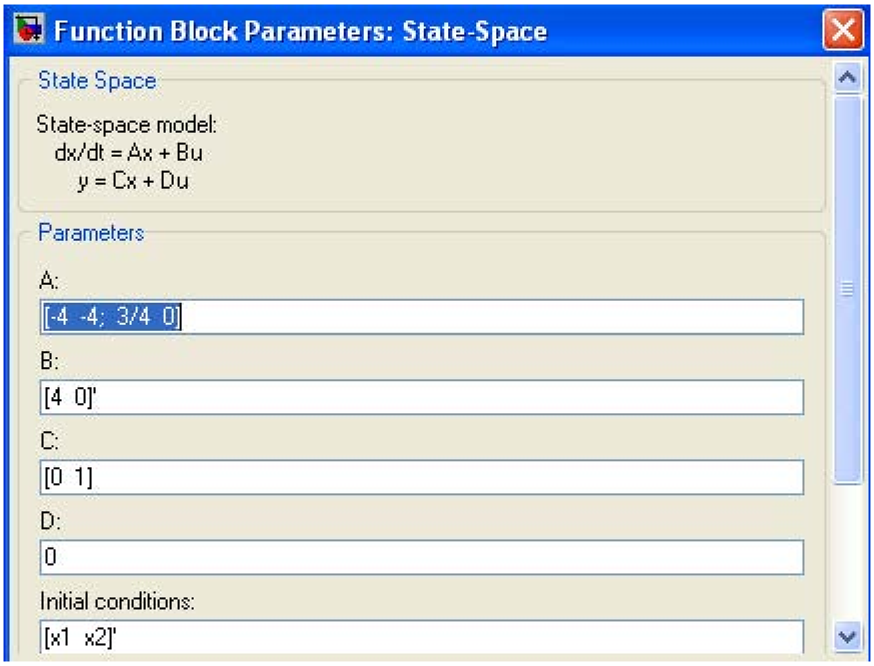
The output equation is

$$y = Cx + du$$

or

$$y = [0 \quad 1] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + [0]u$$

We double–click the **State–Space** block, and in the **Functions Block Parameters** window we enter the constants shown in Figure 1.15.



State Space

State-space model:
dx/dt = Ax + Bu
y = Cx + Du

Parameters

A:
[-4 -4; 3/4 0]

B:
[4 0]'

C:
[0 1]

D:
0

Initial conditions:
[x1 x2]'

Figure 1.15. The Function block parameters for the State–Space block.

* who displays only the variables names, not the function to which each variable belongs. whos lists more information about each variable.

The initials conditions [x1 x2]' are specified at the MATLAB command prompt as

```
x1=0; x2=0.5;
```

As before, to start the simulation we click the ▶ icon, and to see the output waveform, we double click the **Scope** block. Then we click on the **Autoscale** icon, and we scale the vertical axis as we did with the waveform of Figure 1.13. The waveform shown in Figure 1.16.

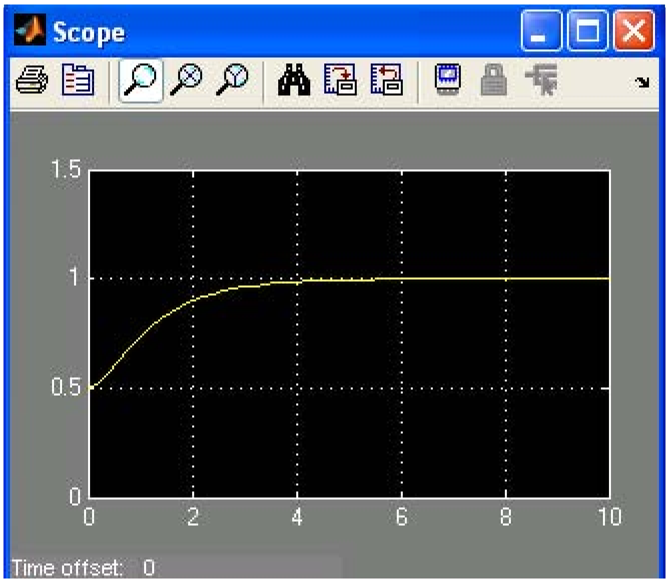


Figure 1.16. The waveform for the function $v_C(t)$ for Example 1.1 with the State–Space block.

The state–space block is the best choice when we need to display the output waveform of three or more variables as illustrated by the following example.

Example 1.2

A fourth–order network is described by the differential equation

$$\frac{d^4y}{dt^4} + a_3\frac{d^3y}{dt^3} + a_2\frac{d^2y}{dt^2} + a_1\frac{dy}{dt} + a_0\,y(t) = u(t) \tag{1.27}$$

where $y(t)$ is the output representing the voltage or current of the network, and $u(t)$ is any input, and the initial conditions are $y(0) = y'(0) = y''(0) = y'''(0) = 0$.

a. We will express (1.27) as a set of state equations

b. It is known that the solution of the differential equation

$$\frac{d^4y}{dt^4} + 2\frac{d^2y}{dt^2} + y(t) = \sin t \tag{1.28}$$

subject to the initial conditions $y(0) = y'(0) = y''(0) = y'''(0) = 0$, has the solution

$$y(t) = 0.125[(3 - t^2) - 3t\cos t] \tag{1.29}$$

In our set of state equations, we will select appropriate values for the coefficients $a_3, a_2, a_1,$ and a_0 so that the new set of the state equations will represent the differential equation of (1.28) and using Simulink, we will display the waveform of the output $y(t)$.

1. The differential equation of (1.28) is of fourth–order; therefore, we must define four state variables that will be used with the four first–order state equations.

We denote the state variables as x_1, x_2, x_3, and x_4, and we relate them to the terms of the given differential equation as

$$x_1 = y(t) \qquad x_2 = \frac{dy}{dt} \qquad x_3 = \frac{d^2y}{dt^2} \qquad x_4 = \frac{d^3y}{dt^3} \tag{1.30}$$

We observe that

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= x_4 \\ \frac{d^4y}{dt^4} = \dot{x}_4 &= -a_0x_1 - a_1x_2 - a_2x_3 - a_3x_4 + u(t) \end{aligned} \tag{1.31}$$

and in matrix form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} u(t) \tag{1.32}$$

In compact form, (1.32) is written as

$$\dot{x} = Ax + bu \tag{1.33}$$

Also, the output is

$$y = Cx + du \tag{1.34}$$

where

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0 & -a_1 & -a_2 & -a_3 \end{bmatrix}, \quad x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \quad \text{and } u = u(t) \tag{1.35}$$

and since the output is defined as

$$y(t) = x_1$$

relation (1.34) is expressed as

$$y = [1 \;\; 0 \;\; 0 \;\; 0] \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + [0]u(t) \tag{1.36}$$

2. By inspection the differential equation of (1.27) will be reduced to the differential equation of (1.28) if we let

$$a_3 = 0 \qquad a_2 = 2 \qquad a_1 = 0 \qquad a_0 = 1 \qquad u(t) = \sin t$$

and thus the differential equation of (1.28) can be expressed in state–space form as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0 & 0 & -2 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \sin t \tag{1.37}$$

where

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix}, \quad A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -a_0 & 0 & -2 & 0 \end{bmatrix}, \quad x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, \quad \text{and } u = \sin t \tag{1.38}$$

Since the output is defined as

$$y(t) = x_1$$

in matrix form it is expressed as

$$y = [1\ \ 0\ \ 0\ \ 0] \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + [0]\sin t \tag{1.39}$$

We invoke MATLAB, we start Simulink by clicking on the Simulink icon, on the **Simulink Library Browser**, we click the **Create a new model** (blank page icon on the left of the top bar), and we save this model as Example_1_2. On the **Simulink Library Browser** we select **Sources**, we drag the **Signal Generator** block on the Example_1_2 model window, we click and drag the **State–Space** block from the **Continuous** on **Simulink Library Browser**, and we click and drag the **Scope** block from the **Commonly Used Blocks** on the **Simulink Library Browser**. We also add the **Display** block found under **Sinks** on the **Simulink Library Browser**. We connect these four blocks and the complete block diagram is as shown in Figure 1.17.

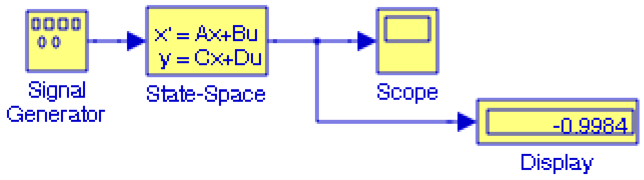


Figure 1.17. Model for Example 1.2 with the entries specified below

We now double–click the **Signal Generator** block and we enter the following in the **Function Block Parameters** dialog box the following:

Wave form: sine

Time (t): Use simulation time

Amplitude: 1

Frequency: 2

Units: Hertz

Next, we double–click the **State–Space** block and we enter the following parameter values in the **Function Block Parameters**:

A: [0 1 0 0; 0 0 1 0; 0 0 0 1; –a0 –a1 –a2 –a3]

B: [0 0 0 1]’

C: [1 0 0 0]

D: [0]

Initial conditions: x0

Absolute tolerance: auto

Now, we switch to the MATLAB Command window and at the command prompt we type the following values:

```
a0=1; a1=0; a2=2; a3=0; x0=[0  0  0  0]';
```

We change the Simulation Stop time to 25, and we start the simulation by clicking on the ▶ icon. To see the output waveform, we double–click the **Scope** block, then we click the Autoscale icon, and we obtain the waveform shown in Figure 1.18.

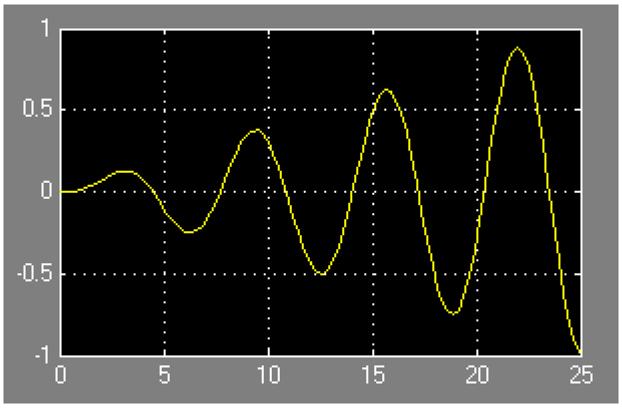


Figure 1.18. Waveform for Example 1.2

The **Display** block in Figure 1.17 shows the value at the end of the simulation stop time.

Examples 1.1 and 1.2 have clearly illustrated that the **State–Space** is indeed a powerful block. We could have also obtained the solution of Example 1.2 using four Integrator blocks.

Example 1.3

We will create a model that will produce the simultaneous solution of three equations with three unknowns using **Algebraic Constraint** blocks found in the **Math Operations** library, **Display** blocks found in the **Sinks** library, and **Gain** blocks found in the **Commonly Used Blocks** library.

The model will display the values for the unknowns z_1, z_2, and z_3 for the system of the equations

$$\begin{aligned} a_1z_1 + a_2z_2 + a_3z_3 + k_1 &= 0 \\ a_4z_1 + a_5z_2 + a_6z_3 + k_2 &= 0 \\ a_7z_1 + a_8z_2 + a_9z_3 + k_3 &= 0 \end{aligned} \tag{1.40}$$

The model is shown in Figure 1.19.

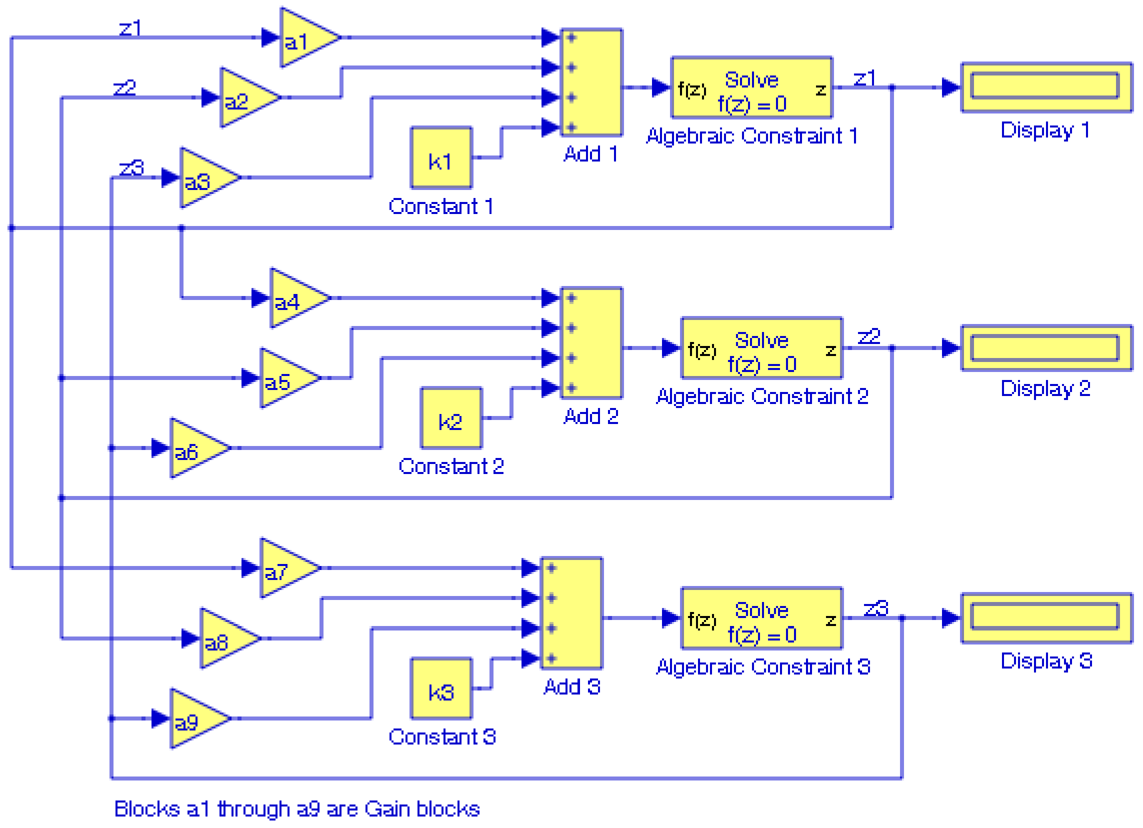


Figure 1.19. Model for Example 1.3 with the entries specified below

Next, at the MATLAB command prompt we enter the following values:

```
a1=2; a2=–3; a3=–1; a4=1; a5=5; a6=4; a7=–6; a8=1; a9=2;...
k1=–8; k2=–7; k3=5;
```

After clicking on the simulation icon, we obtain the values of the unknowns as $z_1 = 2$, $z_2 = -3$, and $z_3 = 5$ as shown in the **Display** blocks in Figure 1.19.

An **Algebraic Constraint** block constrains the input signal $f(z)$ to zero, outputs a value for z, and this value eventually produces a zero at the input. Thus, output is fed back to the input via a feedback path. We can improve the efficiency of the algebraic loop solver by providing an initial guess for the algebraic state z that is close to the final solution value. By default, the initial guess value is zero.

An outstanding feature in Simulink is the representation of a large model consisting of many blocks and lines, to be shown as a single **Subsystem** block.

For instance, to group all blocks and lines in the model of Figure 1.19 except the display blocks, from the **Edit** drop menu we choose **Create Subsystem** and this model will be shown as in Figure 1.20* where at the MATLAB command prompt we have entered the following values:

```
a1=5; a2=–1; a3=4; a4=11; a5=6; a6=9; a7=–8; a8=4; a9=15;...
k1=14; k2=–6; k3=9;
```

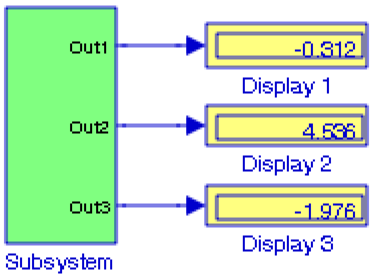


Figure 1.20. The model in Figure 1.19 represented as a subsystem

The Display blocks in Figure 1.20 show the values of z_1, z_2, and z_3 for the values that we specified at the MATLAB command prompt above.

The **Subsystem** block is described in detail in Chapter 2, Section 2.1, Page 2–2.

1.2 Simulink Demos

At this time, the reader with no prior knowledge of Simulink, should be ready to learn Simulink's additional capabilities. We will explore other features in the subsequent chapters. However, it is highly recommended that the reader becomes familiar with the block libraries found in the **Simulink Library Browser**. Then, the reader can follow the steps delineated in The MathWorks Simulink User's Manual to run the Demo Models beginning with the thermo model. This model can invoked by typing thermo at the MATLAB command prompt.

In the subsequent chapters, we will study each of the blocks under each of libraries in the Tree Pane. They are listed in Table 1.1 below in alphabetical order, the library where they appear, the chapter where they are described in this text, section/subsection, and page number in which they are described.

* *The contents of the Subsystem block are not lost. We can double–click on the Subsystem block to see its contents. The Subsystem block replaces the inputs and outputs of the model with Inport and Outport blocks. These blocks along with the Subsystem block are described in Section 2.1, Chapter 2, Page 2–2.*

TABLE 1.1 Simulink blocks

Block Name	Library	Chapter	Section/Subsection	Page
Abs	Math Operations Group	8	8.1.14	8–10
Add	Math Operations Group	8	8.1.2	8–2
Algebraic Constraint	Math Operations Group	8	8.1.23	8–18
Assertion	Model Verification	9	9.9	9–12
Assignment	Vector / Matrix Operations	8	8.2.1	8–19
Atomic Subsystem	Ports & Subsystems	11	11.5	11–4
Averaging Power Spectral Density	Simulink Extras	19	19.3.2	19–37
Averaging Spectrum Analyzer	Simulink Extras	19	19.3.2	19–41
Auto Correlator	Simulink Extras	19	19.3.6	19–45
Backlash	Discontinuities	4	4.7	4–9
Band–Limited White Noise	Signal Generators	15	15.2.12	15–17
Bias	Math Operations Group	8	8.1.5	8–4
Bit Clear	Bit Operations Group	6	6.2.2	6–13
Bit Set	Bit Operations Group	6	6.2.1	6–12
Bitwise Operator	Bit Operations Group	6	6.2.3	6–14
Block Support Table	Modeling Guides	10	10.3	10–9
Bus Assignment	Signal Routing Group	13	13.1.3	13–2
Bus Creator	Commonly Used blocks	2	2.6	2–8
Bus Selector	Commonly Used blocks	2	2.6	2–8
Bus-to-Vector	Signal Attrinutes	12	12.1.10	12–12
Cartesian to Polar	Simulink Extras	19	19.6.2	19–60
Cartesian to Spherical	Simulink Extras	19	19.6.4	19–62
Celsius to Fahrenheit	Simulink Extras	19	19.6.6	19–64
Check Discrete Gradient	Model Verification	9	9.10	9–13
Check Dynamic Gap	Model Verification	9	9.8	9–10
Check Dynamic Lower Bound	Model Verification	9	9.5	9–6
Check Dynamic Range	Model Verification	9	9.7	9–9
Check Dynamic Upper Bound	Model Verification	9	9.6	9–8
Check Input Resolution	Model Verification	9	9.11	9–14
Check Static Gap	Model Verification	9	9.4	9–5
Check Static Lower Bound	Model Verification	9	9.1	9–2
Check Static Range	Model Verification	9	9.3	9–4
Check Static Upper Bound	Model Verification	9	9.2	9–3
Chirp Signal	Signal Generators	15	15.2.9	15–14
Clock	Signal Generators Simulink Extras	15 19	15.2.17 19.4.1	15–26 19–48
CodeReuse Subsystem	Ports & Subsystems	11	11.6	11–9
Combinational Logic	Logic Operations Group	6	6.1.5	6–4
Compare To Constant	Logic Operations Group	6	6.1.7	6–10

TABLE 1.1 Simulink blocks
(con't)

Block Name	Library	Chapter	Section/Subsection	Page
Compare To Zero	Logic Operations Group	6	6.1.6	6–9
Complex to Magnitude–Angle	Complex Vector Conversions Group	8	8.3.1	8–26
Complex to Real–Imag	Complex Vector Conversions Group	8	8.3.3	8–28
Configurable Subsystem	Ports & Subsystems	11	11.8	11–19
Constant	Commonly Used blocks	2	2.4	2–6
Cosine	Lookup Tables	7	7.8	7–17
Coulomb and Viscous Friction	Discontinuities	4	4.11	4–14
Cross Correlator	Simulink Extras	19	19.3.5	19–43
Counter Free–Running	Signal Generators	15	15.2.16	15–24
Counter Limited	Signal Generators	15	15.2.15	15–25
D Flip Flop	Simulink Extras	19	19.4.4	19–51
D Latch	Simulink Extras	19	19.4.2	19–49
Data Store Memory	Signal Storage and Access Group	13	13.2.2	13–19
Data Store Read	Signal Storage and Access Group	13	13.2.1	13–18
Data Store Write	Signal Storage and Access Group	13	13.2.3	13–19
Data Type Conversion	Commonly Used blocks	2	2.17	2–32
Data Type Conversion Inherited	Signal Attribute Manipulation	12	12.1.5	12–5
Data Type Duplicate	Signal Attribute Manipulation	12	12.1.2	12–2
Data Type Propagation	Signal Attribute Manipulation	12	12.1.3	12–4
Data Type Propagation Examples	Signal Attribute Manipulation	12	12.1.10	12–14
Data Type Scaling Strip	Signal Attribute Manipulation	12	12.1.4	12–5
Dead Zone	Discontinuities	4	4.3	4–4
Dead Zone Dynamic	Discontinuities	4	4.4	4–5
Decrement Real World	Increment / Decrement	18	18.2	18–3
Decrement Stored Integer	Increment / Decrement	18	18.4	18–5
Decrement Time To Zero	Increment / Decrement	18	18.6	18–7
Decrement To Zero	Increment / Decrement	18	18.5	18–6
Degrees to Radians	Simulink Extras	19	19.6.7	19–65
Demux	Commonly Used blocks	2	2.7	2–12
Derivative	Continuous–Time Linear Systems	3	3.1.2	3–2
Detect Change	Edge Detection Group	6	6.3.3	6–21
Detect Decrease	Edge Detection Group	6	6.3.2	6–20
Detect Fall Negative	Edge Detection Group	6	6.3.6	6–24
Detect Fall Nonpositive	Edge Detection Group	6	6.3.7	6–25
Detect Increase	Edge Detection Group	6	6.3.1	6–18
Detect Rise Nonnegative	Edge Detection Group	6	6.3.5	6–23

TABLE 1.1 Simulink blocks
(con't)

Block Name	Library	Chapter	Section/Subsection	Page
Detect Rise Positive	Edge Detection Group	6	6.3.4	6–22
Difference	Discrete–Time Linear Systems	5	5.1.8	5–9
Digital Clock	Signal Generators	15	15.2.18	15–27
Direct Lookup Table (n–D)	Lookup Tables	7	7.6	7–10
Discrete Derivative	Discrete–Time Linear Systems	5	5.1.9	5–10
Discrete Filter	Discrete–Time Linear Systems	5	5.1.6	5–5
Discrete FIR Filter	Discrete–Time Linear Systems	5	5.1.14	5-19
Discrete State–Space	Discrete–Time Linear Systems	5	5.1.10	5–11
Discrete Time Integrator	Commonly Used blocks	2	2.16	2–29
Discrete Transfer Fcn	Discrete–Time Linear Systems	5	5.1.5	5–4
Discrete Transfer Fcn (with initial outputs)	Simulink Extras	19	19.1.2	19-5
Discrete Transfer Fcn (with initial states)	Simulink Extras	19	19.1.1	19-2
Discrete Zero–Pole	Discrete–Time Linear Systems	5	5.1.7	5–8
Discrete Zero–Pole (with initial outputs)	Simulink Extras	19	19.1.4	19-12
Discrete Zero–Pole (with initial states)	Simulink Extras	19	19.1.3	19-8
Display	Data Viewers	14	14.2.4	14–16
Divide	Math Operations Group	8	8.1.10	8–7
Doc Text (DocBlock)	Documentation	10	10.2.2	10–9
Dot Product	Math Operations Group	8	8.1.12	8–8
Embedded MATLAB Function	User–Defined Functions	16	16.3	16–3
Enable	Ports & Subsystems	11	11.3	11–2
Enabled and Triggered Subsystem	Ports & Subsystems	11	11.11	11–30
Enabled Subsystem	Ports & Subsystems	11	11.10	11–27
Environment Controller	Signal Routing Group	13	13.1.9	13–10
Extract Bits	Bit Operations Group	6	6.2.5	6–17
Fahrenheit to Celsius	Simulink Extras	19	19.6.5	19–63
Fcn	User–Defined Functions	16	16.1	16–2
First–Order Hold	Sample & Hold Delays	5	5.2.2	5–22
Fixed–Point State–Space	Additional Discrete	17	17.3	17–4
Floating Bar Plot	Simulink Extras	19	19.3.7	19–46
Floating Scope	Data Viewers	14	14.2.2	14–8
For Iterator Subsystem	Ports & Subsystems	11	11.13	11–37
From	Signal Routing Group	13	13.1.13	13–14
From File	Models and Subsystems Inputs	15	15.1.3	15–2

TABLE 1.1 Simulink blocks
(con't)

Block Name	Library	Chapter	Section/Subsection	Page
From Workspace	Models and Subsystems Inputs	15	15.1.4	15−2
Function−Call Generator	Ports & Subsystems	11	11.4	11−3
Function−Call Subsystem	Ports & Subsystems	11	11.12	11−34
Gain	Commonly Used blocks	2	2.10	2−18
Goto	Signal Routing Group	13	13.1.15	13−16
Goto Tag Visibility	Signal Routing Group	13	13.1.14	13−15
Ground	Commonly Used blocks	2	2.2	2−4
Hit Crossing	Discontinuities	4	4.10	4−13
IC (Initial Condition)	Signal Attribute Manipulation	12	12.1.6	12−6
If	Ports & Subsystems	11	11.15	11−41
If Action Subsystem	Ports & Subsystems	11	11.15	11−41
Increment Real World	Increment / Decrement	18	18.1	18−2
Increment Stored Integer	Increment / Decrement	18	18.3	18−4
Index Vector	Signal Routing Group	13	13.1.7	13−8
Inport	Commonly Used blocks	2	2.1	2−2
Integer Delay	Discrete−Time Linear Systems	5	5.1.2	5−2
Integrator	Commonly Used blocks	2	2.14	2−22
Interpolation (n−D) Using PreLookup	Lookup Tables	7	7.5	7−8
Interval Test	Logic Operations Group	6	6.1.3	6−2
Interval Test Dynamic	Logic Operations Group	6	6.1.4	6−3
J−K Flip Flop	Simulink Extras	19	19.4.5	19−52
Level−2 M−File S−Function	User−Defined Functions	16	16.5	16−7
Logical Operator	Commonly Used blocks	2	2.12	2−20
Lookup Table	Lookup Tables	7	7.1	7−2
Lookup Table (2−D)	Lookup Tables	7	7.2	7−3
Lookup Table (n−D)	Lookup Tables	7	7.3	7−6
Lookup Table Dynamic	Lookup Tables	7	7.7	7−16
Magnitude−Angle to Complex	Complex Vector Conversions Group	8	8.3.2	8−27
Manual Switch	Signal Routing Group	13	13.1.10	13−12
Math Function	Math Operations Group	8	8.1.16	8−11
MATLAB Fcn	User−Defined Functions	16	16.2	16−3
Matrix Concatenate	Vector / Matrix Operations	8	8.2.3	8−23
Memory	Sample & Hold Delays	5	5.2.1	5−21
Merge	Signal Routing Group	13	13.1.8	13−8
MinMax	Math Operations Group	8	8.1.19	8−14
MinMax Running Resettable	Math Operations Group	8	8.1.20	8−15

TABLE 1.1 Simulink blocks
(con't)

Block Name	Library	Chapter	Section/Subsection	Page
Model	Ports & Subsystems	11	11.7	11−17
Model Info	Documentation	10	10.2.1	10−7
Multiport Switch	Signal Routing Group	13	13.1.11	13−13
Mux	Commonly Used blocks	2	2.7	2−12
Outport	Commonly Used blocks	2	2.1	2−2
Permute	Math Operations Group	8	8.2.6	8−25
PID Controller	Simulink Extras	19	19.2.6	19−29
PID Controller (with approximate derivative)	Simulink Extras	19	19.2.7	19−31
Polar to Cartesian	Simulink Extras	19	19.6.1	19−59
Polynomial	Math Operations Group	8	8.1.18	8−14
Power Spectral Density	Simulink Extras	19	19.3.1	19−33
Prelookup Index Search	Lookup Tables	7	7.4	7−7
Probe	Signal Attribute Detection	12	12.2.1	12−17
Product	Commonly Used blocks	2	2.4	2−6
Product of Elements	Math Operations Group	8	8.1.11	8−7
Pulse Generator	Signal Generators	15	15.2.3	15−5
Quantizer	Discontinuities	4	4.9	4−12
Radians to Degrees	Simulink Extras	19	19.6.8	19−65
Ramp	Signal Generators	15	15.2.5	15−9
Random Number	Signal Generators	15	15.2.10	15−15
Rate Limiter	Discontinuities	4	4.5	4−6
Rate Limiter Dynamic	Discontinuities	4	4.6	4−8
Rate Transition	Signal Attribute Manipulation	12	12.1.8	12−8
Real−Imag to Complex	Complex Vector Conversions Group	8	8.3.4	8−29
Relational Operator	Commonly Used blocks	2	2.11	2−19
Relay	Discontinuities	4	4.8	4−11
Repeating Sequence	Signal Generators	15	15.2.8	15−13
Repeating Sequence Interpolated	Signal Generators	15	15.2.14	15−22
Repeating Sequence Stair	Signal Generators	15	15.2.13	15−22
Reshape	Vector / Matrix Operations	8	8.2.2	8−21
Rounding Function	Math Operations Group	8	8.1.17	8−13
S−Function	Ports & Subsystems User−Defined Functions	11 16	11.18 16.4	11−49 16−7
S−Function Builder	User−Defined Functions	16	16.6	16−11
S−Function Examples	User−Defined Functions	16	16.7	16−11
S−R Flip Flop	Simulink Extras	19	19.4.3	19−50

TABLE 1.1 Simulink blocks
(con't)

Block Name	Library	Chapter	Section/Subsection	Page
Saturation	Commonly Used blocks Discontinuities	2 4	2.13 4.1	2−21 4−2
Saturation Dynamic	Discontinuities	4	4.2	4−3
Scope	Data Viewers	14	14.2.1	14−6
Selector	Signal Routing Group	13	13.1.6	13−6
Shift Arithmetic	Bit Operations Group	6	6.2.4	6−16
Sign	Math Operations Group	8	8.1.13	8−9
Signal Builder	Signal Generators	15	15.2.4	15−6
Signal Conversion	Signal Attribute Manipulation	12	12.1.7	12−7
Signal Generator	Signal Generators	15	15.2.2	15−4
Signal Specification	Signal Attribute Manipulation	12	12.1.9	12−11
Sine	Lookup Tables	7	7.8	7−17
Sine Wave	Signal Generators	15	15.2.6	15−9
Sine Wave Function	Math Operations Group	8	8.1.22	8−17
Slider Gain	Math Operations Group	8	8.1.8	8−6
Spectrum Analyzer	Simulink Extras	19	19.33	19−38
Spherical to Cartesian	Simulink Extras	19	19.6.3	19−61
Squeeze	Math Operations Group	8	8.2.3	8−21
State−Space	Continuous−Time Linear Systems	3	3.1.3	3−7
State−Space (with initial outputs)	Simulink Extras	19	19.2.5	19−27
Step	Signal Generators	15	15.2.7	15−12
Stop Simulation	Simulation Control	14	14.3	14−17
Subsystem	Commonly Used blocks	2	2.1	2−2
Subsystem Examples	Ports & Subsystems	11	11.17	11−46
Subtract	Math Operations Group	8	8.1.3	8−3
Sum	Commonly Used blocks	2	2.9	2−17
Sum of Elements	Math Operations Group	8	8.1.4	8−4
Switch	Commonly Used blocks	2	2.8	2−15
Switch Case	Ports & Subsystems	11	11.16	11−43
Switch Case Action Subsystem	Ports & Subsystems	11	11.16	11−43
Switched Derivative for Linearization	Simulink Extras	19	19.5.1	19−53
Switched Transport Delay for Linearization	Simulink Extras	19	19.5.2	19−56
Tapped Delay	Discrete−Time Linear Systems	5	5.1.3	5−3

TABLE 1.1 Simulink blocks

(con't)

Block Name	Library	Chapter	Section/Subsection	Page
Terminator	Commonly Used blocks	2	2.3	2−5
Time−Based Linearization	Linearization of Running Models	10	10.1.2	10−4
To File	Model and Subsystem Outputs	14	14.1.3	14−2
To Workspace	Model and Subsystem Outputs	14	14.1.4	14−4
Transfer Fcn	Continuous−Time Linear Systems	3	3.1.4	3−7
Transfer Fcn Direct Form II	Additional Discrete	17	17.1	17−2
Transfer Fcn Direct Form II Time Varying	Additional Discrete	17	17.2	17−3
Transfer Fcn First Order	Discrete−Time Linear Systems	5	5.1.11	5−14
Transfer Fcn Lead or Lag	Discrete−Time Linear Systems	5	5.1.12	5−15
Transfer Fcn Real Zero	Discrete−Time Linear Systems	5	5.1.13	5−18
Transfer Fcn (with initial outputs)	Simulink Extras	19	19.2.2	19-21
Transfer Fcn (with initial states)	Simulink Extras	19	19.2.1	19-18
Transport Delay	Continuous−Time Delay	3	3.2.1	3−11
Trigger	Ports & Subsystems	11	11.2	11−2
Trigger−Based Linearization	Linearization of Running Models	10	10.1.1	10−2
Triggered Subsystem	Ports & Subsystems	11	11.9	11−25
Trigonometric Function	Math Operations Group	8	8.1.21	8−16
Unary Minus	Math Operations Group	8	8.1.15	8−11
Uniform Random Number	Signal Generators	15	15.2.11	15−16
Unit Delay	Commonly Used blocks	2	2.15	2−27
Unit Delay Enabled	Additional Discrete	17	17.7	17−9
Unit Delay Enabled External IC	Additional Discrete	17	17.9	17−12
Unit Delay Enabled Resettable	Additional Discrete	17	17.8	17−11
Unit Delay Enabled Resettable External IC	Additional Discrete	17	17.10	17−13
Unit Delay External IC	Additional Discrete	17	17.4	17−6
Unit Delay Resettable	Additional Discrete	17	17.5	17−7
Unit Delay Resettable External IC	Additional Discrete	17	17.6	17−8
Unit Delay With Preview Enabled	Additional Discrete	17	17.13	17−17
Unit Delay With Preview Enabled Resettable	Additional Discrete	17	17.14	17−19
Unit Delay With Preview Enabled Resettable External RV	Additional Discrete	17	17.15	17−20

TABLE 1.1 Simulink blocks
(con't)

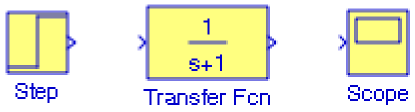
Block Name	Library	Chapter	Section/Subsection	Page
Unit Delay With Preview Resettable	Additional Discrete	17	17.11	17−15
Unit Delay With Preview Resettable External RV	Additional Discrete	17	17.12	17−16
Variable Time Delay	Continuous−Time Delay	3	3.2.2	3−12
Variable Transport Delay	Continuous−Time Delay	3	3.2.3	3−13
Vector Concatenate	Vector / Matrix Operations	8	8.2.4	8−24
Weighted Sample Time	Signal Attribute Detection	12	12.2.2	12−18
Weighted Sample Time Math	Math Operations Group	8	8.1.6	8−5
While Iterator Subsystem	Ports & Subsystems	11	11.14	11−39
Width	Signal Attribute Detection	12	12.2.3	12−19
Wrap To Zero	Discontinuities	4	4.12	4−16
XY Graph	Data Viewers	14	14.2.3	14−12
Zero−Order Hold	Sample & Hold Delays	5	5.2.3	5−23
Zero−Pole	Continuous−Time Linear Systems	3	3.1.5	3−9
Zero−Pole (with initial outputs)	Simulink Extras	19	19.2.4	19−26
Zero−Pole (with initial states)	Simulink Extras	19	19.2.3	19−23

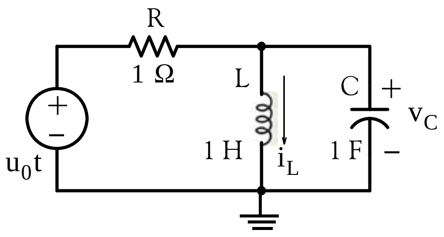
1.3 Summary

- MATLAB and Simulink are integrated and thus we can analyze, simulate, and revise our models in either environment at any point. We invoke Simulink from within MATLAB.
- When Simulink is invoked, the Simulink Library Browser appears. The left side is referred to as the Tree Pane and displays all libraries installed. The right side is referred to as the Contents Pane and displays the blocks that reside in the library currently selected in the Tree Pane.
- We open a new model window by clicking on the blank page icon that appears on the leftmost position of the top title bar. On the Simulink Library Browser, we highlight the desired library in the Tree Pane, and on the Contents Pane we click and drag the desired block into the new model. Once saved, the model window assumes the name of the file saved. Simulink adds the extension `.mdl`.
- The > and < symbols on the left and right sides of a block are connection points.
- We can change the parameters of any block by double–clicking it, and making changes in the Function Block Parameters window.
- We can specify the simulation time on the **Configuration Parameters** from the **Simulation** drop menu. We can start the simulation on **Start** from the **Simulation** drop menu or by clicking on the icon. To see the output waveform, we double click on the **Scope** block, and then clicking on the **Autoscale** icon.
- It is highly recommended that the **simout To Workspace** block be added to the model so all data and variables are saved in the MATLAB workspace. This gives us the ability to delete or modify selected variables at a later time. To see what variables reside in the MATLAB Workspace, we issue the command `who` or `whos`.
- The state–space block is the best choice when we need to display the output waveform of three or more variables.
- We can use Algebraic Constrain blocks found in the Math Operations library, Display blocks found in the Sinks library, and Gain blocks found in the Commonly Used Blocks library, to draw a model that will produce the simultaneous solution of two or more equations with two or more unknowns.
- The Algebraic Constraint block constrains the input signal f(z) to zero and outputs an algebraic state z. The block outputs the value necessary to produce a zero at the input. The output must affect the input through some feedback path. This enables us to specify algebraic equations for index 1 differential/algebraic systems (DAEs). By default, the Initial guess parameter is zero. We can improve the efficiency of the algebraic loop solver by providing an Initial guess for the algebraic state z that is close to the solution value.

1.4 Exercises

1. Use Simulink with the **Step** function block, the **Continuous–Time Transfer Fcn** block, and the **Scope** block shown, to simulate and display the output waveform v_C of the electric RLC circuit[*] shown below where $u_0(t)$ is the unit step function, and the initial conditions are $i_L(0) = 0$, and $v_C(0) = 0$.





2. Repeat Exercise 1 using integrator blocks in lieu of the transfer function block.

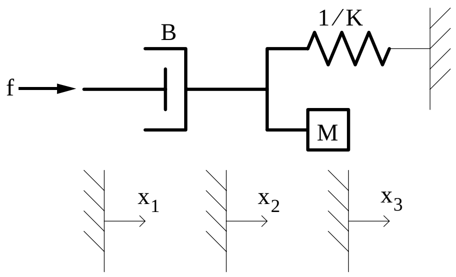
3. Repeat Exercise 1 using the **State Space** block in lieu of the transfer function block.

4. Using the **State–Space** block, create a model for the differential equation shown below.

$$\frac{d^2v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 2\sin(t+30°) - 5\cos(t+60°)$$

subject to the initial conditions $v_C(0^-) = 0$, and $v'_C(0^-) = 0.5\ \text{V}$

* *The electric circuits presented in this texts can be easily converted to their mechanical equivalent circuits where a voltage source can be replaced by a force f, a resistor can be replaced by a dashpot B, an inductor can be replaced by a mass M, and a capacitor can be replaced by an inverse spring constant 1/K. Thus the mechanical analog of the electric circuit above can be converted to the mechanical system shown below.*



1.5 Solutions to End–of–Chapter Exercises

Dear Reader:

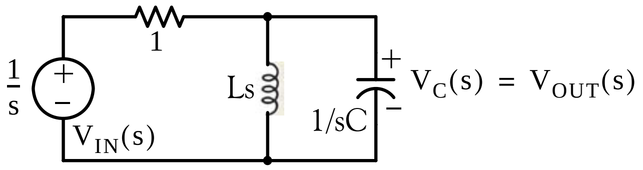
The remaining pages on this chapter contain solutions to all end–of–chapter exercises.

You must, for your benefit, make an honest effort to solve these exercises without first looking at the solutions that follow. It is recommended that first you go through and solve those you feel that you know. For your solutions that you are uncertain, look over your procedures for inconsistencies and computational errors, review the chapter, and try again. Refer to the solutions as a last resort and rework those problems at a later date.

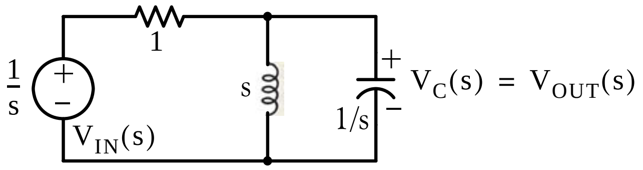
You should follow this practice with all end–of–chapter exercises in this book.

1.

The s–domain equivalent circuit is shown below.



and by substitution of the given circuit constants,



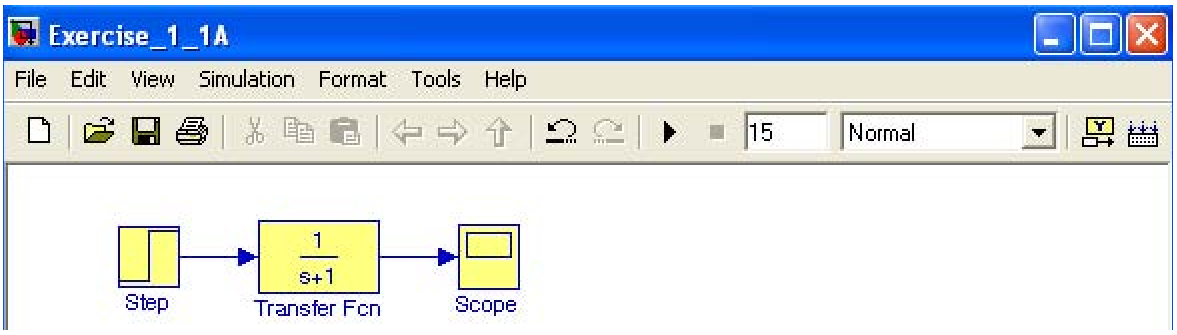
By the voltage division expression,

$$V_{OUT}(s) = \frac{(s \cdot 1/s)/(s + 1/s)}{(s \cdot 1/s)/(s + 1/s) + 1} \cdot V_{IN}(s) = \frac{s}{s^2 + s + 1} \cdot V_{IN}(s)$$

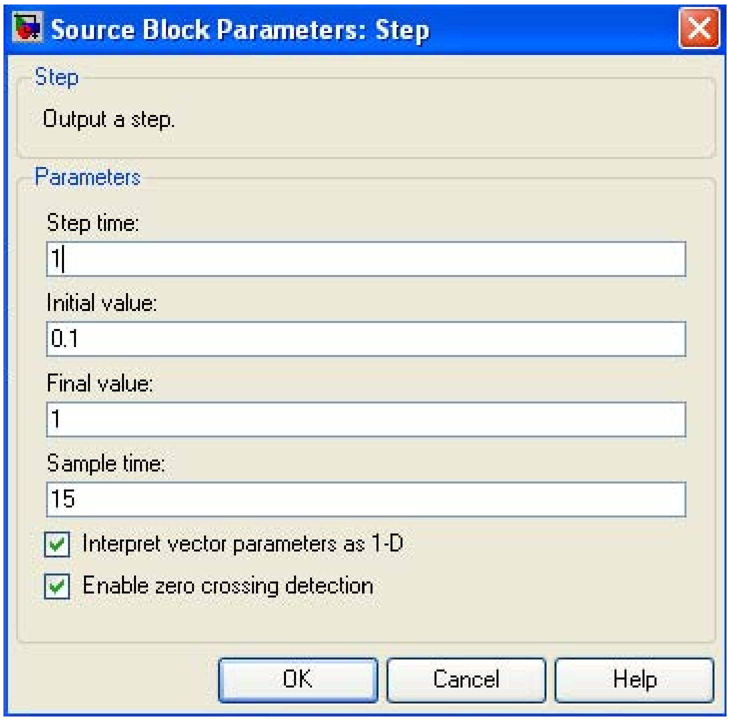
from which

$$\text{Transfer function} = G(s) = \frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{s}{s^2 + s + 1}$$

We invoke Simulink from the MATLAB environment, we open a new file by clicking on the blank page icon at the upper left on the task bar, we name this file Exercise_1_1, and from the **Sources**, **Continuous**, and **Commonly Used Blocks** in the **Simulink Library Browser**, we select and interconnect the desired blocks as shown below.



As we know, the unit step function is undefined at $t = 0$. Therefore, we double click the **Step** block, and in the **Source Block Parameters** dialog box shown below we enter the values indicated. Likewise, we double click the **Transfer Fcn** block and in the **Source Block Parameters** dialog box we enter the values indicated.



Source Block Parameters: Step

Step

Output a step.

Parameters

Step time:

1

Initial value:

0.1

Final value:

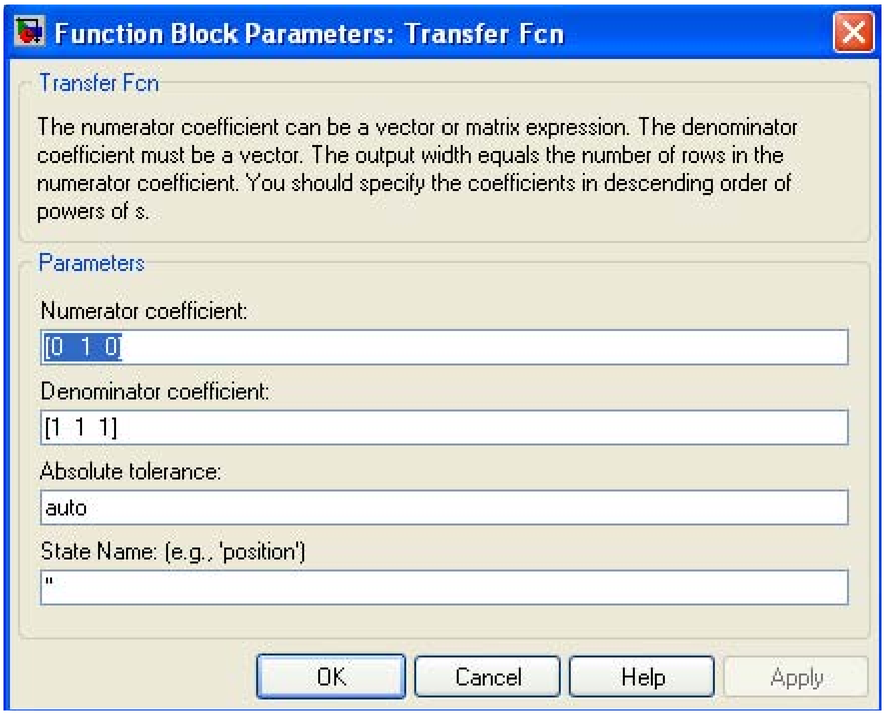
1

Sample time:

15

✓ Interpret vector parameters as 1-D

✓ Enable zero crossing detection



Function Block Parameters: Transfer Fcn

Transfer Fcn

The numerator coefficient can be a vector or matrix expression. The denominator coefficient must be a vector. The output width equals the number of rows in the numerator coefficient. You should specify the coefficients in descending order of powers of s.

Parameters

Numerator coefficient:

[0 1 0]

Denominator coefficient:

[1 1 1]

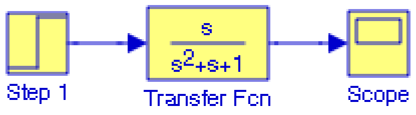
Absolute tolerance:

auto

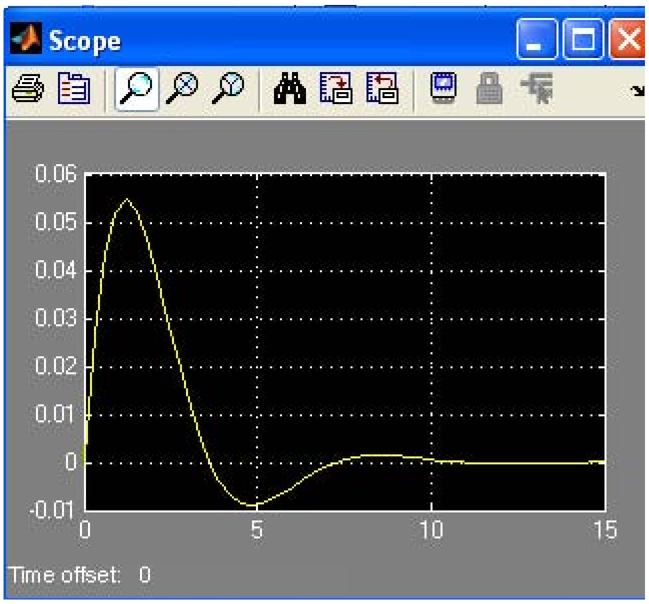
State Name: (e.g., 'position')

''

The model now appears as shown below.



On the model window, we click the **Start Simulation** ▸ icon and at the end of the simulation, we double–click the **Scope** block. The **Scope** block displays the waveform shown below after clicking the Autoscale icon. We observe that at the end of the simulation period (15 sec), the value across the capacitor is 0 and this is to be expected since at this time the inductor behaves as a short, thereby shorting the capacitor.



Let us compare the above waveform with that obtained with MATLAB using the **plot** command. We want the output of the given circuit which we have defined as $v_{out}(t) = v_C(t)$. The input is the unit step function whose Laplace transform is $1/s$. Thus, in the complex frequency domain,

$$V_{OUT}(s) = G(s) \cdot V_{IN}(s) = \frac{s}{s^2+s+1} \cdot \frac{1}{s} = \frac{1}{s^2+s+1}$$

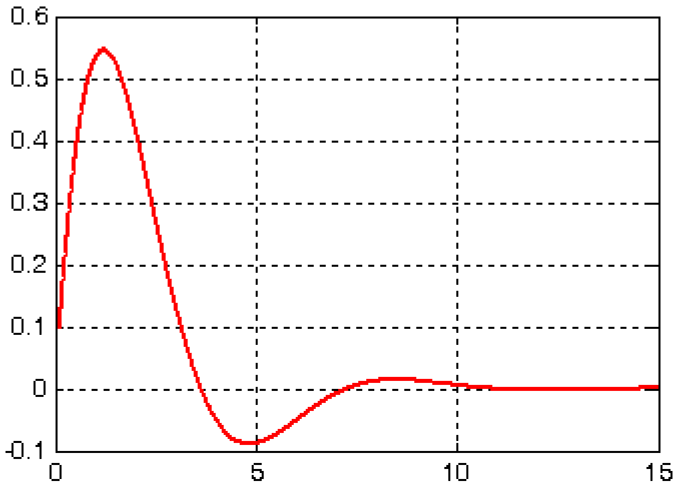
We obtain the Inverse Laplace transform of $1/(s^2+s+1)$ with the following MATLAB script:

```
syms s
fd=ilaplace(1/(s^2+s+1))
```

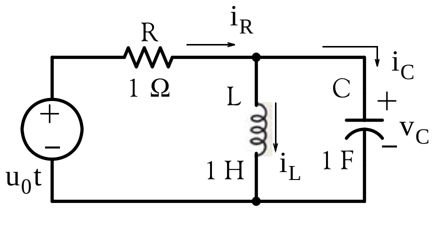
```
fd = 2/3*3^(1/2)*exp(-1/2*t)*sin(1/2*3^(1/2)*t)
```

```
t=0.1:0.01:15; td=2./3.*3.^(1./2).*exp(–1./2.*t).*sin(1./2.*3.^(1./2).*t); plot(t,td); grid
```

The plot shown below is identical to that shown above which was obtained with Simulink.



2.



By Kirchoff's Current Law (KCL),

$$i_L + i_C = i_R$$

$$\frac{1}{L}\int_0^t v_L dt + C\frac{dv_C}{dt} = \frac{1 - v_C}{R}$$

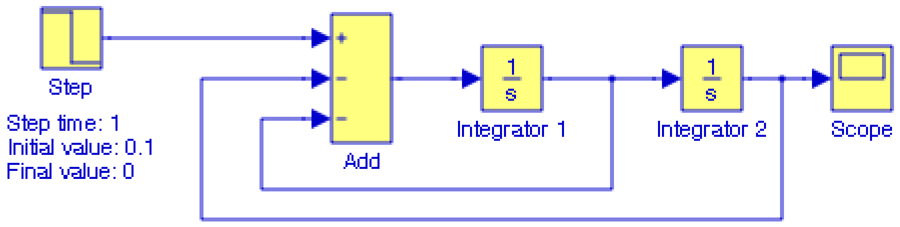
By substitution of the circuit constants, observing that $v_L = v_C$, and differentiating the above integro–differential equation, we obtain

$$\frac{d^2v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 0$$

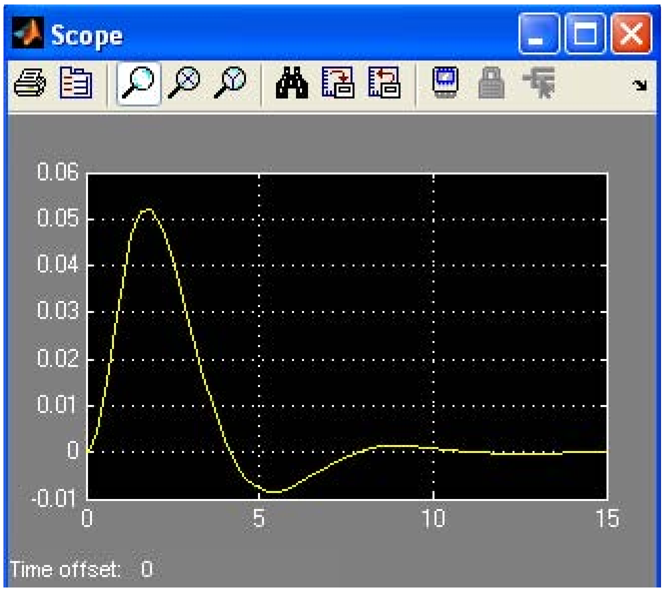
or

$$\frac{d^2v_C}{dt^2} = -\frac{dv_C}{dt} - v_C$$

Invoking MATLAB, starting Simulink, and following the procedures of the examples and Exercise 1, we create the new model Exercise_1_2, shown below where for the **Step** block we specified Final value 0 to account for the fact that the final value across the capacitor will be zero since it will be shorted by the inductor. We double–click the **Integrator 1** block and in the **Function Block Parameters** window we set the initial value to 0. We repeat this step for the **Integrator 2** block and we also set the initial value to 0.

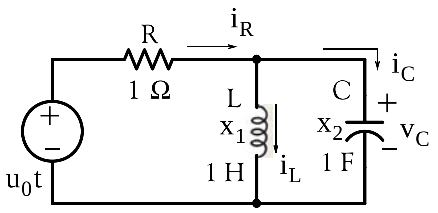


We start the simulation, and double–clicking the **Scope** block we obtain the graph shown below.



3.

We assign state variables x_1 and x_2 as shown below where $x_1 = i_L$ and $x_2 = v_C$.



Then,

$$\dot{x}_1 = x_2$$

$$\frac{x_2 - u_0 t}{1} + x_1 + \dot{x}_2 = 0$$

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = -x_1 - x_2 + u_0 t$$

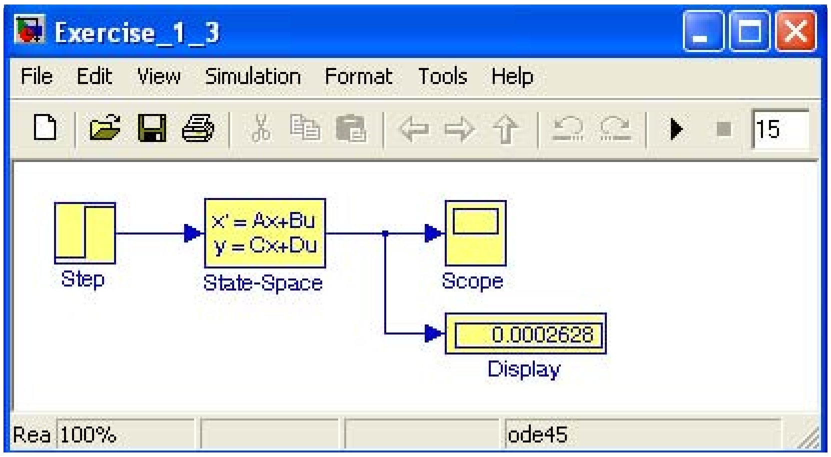
$$\dot{x}_1 = Ax + Bu \rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_0 t$$

$$y = Cx + Du \rightarrow \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} u_0 t$$

and the initial conditions are

$$x0 = \begin{bmatrix} x_{10} \\ x_{20} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

We form the model below and we name it Exercise_1_3.



We double–click the **State–Space** block and we enter the following parameters:

A=[0 1; –1 –1]

B=[0 1]'

C=[0 1]'

D=[0]

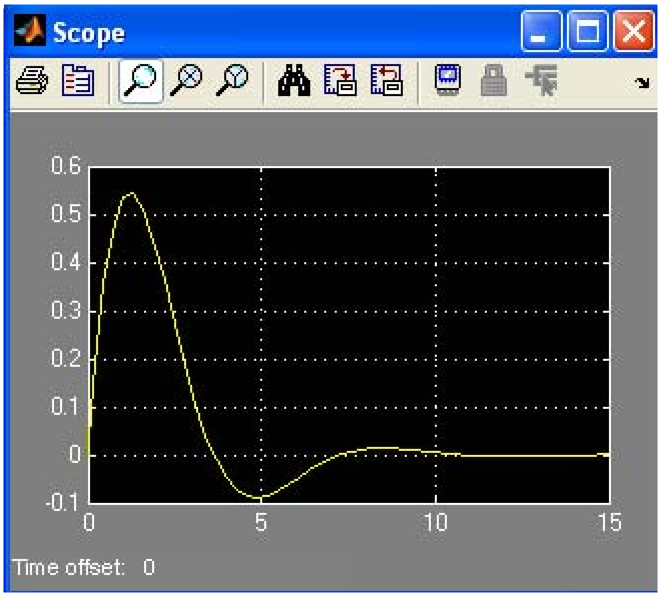
Initial conditions: x0

The initial conditions are entered at the MATLAB command prompt as follows:

```
x0=[0 0]'; % This is a column vector
```

To avoid the unit step function discontinuity at $t = 0$, we double–click the **Step** block, and in the **Source Block Parameters** dialog box, we change the Initial value from 0 to 1.

The Display block shows the output value at the end of the simulation time, in this case 15. We click the **Simulation start** icon, we double–click the **Scope** block, and the output waveform is as shown below. We observe that this waveform is the same as in Exercises 1 and 2.



4.

$$\frac{d^2v_C}{dt^2} + \frac{dv_C}{dt} + v_C = 2\sin(t+30°) - 5\cos(t+60°)$$

subject to the initial conditions $v_c(0^-) = 0$, and $v'_c(0^-) = 0.5\ V$

We let $x_1 = v_C$ and $x_2 = \frac{dv_C}{dt}$. Then, $\dot{x}_1 = \frac{dv_C}{dt} = x_2$, and $\dot{x}_2 = \frac{d^2v_C}{dt^2}$. Expressing the given equation as

$$\frac{d^2v_C}{dt^2} = -\frac{dv_C}{dt} - v_C + 2\sin(t+30°) - 5\cos(t+60°) = -x_2 - x_1 + 2\sin(t+30°) - 5\cos(t+60°)$$

we obtain the state–space equations

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -x_2 - x_1 + 2\sin(t + 30°) - 5\cos(t + 60°)$$

In matrix form,

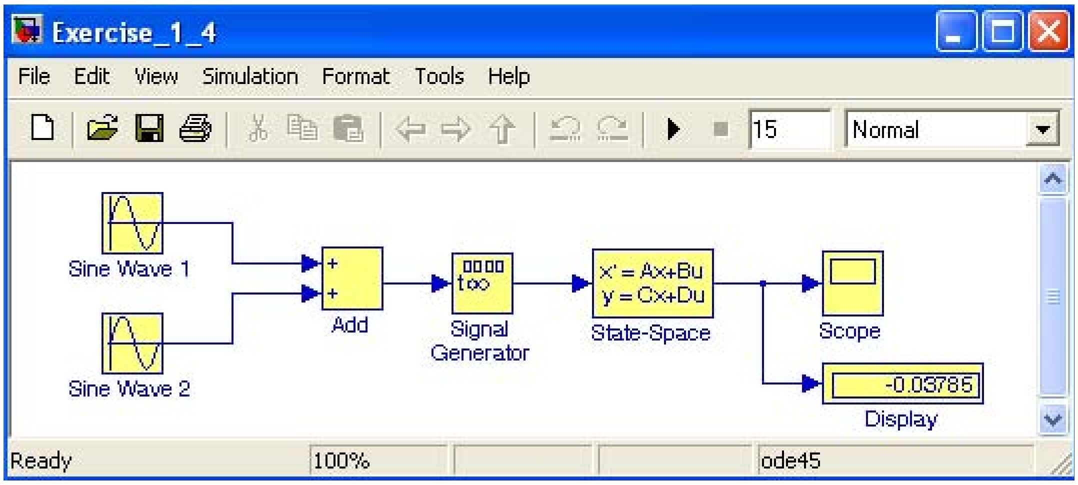
$$\dot{x} = Ax + Bu \Rightarrow \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix}(2\sin(t + 30°) - 5\cos(t + 60°))$$

$$y = Cx + Du \Rightarrow \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix}(2\sin(t + 30°) - 5\cos(t + 60°))$$

subject to the initial conditions

$$x0 = \begin{bmatrix} x_{10} \\ x_{20} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Our simulation model is as shown below after specifying the conditions and values below.



1. We double–click the **Sine Wave 1** block and in the **Source Block Parameters** dialog box we make the following entries:

   Sine type: Time based

   Time (t): Use simulation time

   Amplitude: 2

   Bias: 0

   Frequency (rad/sec): 2

   Phase (rad): pi/6

   and we click **OK**

2. We double–click the **Sine Wave 2** block and in the **Source Block Parameters** dialog box we make the following entries:

   Sine type: Time based

   Time (t): Use simulation time

   Amplitude: −5

   Bias: 0

   Frequency (rad/sec): 2

   Phase (rad): 5*pi/6

   and we click **OK**

3. We double–click on the **Signal Generator** block and in the **Source Block Parameters** dialog box we make the following entries:

   Waveform: Sine

   Time (t): Use external signal

   Amplitude: 1

   Frequency: 2 (Hertz)

   and we click **OK**

4. We double–click on the **State–Space** block and in the **Source Block Parameters** dialog box we make the following entries:

   A: [0 1; −1 −1], B=[1 0]', C=[0 1], D=[0]

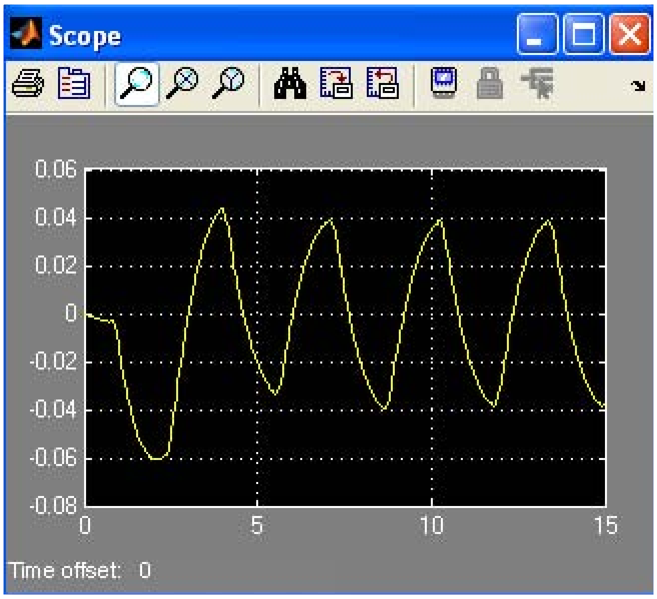
   Initial conditions: [x10 x 20]

   and we click **OK**.

5. At the MATLAB command prompt we enter the initial conditions as

   ```
   x10=0; x20=0;
   ```

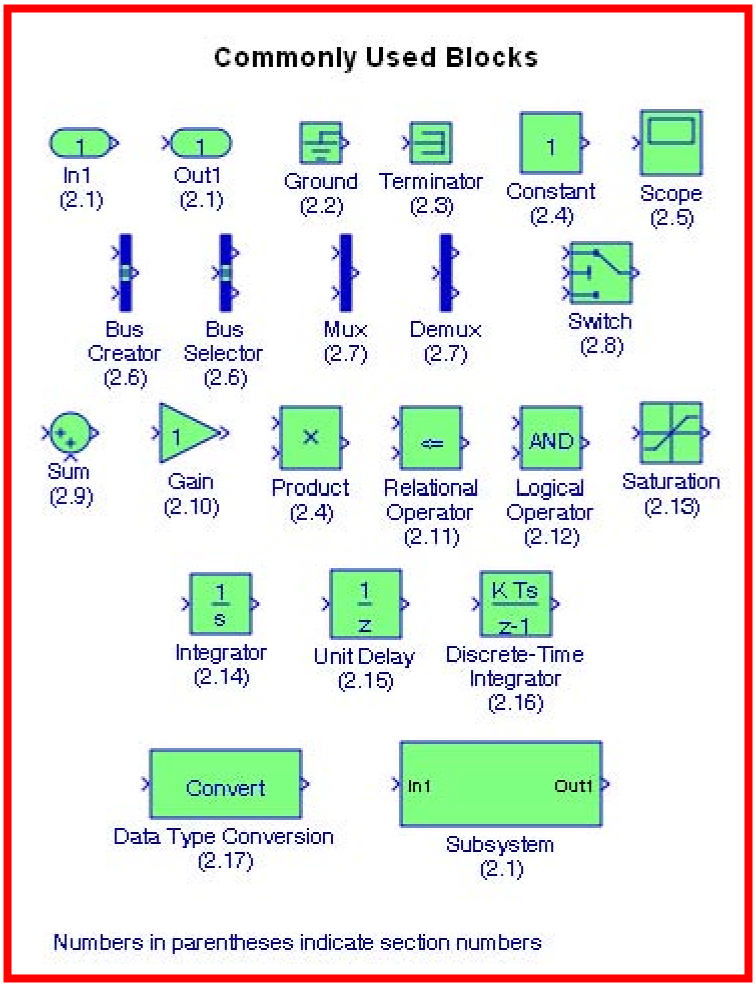
6. We click the **Start Simulation** icon, we double–click the **Scope** block, and after clicking the **Autoscale** icon we observe the waveform below .


Scope
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
5
10
15
Time offset: 0

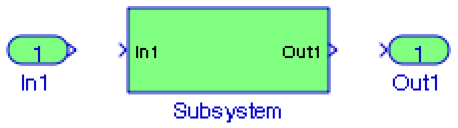
Chapter 2

The Commonly Used Blocks Library

This chapter is an introduction to the **Commonly Used Blocks** Library. This is the first library in the Simulink group of libraries and contains the blocks shown below. In this chapter, we will describe the function of each block included in this library, and their application will be illustrated with examples.



2.1 The Inport, Outport, and Subsystem Blocks



Inport blocks are ports that serve as links from outside a system into the system. **Outport** blocks serve as links from the system to an outside system. A **Subsystem block** represents a subsystem of the system that contains it. As our model increases in size and complexity, we can simplify it by grouping blocks into subsystems. As we can see from Example 1.3 in Chapter 1, if we increase the number of the simultaneous equations, this model increases in size and complexity.

To create a subsystem before adding the blocks it will contain, we add a **Subsystem block** to the model, then we add the blocks that make up the subsystem. If the model already contains the blocks we want to convert to a subsystem, we create the subsystem by grouping the appropriate blocks. A **Subsystem** block can contain other subsystems.

Example 2.1

Figure 2.1 shows the model of Example 1.1, Figure 1.12 in Chapter 1. We will create a subsystem by grouping all blocks except the **Step** and the **Scope** blocks.

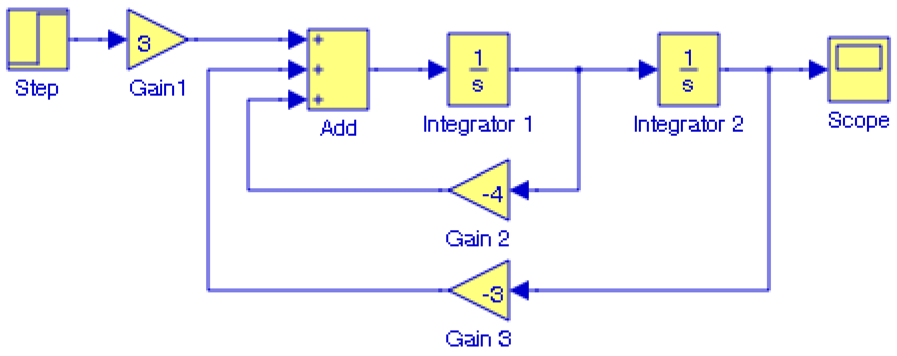


Figure 2.1. Model for Example 2.1

As a first step, we enclose the blocks and connecting lines that we want to include in the subsystem, within a bounding box. This is done by forming a rectangle around the blocks and the connecting lines to select them. Then, from the **Edit** drop menu we choose **Create Subsystem** and we observe that Simulink replaces the selected blocks and connecting lines with a Subsystem block as shown in Figure 2.2 where the **Subsystem** block was reshaped using the handles at the corners of the block.

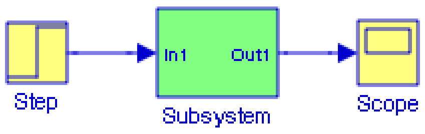


Figure 2.2. Model for Example 2.1 with Subsystem block

Next, we double–click the **Subsystem** block in Figure 2.2, and we observe that Simulink displays all blocks and interconnecting lines as shown in Figure 2.3 where the Step and Scope blocks in Figure 2.2, have been replaced by **In1** and **Out1** blocks respectively.

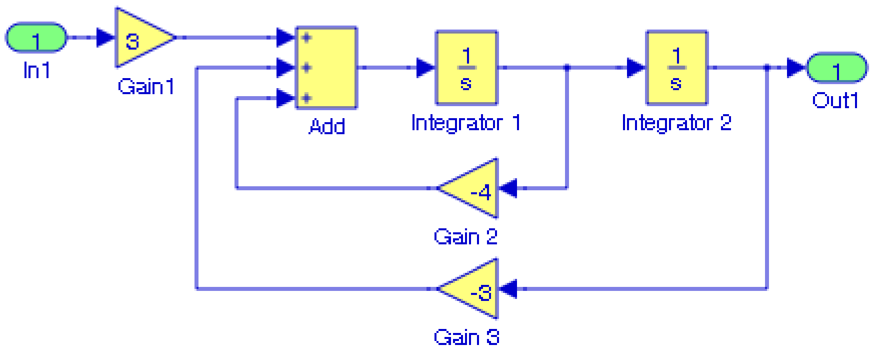


Figure 2.3. Model for Example 2.1 with Inport and Outport blocks replacing the Step and Scope blocks

The Inport (**In1**) and Outport (**Out1**) blocks represent the input to the subsystem and the output from the subsystem respectively. The Inport block name appears in the Subsystem icon as a port label. To suppress display of the label In1, we select the **Inport** block, we choose **Hide Name** from the **Format** menu, then choose **Update Diagram** from the **Edit** menu.

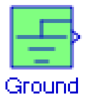
The Simulink demo **F–14 Longitudinal Flight Control** includes several Subsystem blocks. It can be accessed by typing sldemo_f14 at the MATLAB command prompt.

We can create any number of duplicates of an **Inport block**. The duplicates are graphical representations of the original intended to simplify block diagrams by eliminating unnecessary lines. The duplicate has the same port number, properties, and output as the original. Changing a duplicate's properties changes the original's properties and vice versa.

To create a duplicate of an **Inport block**, we select the block, we select **Copy** from the Simulink **Edit** menu or from the block's context menu, we position the mouse cursor in the model's block diagram where we want to create the duplicate. and we select **Paste Duplicate Inport** from the Simulink **Edit** menu or the block diagram's context menu.

For the rules by which Simulink assigns port numbers, please refer to the Simulink's Help menu for this block.

2.2 The Ground Block



The **Ground** block can be used to connect blocks whose input ports are not connected to other blocks. If we run a simulation with blocks having unconnected input ports, Simulink issues warning messages. We can avoid the warning messages by using Ground blocks. Thus, the Ground block outputs a signal with zero value. The data type of the signal is the same as that of the port to which it is connected.

Example 2.2

Let us consider the model shown in Figure 2.4 where K1 = 3 + j1 and K2 = 4 + j3 and these values have been entered at the MATLAB command prompt. Upon execution of the Simulation start command, the sum of these two complex numbers is shown in the **Display** block.

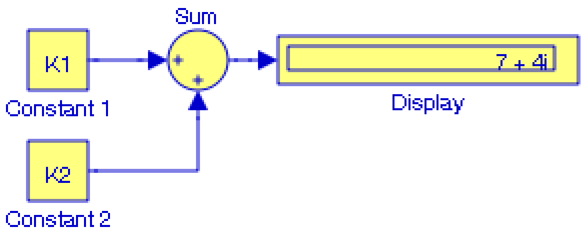


Figure 2.4. Display of the sum of two complex numbers for Example 2.2

Next, let us delete the block with the K2 value and execute the Simulation start command. The model is now shown as in Figure 2.5.

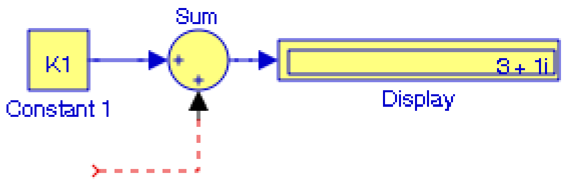


Figure 2.5. Model for Example 2.2 with Block K2 deleted.

Now, let us add a **Ground** block at the unconnected input of the **Sum** block and execute the Simulation start command. The model is now as shown in Figure 2.6.

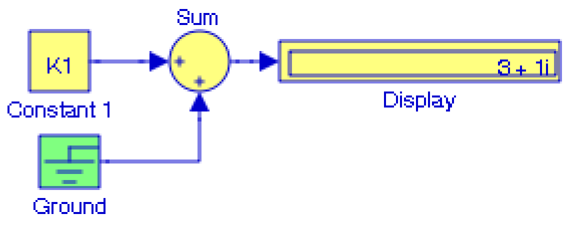
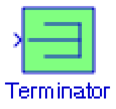


Figure 2.6. Model of Figure 2.5 with a Ground block connected to the Sum block

More examples can be seen in the **Bouncing Ball Demo** model[*] by typing sldemo_bounce at the MATLAB command prompt, and in the **Triggered Subsystem Demonstration** model by typing triggeredsub at the MATLAB command prompt.

2.3 The Terminator Block



The **Terminator** block can be used to cap blocks whose output ports are not connected to other blocks. If we run a simulation with blocks having unconnected output ports, Simulink issues warning messages. We can avoid the warning messages by using **Terminator** blocks.

Example 2.3

Let us consider the unconnected output of the **Product** block in Figure 2.7 where the values for K1 and K2 are the same as in the previous example and are defined at the MATLAB command prompt.

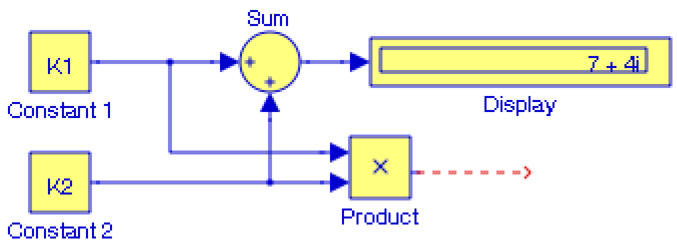


Figure 2.7. Sum block with unconnected output for Example 2.3

When the simulation command is issued, the following message is displayed at the MATLAB Command Window:

* *A similar demo is presented in Chapter 20.*

```
Warning: Unconnected output line found on 'Figure_2_7R/Product' (output port: 1).
```

Figure 2.8 shows the **Product** block output connected to a **Terminator** block.

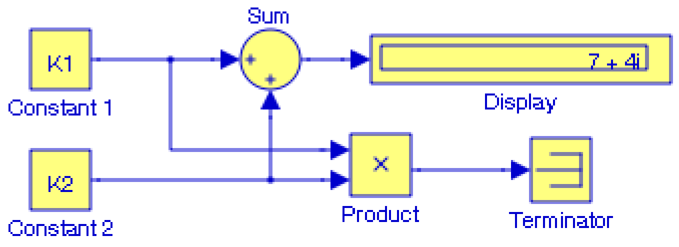
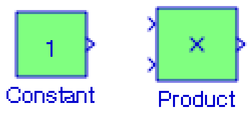


Figure 2.8. Sum block of Figure 2.7 with the Product block output connected to a Terminator block

For another example, refer to the **Bouncing Ball Demo** model by typing sldemo_bounce at the MATLAB command prompt.

2.4 The Constant and Product Blocks



The **Constant block** is used to define a real or complex constant value. This block accepts scalar (1x1 2–D array), vector (1–D array), or matrix (2–D array) output, depending on the dimensionality of the Constant value parameter that we specify, and the setting of the Interpret vector parameters as 1–D parameter. The output of the block has the same dimensions and elements as the Constant value parameter. If we specify a vector for this parameter, and we want the block to interpret it as a vector (i.e., a 1–D array), we select the Interpret vector parameters as 1–D parameter; otherwise, the block treats the Constant value parameter as a matrix (i.e., a 2–D array).

By default, the **Constant** block outputs a signal whose data type and complexity are the same as that of the block's Constant value parameter. However, we can specify the output to be any supported data type supported by Simulink, including fixed–point data types. For a discussion on the data types supported by Simulink, please refer to **Data Types Supported by Simulink** in the Using Simulink documentation.

The **Product block** performs multiplication or division of its inputs. This block produces outputs using either element–wise or matrix multiplication, depending on the value of the **Multiplication parameter**. We specify the operations with the Number of inputs parameter. Multiply(*) and divide(/) characters indicate the operations to be performed on the inputs.

Example 2.4

The model is shown in Figure 2.9 performs the multiplication $(3+j4)\times(4+j3)\times(5-j8)$ where in the **Function Block Parameters** dialog box for the **Product** block we have entered:

Number of inputs: 3

After the Start simulation command is executed, it may be necessary to stretch the **Display** block horizontally to read the result.

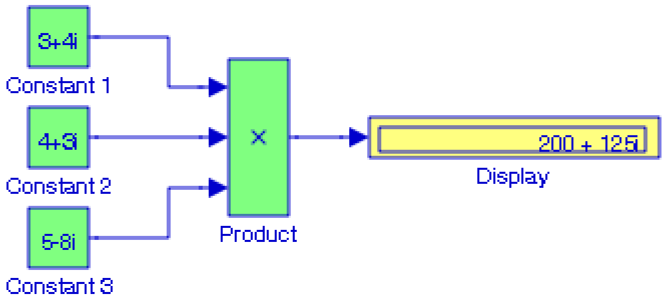


Figure 2.9. Model for Example 2.4

The **Divide block** is an implementation of the **Product** block. It can be used to multiply or divide inputs.

Example 2.5

The model shown in Figure 2.10 performs the division $(3+j4)/(4+j3)$ where in the **Function Block Parameters** dialog box for the **Product** block shown as **Divide** we have entered:

Number of inputs: */

After the Start simulation command is executed, it may be necessary to stretch the **Display** block horizontally to read the result.

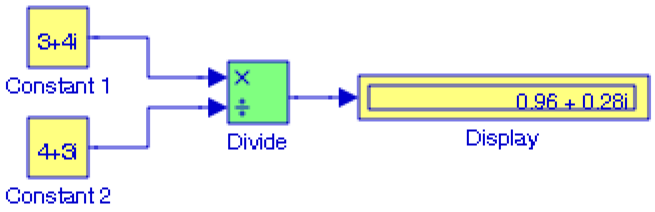
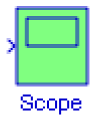


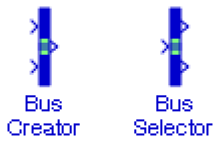
Figure 2.10. Model for Example 2.5

2.5 The Scope Block



The **Scope** block displays waveforms as functions of simulation time. The **Scope** block can have multiple y–axes with a common time range. We can adjust the amount of time and the range of input values displayed, we can move and resize the Scope window, and we can modify the Scope's parameter values during the simulation. The **Scope** block does not automatically display the waveforms, but it does write data to connected Scopes. The Scope's input signal or signals will be displayed if after a simulation is terminated, we double–click the **Scope** block and the signal(s) will then be displayed. The **Scope** block assigns colors to each signal element in this order: **yellow**, **magenta**, **cyan**, **red**, **green**, and **dark blue**. When more than six signals are displayed, the **Scope** block cycles through the colors in the order listed. The **Scope** block is described in detail in Subsection 14.2.1, Chapter 14, Page 14–6.

2.6 The Bus Creator and Bus Selector Blocks



To understand the uses of the **Bus Creator** and **Bus Selector** blocks, let us review the concept of a signal bus which can be thought of as a bundle of several wires held together by tie wraps. Graphically, we can represent a bus as a composite signal comprised of a set of individual signals with a group of lines, each line representing an individual signal. We use **Bus Creator** blocks to create signal buses and **Bus Selector** blocks to access the components of a bus. Simulink hides the name of a **Bus Creator** and **Bus Selector** blocks when we copy them from the Simulink library to a model. However, we can make the names visible by clicking **Show Name** on the **Format** menu. Making the names visible is recommended since the **Bus Creator**, **Bus Selector**, **Mux**, and **Demux** blocks are all represented by a heavy vertical line. The **Mux** and **Demux** blocks are described in the next section. The **Bus Creator** and **Mux** blocks can in most cases be used interchangeably. Likewise, the **Bus Selector** and **Demux** blocks can be used interchangeably. Whereas the **Bus Creator** and **Bus Selector** blocks are used with bus signals, the **Mux** and **Demux** blocks are used with vectors. The **Bus to Vector** block discussed in Chapter 12 performs the conversion.

The **Bus Creator** block is normally shown as a heavy vertical line. We use this block to combine a set of signals into a bus, i.e., a group of signals represented by a single line. The **Bus Creator** block, when used in conjunction with the **Bus Selector block**, described later also in this section, allows us to reduce the number of lines required to route signals from one part of a diagram to another. This makes our diagram easier to understand.

Example 2.6

The model of Figure 2.11 simulates the combined functions $\sin 2t$, $\frac{d}{dt}\sin 2t$, and $\int \sin 2t dt$ into a bus and displays all three on a single **Scope** block.

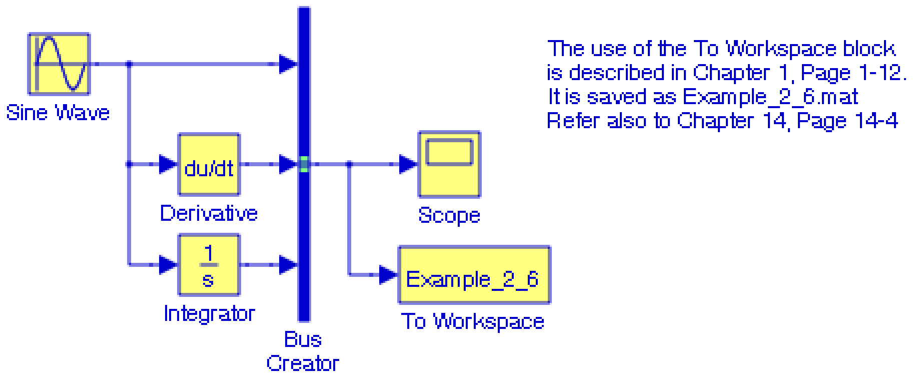

Sine Wave
du/dt
Derivative
1/s
Integrator
Bus Creator
Scope
Example_2_6
To Workspace
The use of the To Workspace block is described in Chapter 1, Page 1-12.
It is saved as Example_2_6.mat
Refer also to Chapter 14, Page 14-4

Figure 2.11. Model for Example 2.6

We begin by entering the following at the MATLAB command prompt:

```
syms t; y=sin(2*t), der_y=diff(y), int_y=int(y)  % Requires the Symbolic Math Toolbox–see Pg A–10
```

and MATLAB displays

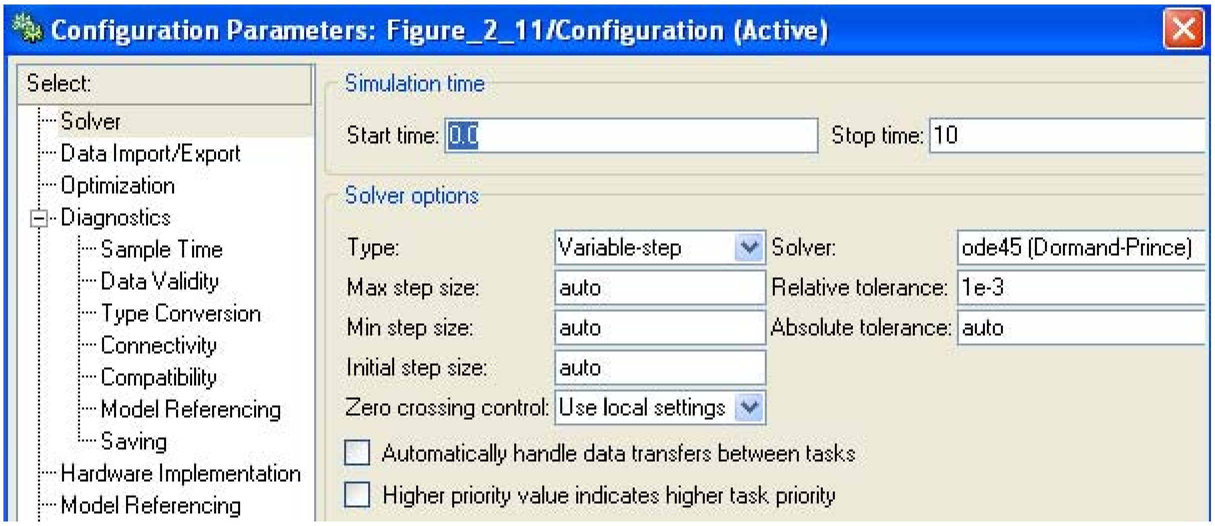
```
y =
sin(2*t)

der_y =
2*cos(2*t)

int_y =
-1/2*cos(2*t)
```

From the **Sources Library**[*] browser, we select the **Sine Wave** block and we drag it into a new model window which we name Figure_2_11. From the **Continuous Library**[†] Browser we select the **Derivative** block and we drag it into the model window. Also, from the **Continuous Library** Browser, we select the **Integrator** block and we drag it into our model. From the **Commonly Used Blocks** Library Browser we select the **Bus Creator** block and we drag it into the model window. Then, we select the **Scope** and **Simout to Workspace** blocks from the **Sinks Library**[‡] and we drag them into the model window. On the model window we click the **Integrator** block and in the **Function Block Parameters** dialog box we set the initial condition to zero. Also, in the model

* *The Sources Blocks Library is described in Chapter 15.*
† *The Continuous Blocks Library is described in Chapter 3.*
‡ *The Sinks Blocks Library is described in Chapter 14.*

window we click the **Bus Creator** block and on the **Function Block Parameters** dialog box we change the number of inputs from 2 to 3. We connect the blocks as shown in Figure 2.11.

Now, we configure Simulink to run the simulation for 10 seconds (the default value). We choose the parameters shown in Figure 2.12 from the **Simulation** menu of the model, and other parameters not shown, are left in their default states.


Configuration Parameters: Figure_2_11/Configuration (Active)

Select:
- Solver
- Data Import/Export
- Optimization
- Diagnostics
  - Sample Time
  - Data Validity
  - Type Conversion
  - Connectivity
  - Compatibility
  - Model Referencing
  - Saving
- Hardware Implementation
- Model Referencing

Simulation time

Start time: 0.0 Stop time: 10

Solver options

Type: Variable-step Solver: ode45 (Dormand-Prince)

Max step size: auto Relative tolerance: 1e-3

Min step size: auto Absolute tolerance: auto

Initial step size: auto

Zero crossing control: Use local settings

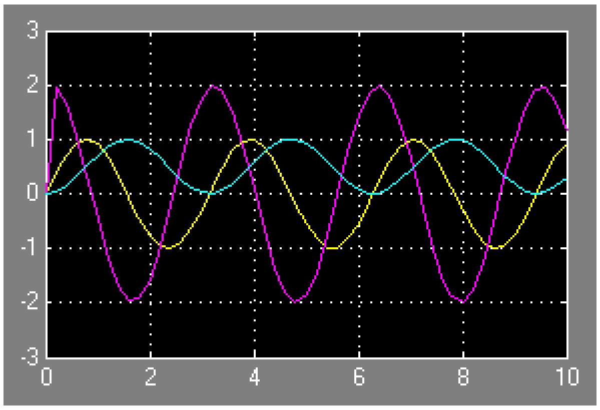
☐ Automatically handle data transfers between tasks

☐ Higher priority value indicates higher task priority

Figure 2.12. Specifying the configuration parameters for the model in Figure 2.11

We close the **Configuration Parameters** dialog box by clicking the **OK** button, and Simulink applies the parameters. Finally, we double click the **Scope** block and the output is as shown in Figure 2.13. To scale the vertical axis as shown in Figure 2.13, we move the cursor close to the vertical axis, we right–click, and we enter the lower and upper limits shown in Figure 2.13.

The **Bus Creator** block assigns a name to each signal on the bus that it creates. This allows us to refer to signals by name when searching for their sources (see **Browsing Bus Signals** in the Help menu for this block) or selecting signals for connection to other blocks. The block offers two bus signal naming options. We can specify that each signal on the bus inherit the name of the signal connected to the bus (the default) or that each input signal must have a specific name. To specify that bus signals inherit their names from input ports, we select **Inherit bus signal names from input ports** from the list box on the block's parameter dialog box. The names of the inherited bus signals appear in the Signals in bus list box shown in Figure 2.14.



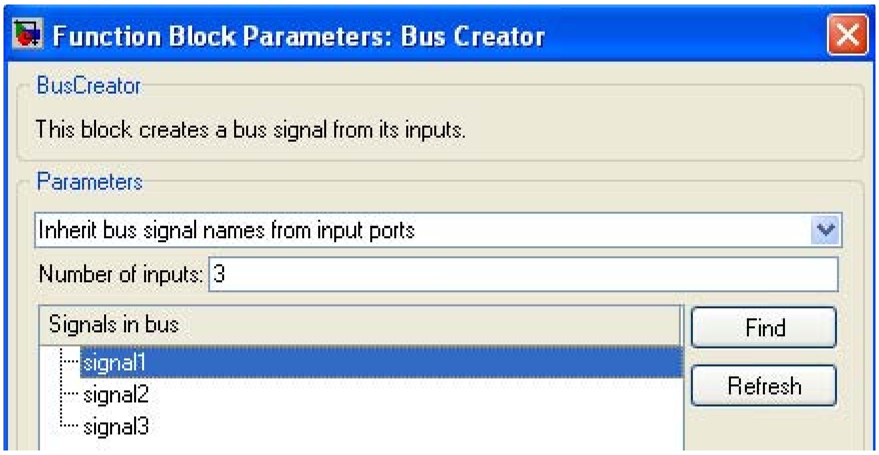
The integral of the sine wave appears with a DC component of value 0.5 being added to it. We recall that the evaluation of an indefinite integral requires the addition of a constant of integration, and for this example

$$\int \sin 2t dt = -\frac{1}{2}\cos 2t + C$$

but the Symbolic ToolBox ignores C whereas for t=0, C=1/2, and Simulink displays

$$-\frac{1}{2}\cos 2t + \frac{1}{2} = \frac{1}{2}(1 - \cos 2t)$$

Figure 2.13. Output waveforms for Example 2.6


Function Block Parameters: Bus Creator

BusCreator

This block creates a bus signal from its inputs.

Parameters

Inherit bus signal names from input ports

Number of inputs: 3

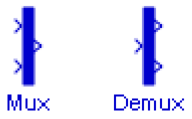
Signals in bus
- signal1
- signal2
- signal3

Figure 2.14. Bus Creator function block parameters dialog box

The **Bus Editor** allows us to change the properties of the bus types objects. We select the **Bus Editor** from the model's **Tools** drop menu. For details, please refer to the Simulink Owner's Manual or Simulink's Help menu.

Often, it is desirable to annotate our models. These annotations provide textual information about a model. We can add an annotation to any unoccupied area of our model. To insert an annotation, we double–click an unoccupied section of the model, then a small rectangle appears, and the cursor changes to an insertion point. We start typing the annotation text and we observe that each line is centered within the rectangle. We can also left– or right–justify the annotation by first highlighting it, and making the desired selection using the T**ext Alignment** from the **Format** drop menu. Then we can move it to the desired location by dragging it. We can choose another **Font** and **Size** from the **Format** menu. We can delete an annotation by first selecting it, holding down the Shift key and pressing the Delete or Backspace key.

2.7 The Mux and Demux Blocks



Before describing the **Mux** and **Demux** blocks, let us review the functions of a *multiplexer* (mux) and *demultiplexer* (demux).

Multiplexing is a method of sending multiple signal streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. Analog signals are commonly multiplexed using *Frequency Division Multiplexing* (FDM), in which the carrier bandwidth is divided into subchannels of different frequency widths, each carrying a signal at the same time in parallel. Cable television is an example of FDM. Digital signals are commonly multiplexed using *Time Division Multiplexing* (TDM), in which the multiple signals are carried over the same channel in alternating time slots. If the inputs take turns to use the output channel (time division multiplexing) then the output bandwidth need be no greater than the maximum bandwidth of any input. If many inputs may be active simultaneously then the output bandwidth must be at least as great as the total bandwidth of all simultaneously active inputs. In this case the multiplexer is also known as a *concentrator*.

A demultiplexer performs the reverse operation of a multiplexer. Figure 2.15 shows a simplified 5–channel multiplexer / demultiplexer pair.

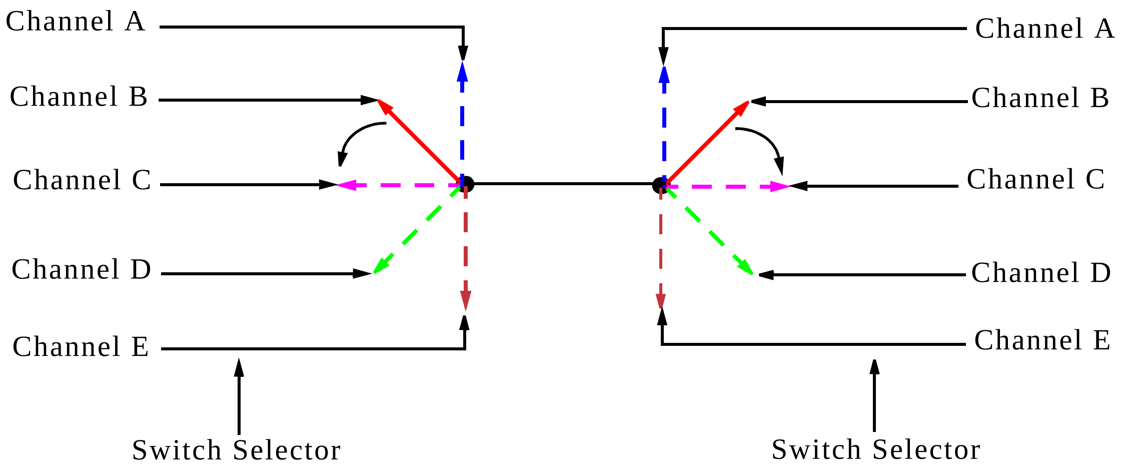
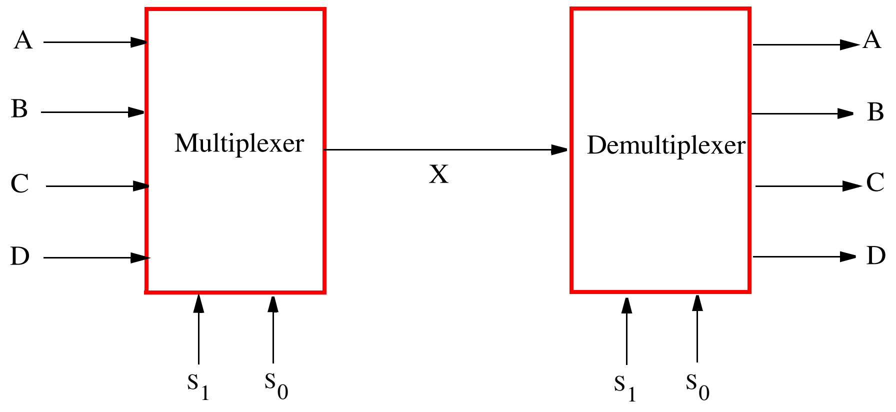


Figure 2.15. Multiplexer shown as a controlled switch

Figure 2.16 shows a functional block diagram of a typical 4–line time–division digital multiplexer / demultiplexer pair.



Truth Table

S_1	S_0	X
0	0	A
0	1	B
1	0	C
1	1	D

Figure 2.16. Digital Mux–Demux pair

In Figure 2.16, A, B, C, and D represent input data to be multiplexed and appear on a single transmission path denoted as X. This path will carry the data of input A, B, C, or D depending on the settings of the selection switches S_0 and S_1. These setting must be the same on both the multiplexer and demultiplexer. For instance, if the setting are $S_0 = 0$ and $S_1 = 1$, the output line X of the multiplexer will carry the data of signal C and it will appear at the output line C on the demultiplexer. The other combinations are shown in the truth table of Figure 2.15. A model for a digital multiplexer is presented in Chapter 11, Example 11.2, Page 11–4.

The Simulink **Mux block** combines its inputs into a single output. An input can be a scalar, vector, or matrix signal. For details, please refer to the Simulink Owner's Manual or Simulink's Help menu. The Mux block's Number of Inputs parameter allows us to specify input signal names and dimensionality as well as the number of inputs. A value of −1 means that the corresponding port can accept signals of any dimensionality. Simulink hides the name of a **Mux block** when we drag it from the Simulink block library to a model. However, we can make the name visible by clicking **Show Name** on the **Format** drop menu.

The Simulink **Demux block** extracts the components of an input signal and outputs the components as separate signals. The block accepts either vector (1–D array) signals or bus signals (see **Signal Buses** in the Using Simulink documentation for more information). The Number of outputs parameter allows us to specify the number and the dimensionality of each output port. If we do not specify the dimensionality of the outputs, the block determines the dimensionality of the outputs for us.

Simulink hides the name of a **Demux** block when we drag it from the Simulink library to a model. However, we can make the name visible by clicking **Show Name** on the **Format** menu.

Let n represent an n–element input vector, and p represent the block output scalar signals where p cannot be greater than n.

Case I: $p = n$

If we specify p outputs for a n–element input vector, the **Demux** block will output the same number of outputs as the number of elements in the input vector. For instance, if the input to the **Demux** block is a four–element vector, and we specify four outputs, the **Demux** block will output four scalar signals. However, if we specify the number of outputs as fewer than the number of input elements, the **Demux** block will distribute the elements as evenly as possible over the outputs.

Case II: $p < n$

a. $n \bmod p = 0$: The **Demux** block outputs p vector signals each having n/p elements. For instance, if the input to the **Demux** block is an eight–element vector, and we specify four outputs, the **Demux** block will output four two–element vectors.

b. $n \bmod p = m$: The **Demux** block outputs m vector signals each having $n/p + 1$ elements and $p - m$ signals having n/p elements. For instance, if the input to the **Demux** block is a five–element vector, and we specify three outputs, the **Demux** block will output two 2–element vector signals and one scalar signal.

For other cases please refer to the Simulink Owner's Manual or Simulink's Help menu.

We use -1 in a vector expression to indicate that the block should dynamically size the corresponding port. If a vector expression comprises positive values and -1 values, the **Demux** block assigns as many elements as needed to the ports with positive values and distributes the remain elements as evenly as possible over the ports with -1 values.

Example 2.7

The input to a **Demux** block is a $[1 \times 9]$ row vector (digits 1 through 9) and the block output has three ports. We want to specify that there will be four elements on the second port, and the first and third ports will be dynamically sized. We will create a model that will meet these specifications.

The model is shown in Figure 2.17. We first drag the **Constant** block from the **Sources** of the Simulink Library Browser into a new model window, we drag the **Demux** block from the **Commonly Used Blocks** Library Browser, we drag the **Display** blocks from the **Sinks** Library Browser, and we make the connections as indicated.

We double–click the **Constant** block and we enter the row vector `[1 2 3 4 5 6 7 8 9]`. We uncheck the Interpret vector parameter as 1–D. We double click the **Demux** block and for the **Number of outputs** we enter `[–1, 4 –1]`. The numbers displayed appear after we start the simulation. We observe that there are three elements on the first output port, four on the second, and two on the third. The elements on the second port are as specified, and those on the first and third rows are dynamically sized.

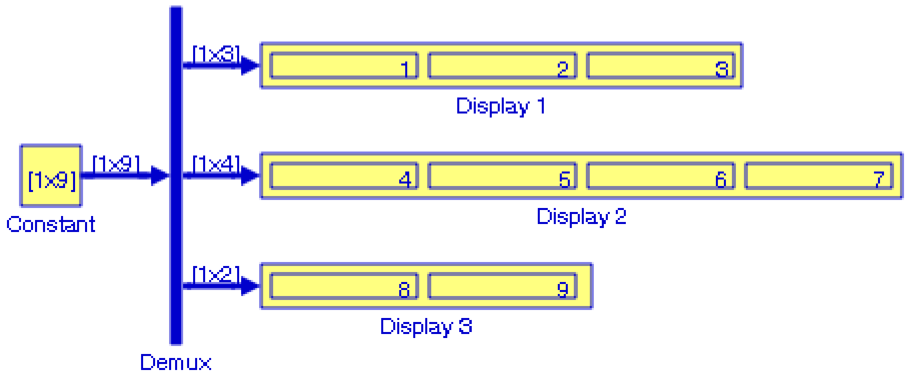
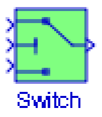


Figure 2.17. Model for Example 2.7

For additional examples please refer to Simulink's Help menu. Some of these examples have replaced the **Display** blocks with **Terminator** blocks. As we've learned earlier, a **Terminator** block prevents warnings about unconnected output ports.

2.8 The Switch Block



The **Switch** block will output the first input or the third input depending on the value of the second input. The first and third inputs are called **data inputs**. The second input is called the **control input** and it is specified on the **Function Block Parameters** for the **Switch** block. The following options are available:

u2>=Threshold

u2>Threshold

u2~=0

where u2~=0 indicates a non–zero condition.

Example 2.8

For the model in Figure 2.18, and at the MATLAB command prompt we have entered the statement T=75; the **Function Block Parameters** dialog box for the **Switch** block has been set for u2>Threshold, Threshold =T, in the **Source Block Parameters** dialog box for the $y = 75 + \sin x$

function block we have entered Amplitude=1, Bias=75, Frequency =1, and for the $z = 75 - \sin x$ function block we have entered Amplitude=1, Bias=75, Frequency =1, Phase $= -\pi$. With the simulation time set at 10 sec, the waveforms indicated on the **Scope** block in Figure 2.19 show that at the end of the simulation time the $z = 75 - \sin x$ function has attained the value of 75.54 and the $y = 75 + \sin x$ function has attained the value of 74.46. Since the Threshold value is set at 75 and the criterion is u2>Threshold, the **Switch** block outputs the value of 75.54, that is, the value of the **Display 3** block at the end of the simulation time.

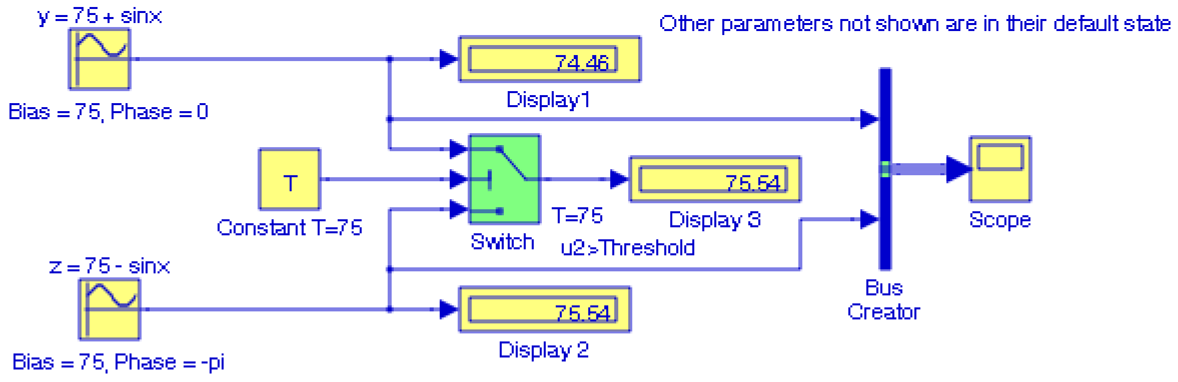


Figure 2.18. Switch block set for u2>Threshold, Threshold T=75

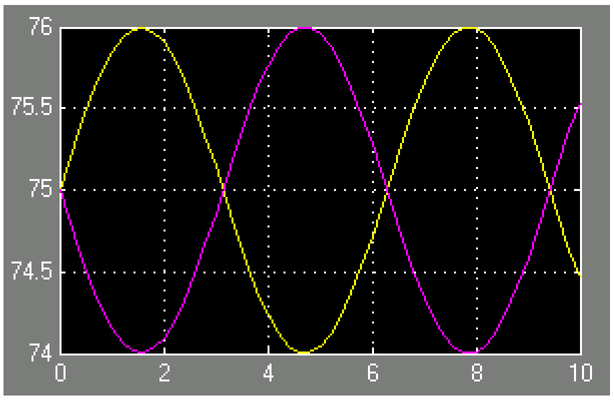
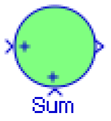


Figure 2.19. Input waveforms for the model in Figure 2.18

The **Accurate Zero Crossing Detection** demo is another example with a **Switch** block. It can be accessed by typing sldemo_zeroxing at the MATLAB command prompt.

2.9 The Sum Block



The **Sum** block is an implementation of the **Add** block which is described in Subsection 8.1.2, Chapter 8, Page 8–2. This block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. We can choose the icon shape of the block, rectangular or round, from the **Block Parameters** dialog box. We specify the operations of the block with the List of Signs parameter. Plus (+), minus (–), and spacer (|) characters indicate the operations to be performed on the inputs. If there are two or more inputs, then the number of characters must equal the number of inputs. For example, "+–+" requires three inputs and configures the block to subtract the second (middle) input from the first (top) input, and then add the third (bottom) input.

Example 2.9

Let us consider the matrices A, B, and C defined at the MATLAB command prompt as:

```
A=[3+4j  1+0j  5–2j; 2–3j  4+j  7–4j; 1+6j  8–5j  4+7j];
B=[4+3j  0+2j  –2+5j; –3+2j  6+7j  –3–4j; 1+8j  –5–3j  2–7j];
C=[–2+3j  7+2j  –5–2j; 3–2j  4–7j  –4+3j; –3+8j  7–4j  –6+9j];
```

The model in Figure 2.20 performs the operation $A + B - C$.

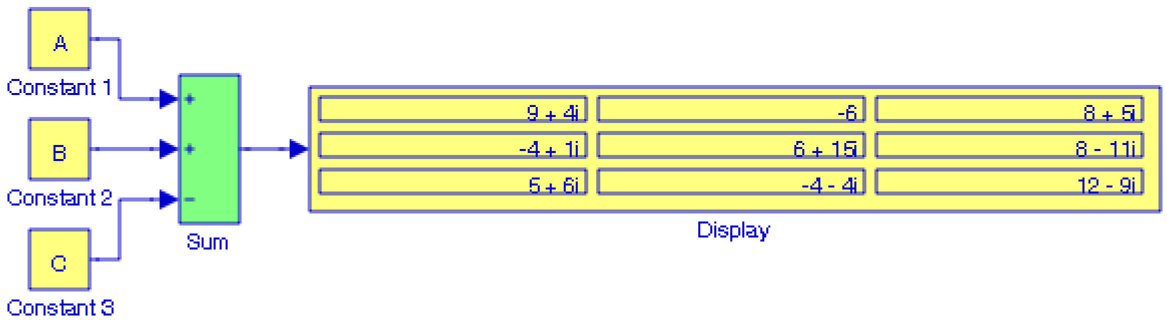
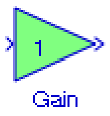


Figure 2.20. Model for Example 2.9

2.10 The Gain Block



The **Gain block** multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix. We specify the value of the gain in the Gain parameter. The Multiplication parameter lets us specify element–wise or matrix multiplication. For matrix multiplication, this parameter also lets us indicate the order of the multiplicands.

Example 2.10

The model shown in Figure 2.21 performs the matrix multiplication $A \cdot B$ where $A = [1 \quad -1 \quad 2]'$ and $B = [2 \quad 3 \quad 4]$.

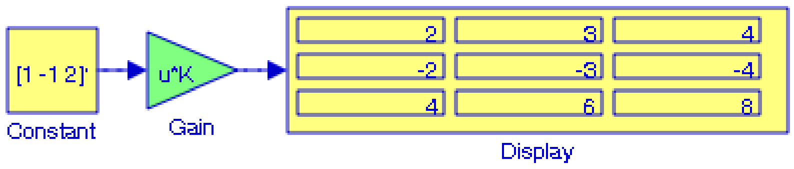
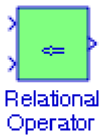


Figure 2.21. Model for Example 2.10

We double–click the **Constant block** and we enter $[1 \quad -1 \quad 2]'$. The apostrophe is required to indicate that this is a column vector. Next, we double click the **Gain block,** we enter the row vector $[2 \quad 3 \quad 4]$, and for Multiplication we choose Matrix (u*K). Initially, the Display block may show just one value with two small black triangles at the lower right corner. This tells us that we must resize the Display block in both directions to see all the elements of the resultant 3×3 matrix.

The **Foucault Pendulum Model** demo is another example with several **Gain** blocks. It can be accessed by typing sldemo_foucault at the MATLAB command prompt.

2.11 The Relational Operator Block



The **Relational Operator block** performs the specified comparison of its two inputs. We select the relational operator connecting the two inputs with the Relational Operator parameter. The block updates to display the selected operator. The supported operations are listed below.

Operation Description:

==	TRUE if the first input is equal to the second input
~=	TRUE if the first input is not equal to the second input
<	TRUE if the first input is less than the second input
<=	TRUE if the first input is less than or equal to the second input
>=	TRUE if the first input is greater than or equal to the second input
>	TRUE if the first input is greater than the second input

Example 2.11

The model shown in Figure 2.22 determines whether the determinants of the matrices A and B defined below are equal or unequal.

$$A = \begin{bmatrix} 2 & -3 & 5 \\ 1 & 0 & -1 \\ -2 & 1 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 2 & 1 & -2 \\ -3 & 0 & 1 \\ 5 & -1 & 0 \end{bmatrix}$$

At the MATLAB command prompt we enter A and B as follows:

```
A=[2 –3  5;  1  0 –1; –2  1  0];  B=[2  1 –2;  –3  0  1; 5 –1  0];
```

In the **Source Block Parameters** dialog box of the **Constant** blocks we enter det(A) and det(B). The **Display** block in Figure 2.22 indicates that the determinants of Matrices A and B are equal.

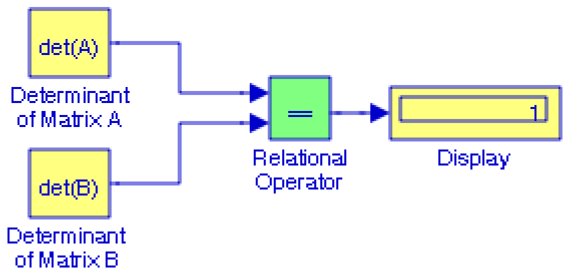
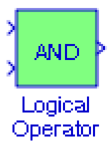


Figure 2.22. Model for Example 2.11

The **Tank Fill and Empty with Animation** demo is another example with a **Relational Operator** block. It can be accessed by typing sldemo_tank at the MATLAB command prompt. Select the **In Valve** subsystem, and from the **Edit** drop menu click the **Look under mask** option.

2.12 The Logical Operator Block



The **Logical Operator** block performs the specified logical operation on its inputs. An input value is TRUE (1) if it is nonzero and FALSE (0) if it is zero. The Boolean operation connecting the inputs is selected with the Operator parameter list in the Function **Block Parameters** dialog box. The block updates to display the selected operator. The logical operations are given below.

Operation Description:

AND – TRUE if all inputs are TRUE

OR – TRUE if at least one input is TRUE

NAND – TRUE if at least one input is FALSE

NOR – TRUE when no inputs are TRUE

XOR – TRUE if an odd number of inputs are TRUE

NOT – TRUE if the input is FALSE and vice–versa

The number of input ports is specified with the Number of input ports parameter. The output type is specified with the Output data type mode and/or the Output data type parameters. An output value is 1 if TRUE and 0 if FALSE.

Example 2.12

The model shown in Figure 2.23 simulates the Boolean expression $D = A \cdot B + C$ [*] where the dot denotes the ANDing of the variables A, B, and the plus $(+)$ sign denotes the ORing of $A \cdot B$ with C. The blocks indicated as Variable A, Variable B, and Variable C are **Constant** blocks. We specify the values $A = 1$, $B = 0$, and $C = 1$ at the MATLAB command prompt, and after execution of the Simulation start command, we observe the values 0 and 1 in **Display 1** and **Display 2** blocks respectively.

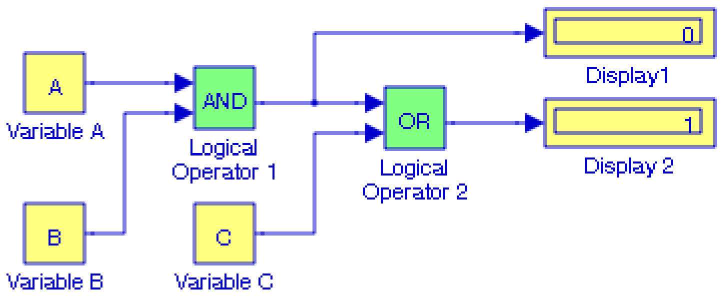
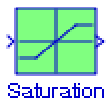


Figure 2.23. Model for Example 2.12

2.13 The Saturation Block



The **Saturation block** establishes upper and lower bounds for an input signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. When the Lower limit and Upper limit parameters are set to the same value, the block outputs that value.

* *The ANDing operation has precedence over the ORing operation. For instance, the Boolean expression* $A \cdot B + C$ *implies that* A *must first be ANDed with* B *and the result must be ORed with* C *as shown in Figure 2.22. The dot symbol between* A *and* B *is often omitted. For a detailed discussion on Boolean expressions, please refer to Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–06–5.*

Example 2.13

For the model shown in Figure 2.24 the **Constant** block performs the function $y = 3x^2$ where x and y are specified at the MATLAB command prompt as

```
x=0: 1: 6; y=3.*x.^2;
```

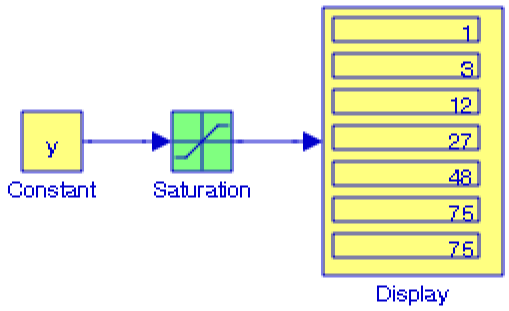
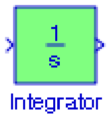


Figure 2.24. Model for Example 2.13

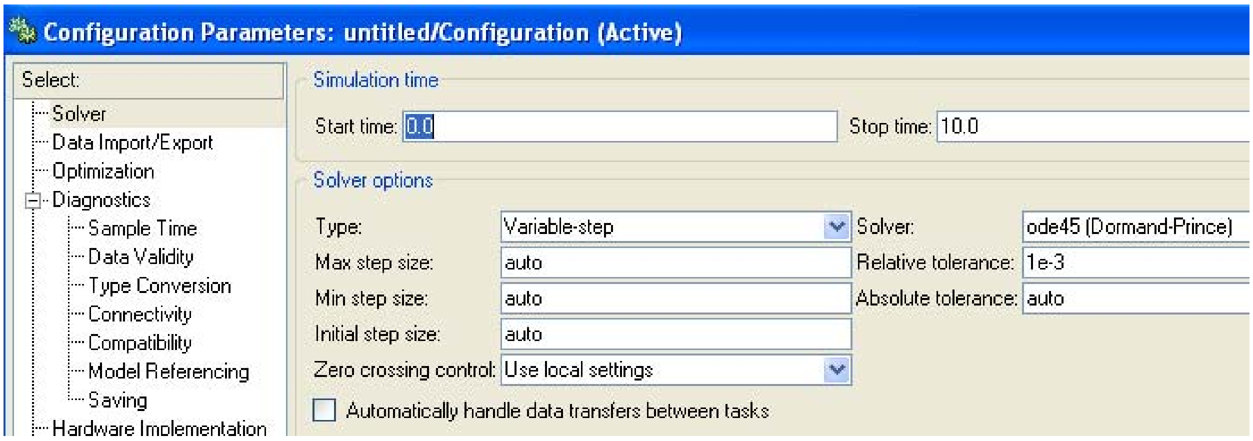
and on the **Function Block Parameters** dialog box for the **Saturation** block we have specified the Upper limit at 75 and the Lower limit at 1. The MATLAB statement above specifies 7 (0 through 6) values of x and these are shown on the **Display** block of Figure 2.24. The last is also 75 because we specified the Upper limit to be that value.

For another example, refer to the **Inverted Pendulum on Cart with Animation Demo** model by typing penddemo at the MATLAB command prompt. The **Accurate Zero Crossing Detection** demo is another example with a Switch block. It can be accessed by typing sldemo_zeroxing at the MATLAB command prompt.

2.14 The Integrator Block



The **Integrator** block integrates its input and it is used with continuous–time signals. As shown in the **Configuration Parameters** dialog box which is displayed after selecting the **Integrator** block and clicking on **Simulation** in the model window, we can use different numerical integration methods to compute the **Integrator** block's output. The **Configuration Parameters** dialog box shown in Figure 2.25 appears when we double–click an **Integrator** block and it is dragged on a new model window, and then selecting **Configuration Parameters** from the **Simulation** drop menu.



Simulation time

Start time: 0.0 Stop time: 10.0

Solver options

Type: Variable-step Solver: ode45 (Dormand-Prince)

Max step size: auto Relative tolerance: 1e-3

Min step size: auto Absolute tolerance: auto

Initial step size: auto

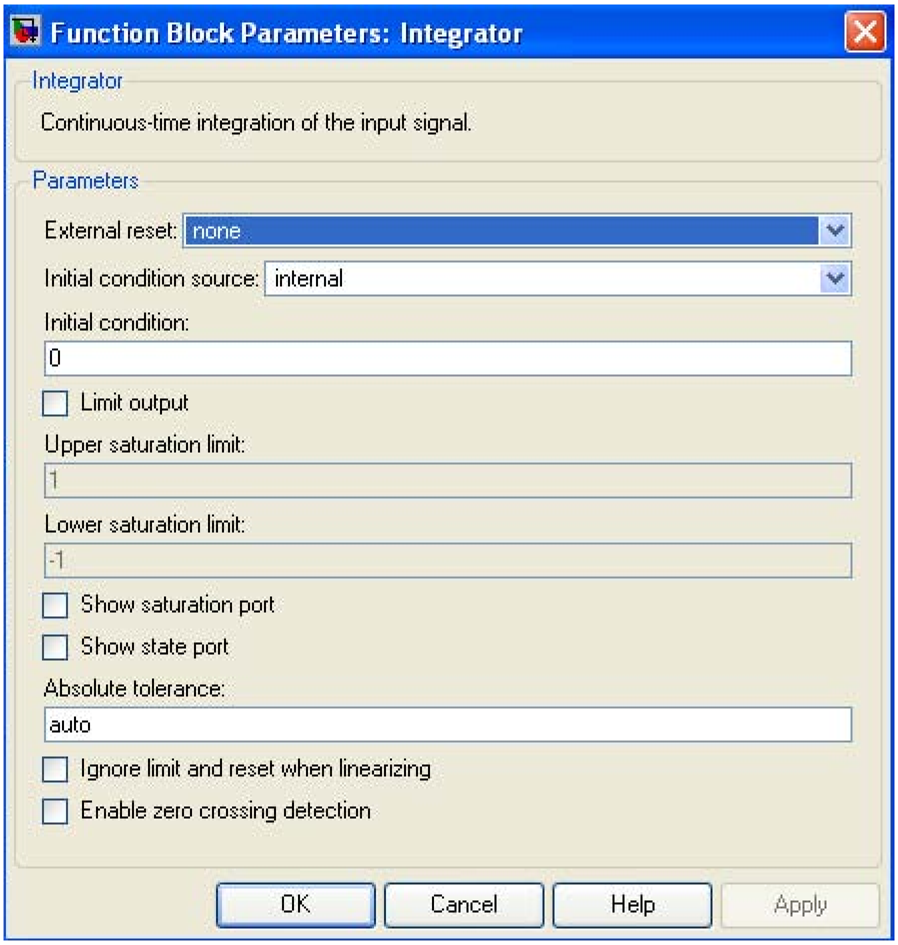
Zero crossing control: Use local settings

☐ Automatically handle data transfers between tasks

Figure 2.25. The configuration parameters window for the Integrator block

Simulink treats the **Integrator** block as a dynamic system with one state, its output. The Integrator block's input is the state's time derivative. The selected solver computes the output of the **Integrator** block at the current time step, using the current input value and the value of the state at the previous time step. The block also provides the solver with an initial condition for use in computing the block's initial state at the beginning of a simulation run. The default value of the initial condition is 0 .

The **Function Block Parameter** dialog box shown in Figure 2.26 allows us to specify another value for the initial condition or create an initial value input port on the block. It also allows us to specify the upper and lower limits of integration, create an input that resets the block's output (state) to its initial value, depending on how the input changes, and create an optional state output that allows us to use the value of the block's output to trigger a block reset. Depending on the options selected, the **Integrator** block appears in any of the nine forms shown in Figure 2.27.


Function Block Parameters: Integrator

Integrator

Continuous-time integration of the input signal.

Parameters

External reset: none

Initial condition source: internal

Initial condition:

0

☐ Limit output

Upper saturation limit:

1

Lower saturation limit:

-1

☐ Show saturation port

☐ Show state port

Absolute tolerance:

auto

☐ Ignore limit and reset when linearizing

☐ Enable zero crossing detection

Figure 2.26. The Function Block Parameters dialog box for the Continuous Integrator block

The **Integrator 1** block in Figure 2.27 is the default block. This block appears when the Function Block Parameters in the dialog box are in their default states. The appearance of the Integrator 2 through Integrator 9 blocks depends on the settings in the block's parameter dialog box. Thus,

Integrator 2 block – Initial condition source: external. All other parameters in their default states.

Integrator 3 block – Limit output: check mark. All other parameters in their default states.

Integrator 4 block – External reset: rising. All other parameters in their default states.

Integrator 5 block – External reset: falling. All other parameters in their default states.

Integrator 6 block – External reset: either. All other parameters in their default states.

Integrator 7 block – External reset: level. All other parameters in their default states.

Integrator 8 block – Show state port: check mark. All other parameters in their default states.

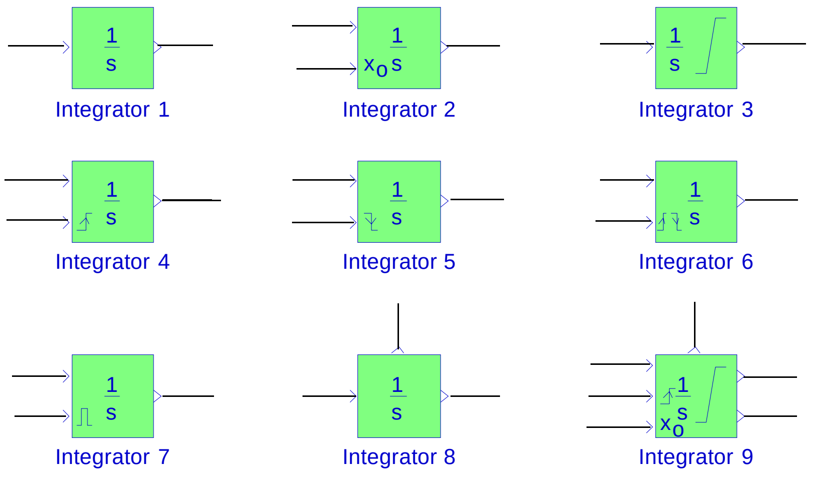


Figure 2.27. Different configurations for the Integrator block

Integrator 9 block – External reset: rising.

Initial condition source: external.

Limit output: check mark

Show saturation port: check mark

Show state port: check mark

The **Integrator** block's state port make it possible to avoid creating algebraic loops when creating an integrator that resets itself based on the value of its output. An algebraic loop is formed when two or more blocks with direct feedthrough (the output of the block at time t, is a function of the input at time t) form a feedback loop. The basic problem with algebraic loops is that the output, y, at time, t, is a function of itself. An **algebraic loop** generally occurs when an input port with direct feedthrough is driven by the output of the same block, either directly, or by a feedback path through other blocks with direct feedthrough. An example of an algebraic loop is the simple loop shown in Figure 2.28 where $y = 10 - y$ or $y = 5$.

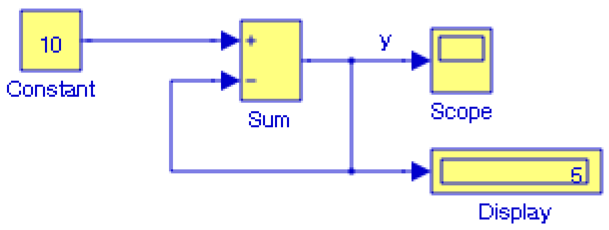


Figure 2.28. An example of an algebraic loop

For further discussion on algebraic loops, please refer to Simulink's User Manual, Help menu for the Integrator block, and MATLAB Technical Report 7.1 – Algebraic Loops and S–Functions, http://www.utexas.edu/math/Matlab/Manual/tec7.1.html. S–Functions are described in Chapter 15.

The **Integrator** block's state port makes it possible to avoid creating algebraic loops when creating an integrator that resets itself based on the value of its output. The state port shown in Integrators 8 and 9 in Figure 2.26 is intended to be used specifically for self–resetting integrators (see Creating Self–Resetting Integrators), and Handing off a state from one enabled subsystem to another (see Handing Off States Between Enabled Subsystems) in Simulink's Help menu. The state port should only be used in these two scenarios. When updating a model, Simulink checks to ensure that the state port is being used in one of these two scenarios. If not, Simulink signals an error.

Example 2.14

The model in Figure 2.29 simulates the differential equation

$$\frac{d^2v_C}{dt^2} + 4\frac{dv_C}{dt} + 3v_C = 3u_0(t)$$

subject to the initial conditions $v_C(0) = 0.5$ and $v'_C(0) = 0$. The **Constant 1** and **Constant 2** blocks represent the initial conditions.

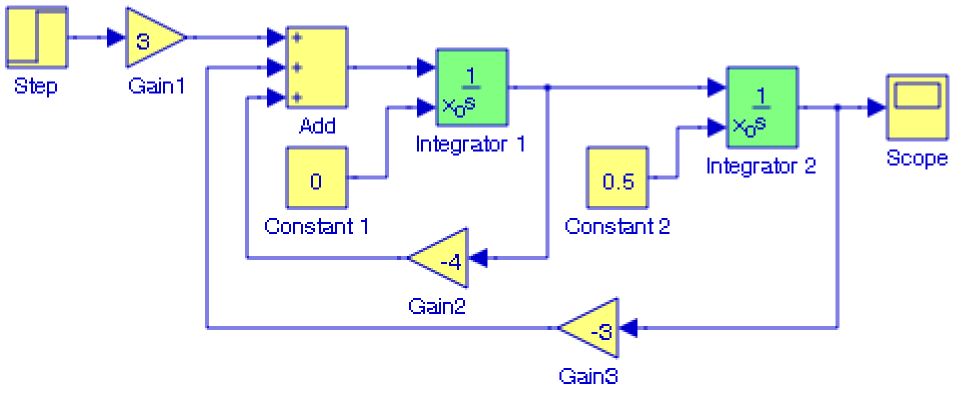
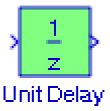


Figure 2.29. Model for Example 2.14

For another example, refer to the **Bouncing Ball Demo** model by typing sldemo_bounce at the MATLAB command prompt.

2.15 The Unit Delay Block



The **Unit Delay** block delays its input by the specified sample period. That is, the output equals the input delayed by one sample. If the model contains multirate transitions, we must add **Unit Delay** blocks between the slow–to–fast transitions. For fast–to–slow transitions we use **Zero–Order Hold** blocks. The **Zero–Order Hold** block is described in Subsection 5.2.3, Chapter 5, Page 5–23. For multirate transitions it is preferable to use the **Rate Transition** block since it is easier to use and offers a wider range of options. Multirate transitions and the **Rate Transition** block are described in Subsection 12.1.8, Chapter 12, Page 12–8.

This **Unit Delay** block is equivalent to the z^{-1} discrete–time operator shown in Figure 2.30. It is one of the basic blocks for designing digital filters as shown in Figure 2.31.

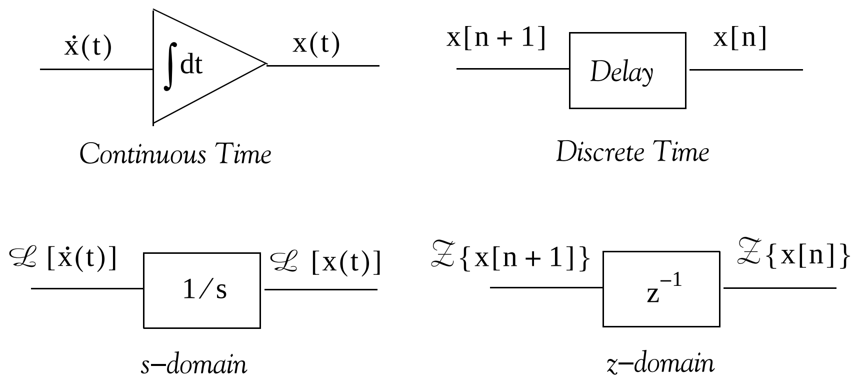


Figure 2.30. Analogy between integration and delay devices

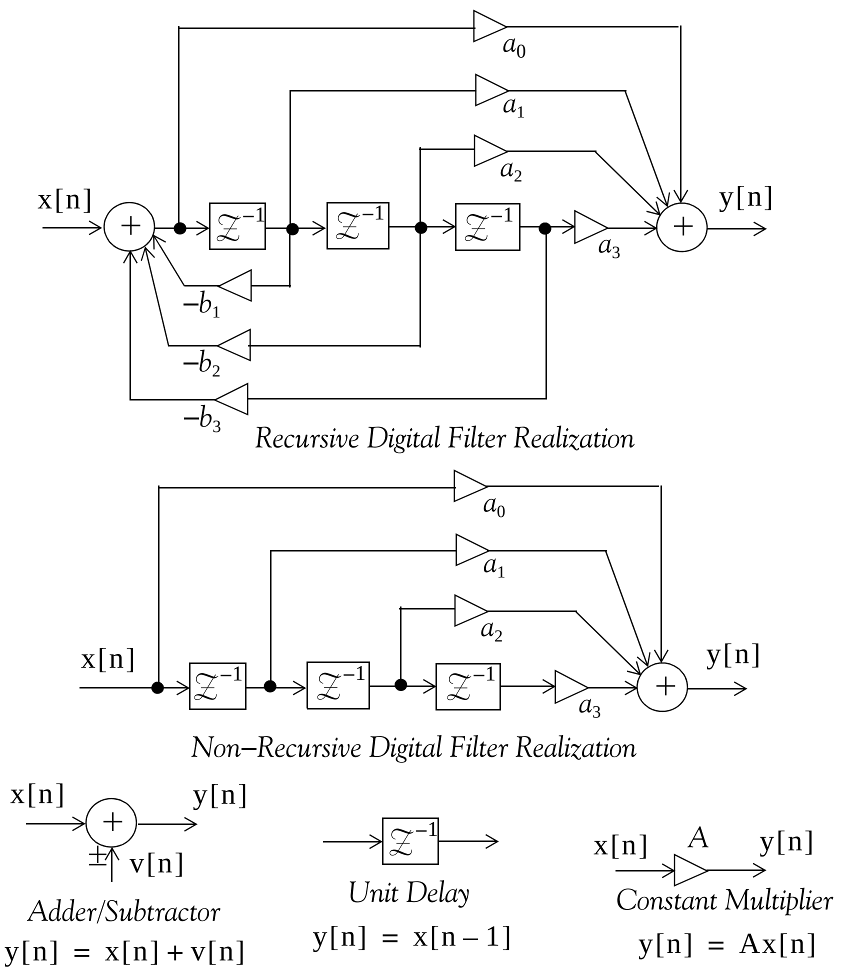


Figure 2.31. Recursive and non–recursive digital filters

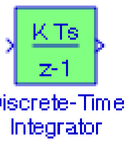
The unit delay appears also in the definition of the discrete time system transfer function $H(z)$ shown in relation (2.1) below.

$$H(z) = \frac{N(z)}{D(z)} = \frac{a_0 + a_1 z^{-1} + a_2 z^{-2} + \ldots + a_k z^{-k}}{1 + b_1 z^{-1} + b_2 z^{-2} + \ldots + b_k z^{-k}} \tag{2.1}$$

With the **Unit Delay** block, the first sampling period and initial conditions are specified in the **Function Block Parameters** dialog box. The time between samples is specified with the Sample time parameter. A setting of −1 means the sample time is inherited.

The **Unit Delay** block also allows for discretization of one or more signals in time, or for resampling the signal at a different rate. If our model contains multirate transitions, then we must add **Unit Delay** blocks between the slow–to–fast transitions. The sample rate of this block must be set to that of the slower block. An example is presented in the next section of this chapter.

2.16 The Discrete–Time Integrator Block



The **Discrete–Time Integrator** block performs discrete–time integration or accumulation of a signal. We use this block in discrete–time systems instead of the **Continuous Integrator** block in continuous–time systems. This block can integrate or accumulate using the **Forward Euler**, **Backward Euler**, and **Trapezoidal** methods. For a given step n, Simulink updates $y(n)$ and $x(n+1)$. The block's sample time in integration mode is T and in triggered sample time is ΔT. In accumulation mode, $T = 1$ and the block's sample time determines when the block's output is computed but not the output's value. The constant K is the gain value. Values are clipped according to upper or lower limits. Purely discrete systems can be simulated using any of the solvers. For additional information, please refer to the Simulink Owner's Manual or Simulink's Help menu.

The **Discrete–Time Integrator** block allows us to:

1. Define initial conditions on the block dialog box or as input to the block.
2. Define an input gain (K) value.
3. Output the block state.
4. Define upper and lower limits on the integral.
5. Reset the state depending on an additional reset input.

With continuous time systems, the **Forward Euler** method, also known as **Forward Rectangular**, or **left–hand approximation**, truncates the Taylor series* after two terms. Thus,

$$y(t+h) = y(t) + hy'(t) \tag{2.2}$$

and assuming that the value at point t is correct, the Forward Euler method computes the value at point $t+h$. With Simulink, the continuous time integrator $1/s$ in discrete time integration with the Forward Euler method is approximated by $T/(z-1)$. As mentioned earlier, T is the block's sample time. The Forward Euler method is the default. With this method, input port 1 does not have direct feedthrough. The resulting expression for the output of the block at step n is

$$y(n) = y(n-1) + K \cdot T \cdot u(n-1) \tag{2.3}$$

The steps to compute the output are listed in the Help menu for this block.

* *For a detailed discussion on Taylor series, please refer to Numerical Analysis Using MATLAB and Excel, ISBN 978–1–934404–03–4*

The **Backward Euler method**, also known as **Backward Rectangular** or **right–hand approximation**, also truncates the Taylor series after two terms. The difference is that the derivative is evaluated at point $t + h$ instead of at point t. Thus,

$$y(t+h) = y(t) + hy'(t+h) \tag{2.4}$$

With Simulink, the continuous time integrator $1/s$ in discrete time integration with the Backward Euler method is approximated by $Tz/(z-1)$. With this method, input port 1 has direct feedthrough. The resulting expression for the output of the block at step n is

$$y(n) = y(n-1) + K \cdot T \cdot u(n) \tag{2.5}$$

The steps to compute the output are listed in the Help menu.

In numerical analysis, relation (2.6) below is known as the first–order trapezoidal integration rule.

$$y(n) = \frac{1}{2}[x(n) + x(n-1)] + y(n-1) \qquad n \ge 0 \tag{2.6}$$

With Simulink, the continuous time integrator $1/s$ in discrete time integration with the **Trapezoidal method** is approximated by $(T/2)(z+1)/(z-1)$. With this method, input port 1 has direct feedthrough. For any T, the resulting expression for the output of the block at step n is

$$y(n) = y(n-1) + K \cdot (T/2) \cdot [u(n) + u(n-1)] \tag{2.7}$$

It is left as an end–of–chapter exercise for the reader to prove that for very small fixed T, relation (2.7) above can be approximated by

$$y(n) \approx y(n-1) + K \cdot (T/2) \cdot u(n-1)$$

If T is variable (i.e. obtained from the triggering times), the block uses another algorithm to compute its outputs. The steps to compute the output are listed in the Help menu.

A **discrete–time accumulator** is characterized by the difference equation

$$y(n) = \sum_{\ell=-\infty}^{n} x[\ell] = \sum_{\ell=-\infty}^{n-1} x[\ell] + x[n] = y[n-1] + x[n] \tag{2.8}$$

The output $y[n]$ at time instant n is the sum of the input sample $x[n]$ at time instant n and the previous output $y[n-1]$ at time instant $n-1$, which is the sum of all previous input sample values from $-\infty$ to $n-1$. In other words, the accumulator cumulative adds, i.e., it accumulates all input sample values.

A discrete–time integrator may be represented by any of the blocks shown in Figure 2.32. Any of these blocks can be selected from the Integrator method menu in the **Function Blocks Parameters** dialog box.

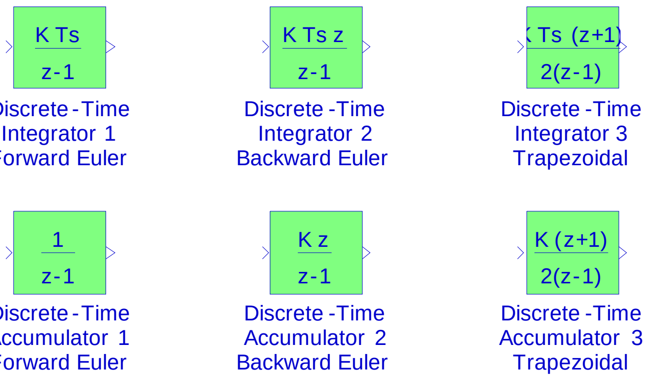

K Ts / z-1
Discrete-Time Integrator 1 Forward Euler
K Ts z / z-1
Discrete-Time Integrator 2 Backward Euler
K Ts (z+1) / 2(z-1)
Discrete-Time Integrator 3 Trapezoidal
1 / z-1
Discrete-Time Accumulator 1 Forward Euler
K z / z-1
Discrete-Time Accumulator 2 Backward Euler
K (z+1) / 2(z-1)
Discrete-Time Accumulator 3 Trapezoidal

Figure 2.32. Discrete–time integrator blocks

Example 2.15

For the model of Figure 2.33, the parameters of a **Pulse Generator Block** found under the **Sources** Simulink Library are set as follows:

Pulse type: Time based

Time (t): Use simulation time
Amplitude: 0.25

Period (secs): 2

Pulse width (% of period): 50

Phase delay (secs): 0

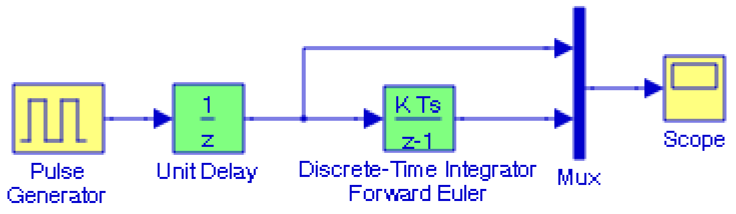


Figure 2.33. Model for Example 2.15

After the Simulation start command is issued, the **Scope** block in Figure 2.34 displays the pulse waveform which is the output of the **Unit Delay** block and the output of the **Discrete–Time Integrator** which is the accumulation (integration) of the input waveform. To center the waveform on the **Scope** block, we right–click the y–axis, we left–click the **Axes properties**, and in the **Scope** properties window we enter Y–min: –1.5, and Y–max: 1.5.

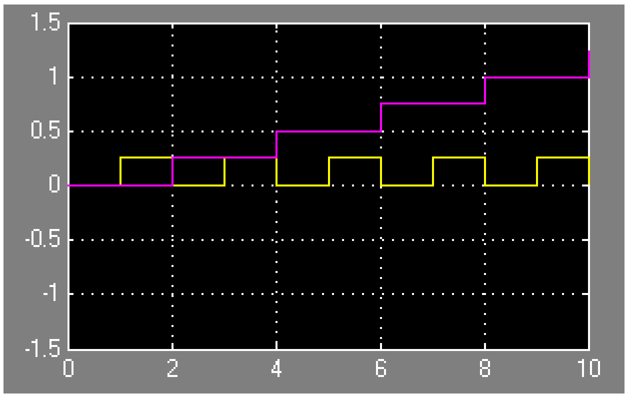
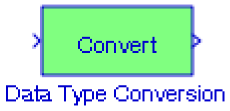


Figure 2.34. Waveforms for the model of Figure 2.32

2.17 Data Types and The Data Type Conversion Block



There are two classes of data types: those defined by MATLAB and Simulink users, and those strictly defined by MATLAB. The latter type is referred to as MATLAB built–in data types. Simulink supports all built–in MATLAB data types except int64 and uint64. The built–in data types supported by Simulink are listed in Table 2.1 below

TABLE 2.1 Built–in data types supported by Simulink

Type Name	Description
single	Single–precision floating point
double	Double–precision floating point
int8	Signed 8–bit integer
uint8	Unsigned 8–bit integer
int16	Signed 16–bit integer
uint16	Unsigned 16–bit integer
int32	Signed 32–bit integer
uint32	Unsigned 32–bit integer

In addition to the above, Simulink defines the boolean (1 or 0) type and these are represented internally by the uint8 values.

The **Data Type Conversion** block converts an input signal of any Simulink data type to the data type and scaling specified by the block's Output data type parameter. The input can be any real– or complex–valued signal. If the input is real, the output is real. If the input is complex, the output is complex. We must specify the data type and/or scaling for the conversion. If we want to inherit this information from an input signal, you should use the **Data Type Conversion Inherited** block which is discussed in the **Signal Attributes Library**, Chapter 12

The **Data Type Conversion** block converts an input signal of any Simulink data type to the data type and scaling specified by the block's Output data type mode, Output data type, and/or Output scaling parameters. The input can be any real– or complex–valued signal. Thus, if the input is real, the output is real, and if the input is complex, the output is complex. We must specify the data type and/or scaling for the conversion. The **Data Type Conversion** block handles any data type supported by Simulink, including fixed–point data types.

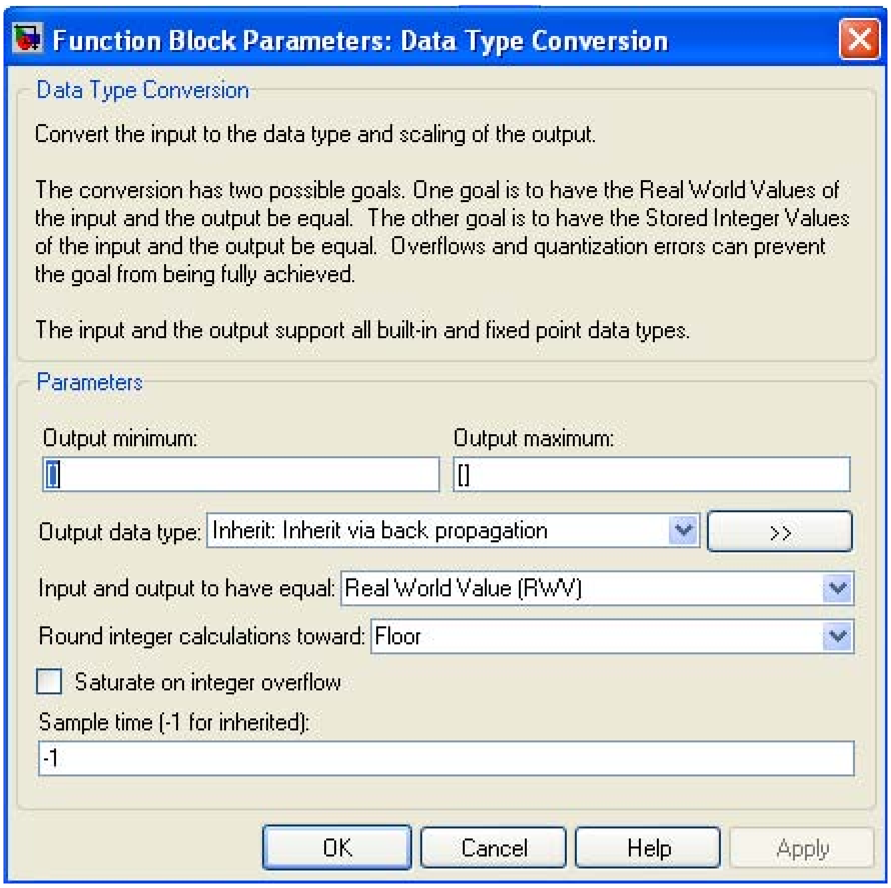
The **Input and output to have equal** parameter is used to select the method by which the input is processed. The possible values are **Real World Value (RWV)** and **Stored Integer (SI)**:

We select **Real World Value (RWV)** to treat the input as $V = SQ + B$[*] where S is the slope and B is the bias. V is used to produce $Q = (V - B)/S$, which is stored in the output. This is the default value. Select **Stored Integer (SI)** to treat the input as a stored integer, Q. The value of Q is directly used to produce the output. In this mode, the input and output are identical except that the input is a raw integer lacking proper scaling information. Selecting **Stored Integer** may be useful if we are generating code for a fixed–point processor so that the resulting code only uses integers and does not use floating–point operations. We also can use **Stored Integer** if we want to partition our model based on hardware characteristics. For example, part of our model may involve simulating hardware that produces integers as output.

Initially, the **Function Block Parameters** dialog box displays the parameters shown in Figure 2.36 below.

The default values [ ] for the **Output minimum** and **Output maximum** fields in Figure 2.35 are equivalent to $-\infty$ and $+\infty$ respectively, and they can also be specified as –inf and inf. Simulink uses these values for simulation range checking, and automatic scaling of fixed–point data types. The **Output data type** field is used to specify the output data type from the **Data Type Conversion** block, and as indicated in Figure 2.35, the default is **Inherit via back propagation**. The button shown as >> displays the **Data Type Assistant** and it helps us to set the **Output data type** parameter. The **Input and output to have equal** field is used to specify whether the **Real World Value (RWV)** or **the Stored Integer (SI)** input and output should be the same.

* *We observe that this is the equation of a straight line with non–zero y–intercept, that is,* $y = mx + b$



Function Block Parameters: Data Type Conversion

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: Inherit: Inherit via back propagation

Input and output to have equal: Real World Value (RWV)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1

Figure 2.35. Default settings for a Data Type Conversion block

Example 2.16

The model shown in Figure 2.36 uses three **Data Type Conversion** blocks.

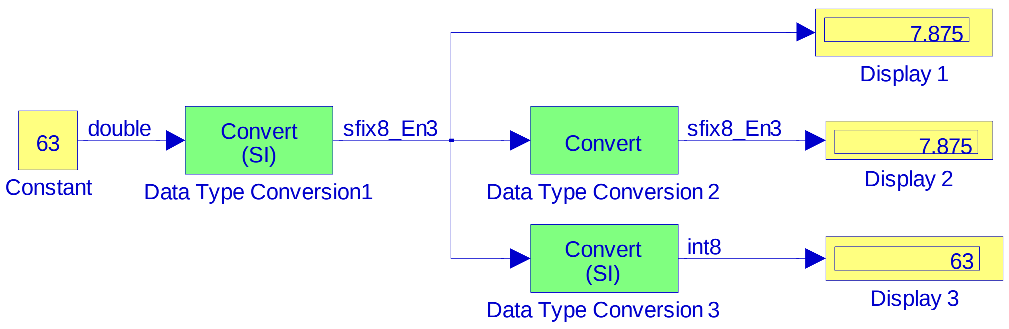
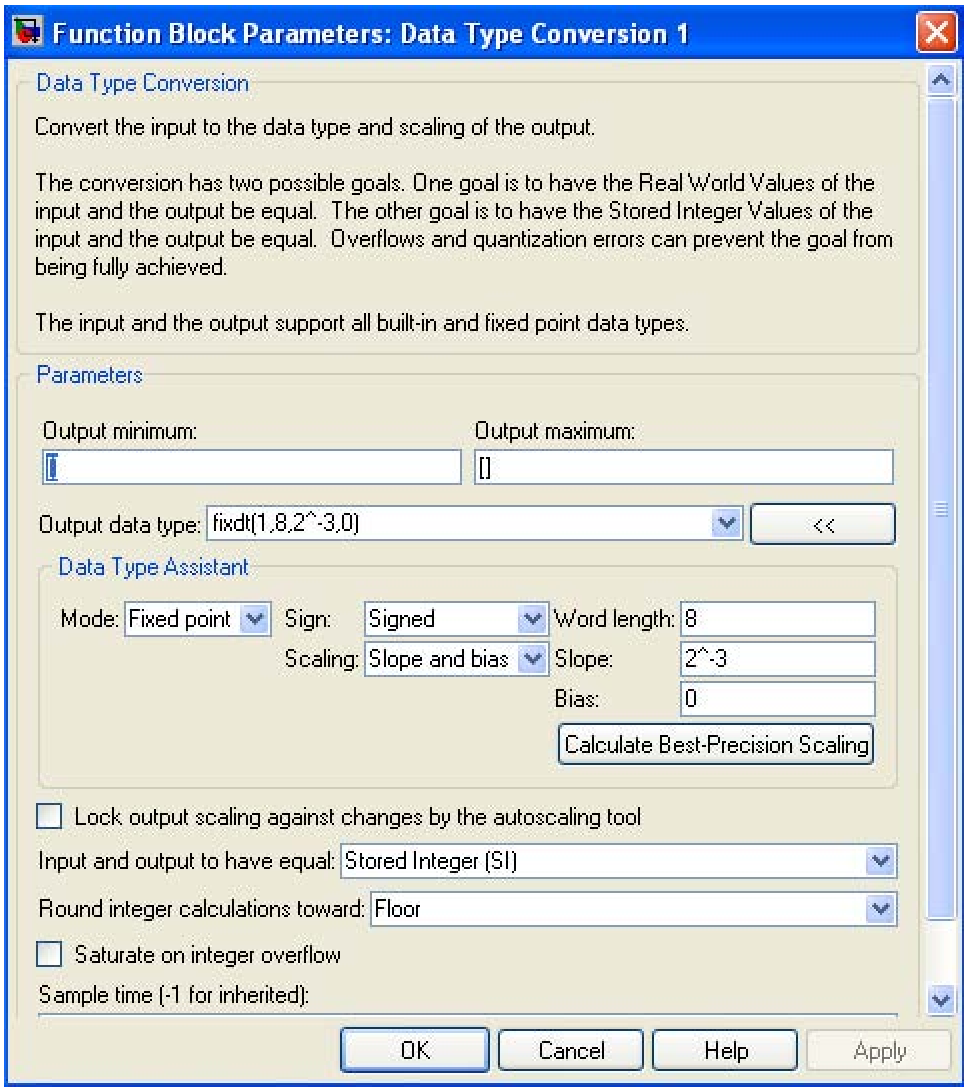


Figure 2.36. Model for Example 2.16

The labels in Figure 2.36 are displayed by choosing **Format>Port/Signal Displays>Port Data Types**.

In the **Data Type Conversion 1** block the input is processed as **Stored Integer (SI)** and scales the value 63 to be shown as 7.875. This is because the **Data Type Conversion 1** block parameters are specified as shown in Figure 2.37.


Function Block Parameters: Data Type Conversion 1
OK
Cancel
Help
Apply
<<
Calculate Best-Precision Scaling

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: fixdt(1,8,2^-3,0)

Data Type Assistant

Mode: Fixed point

Sign: Signed

Word length: 8

Scaling: Slope and bias

Slope: 2^-3

Bias: 0

☐ Lock output scaling against changes by the autoscaling tool

Input and output to have equal: Stored Integer (SI)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

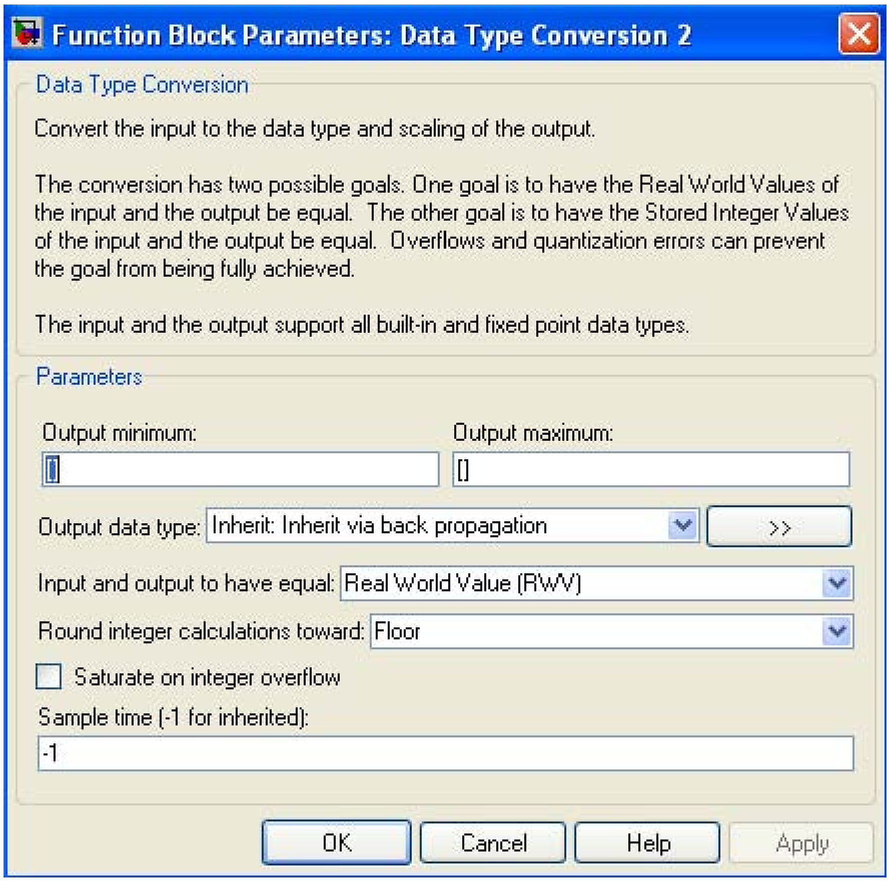
Sample time (-1 for inherited):

Figure 2.37. Function Block Parameters dialog box for the Data Type Conversion 1 block in Figure 2.36

We observe that the **Output data type** field in Figure 2.37 displays `fixdt(1,8,2^-3,0)` indicating that the output data are expressed in fixed point, the first number (1) within the parentheses indicates a signed number (it would be 0 for an unsigned number), the second number (8) is the Word length, the third number (2 ^ –3) is the slope, and the last number (0) is the Bias.

Display 1 block shows the value `7.875`. This is because the binary presentation of 63 with 8 bits is 00111111 and since we specified the Slope value as `2^–3`, the binary point is shifted 3 places to the left of the least significant bit, and becomes 00111.111 whose value in decimal is 7.875.

In the **Data Type Conversion 2** block the input is processed as **Real World Value (RWV)** so that the input and output will be equal. The **Function Block Parameters** dialog box for the **Data Type Conversion 2** block is shown in Figure 2.38.


Function Block Parameters: Data Type Conversion 2

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: Inherit: Inherit via back propagation

Input and output to have equal: Real World Value (RWV)

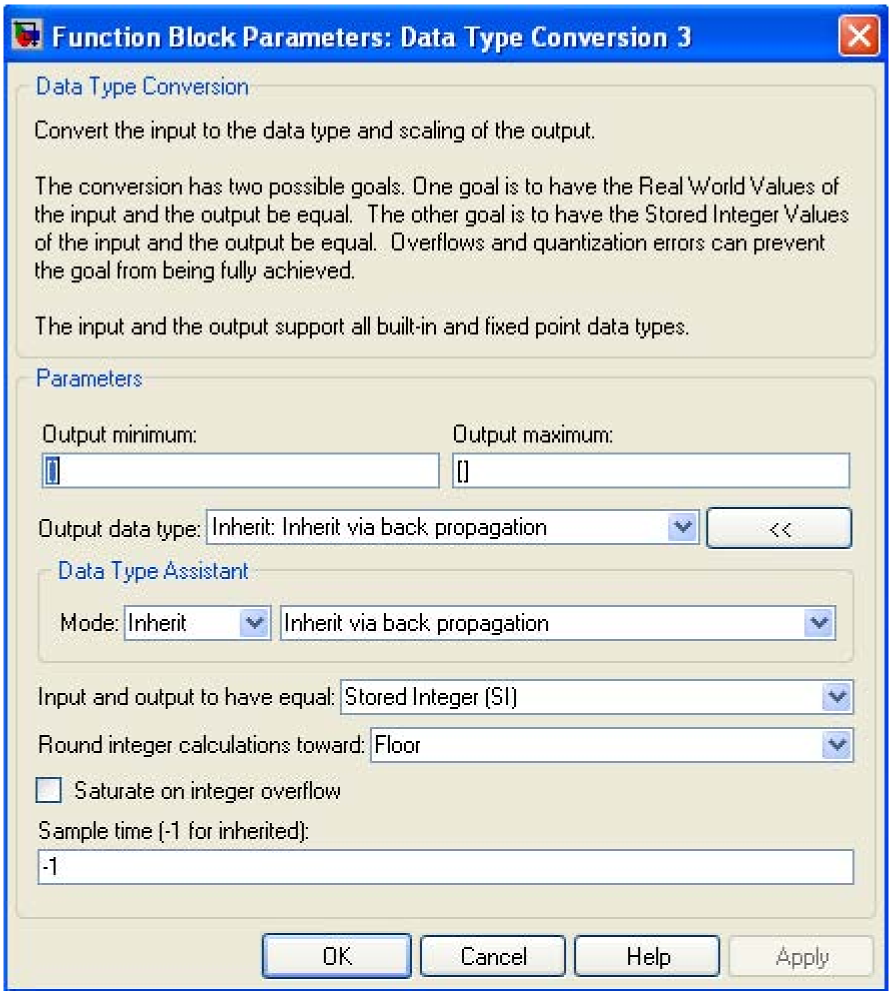
Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1

Figure 2.38. Function Block Parameters dialog box for the Data Type Conversion 2 block in Figure 2.36

In the **Data Type Conversion 3** block the input is processed as **Stored Integer (SI)** so that the input is treated as a raw integer with no scaling information and thus **Display 3** block shows the true value `63`. The **Function Block Parameters** dialog box for the **Data Type Conversion 3** block is shown in Figure 2.39.


Function Block Parameters: Data Type Conversion 3

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: Inherit: Inherit via back propagation

Data Type Assistant

Mode: Inherit — Inherit via back propagation

Input and output to have equal: Stored Integer (SI)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1

Figure 2.39. Function Block Parameters dialog box for the Data Type Conversion 3 block in Figure 2.36

Example 2.17

The model shown in Figure 2.40 uses three **Data Type Conversion** blocks. The **Data Type Conversion 1** block treats the input as a Real World Value (RWV), and maps that value to an 16–bit fixed point data type with scaling (slope) of 2^{-3} and thus its output is 0000000111111.000. The Function Block Parameters for the block is shown in Figure 2.41.

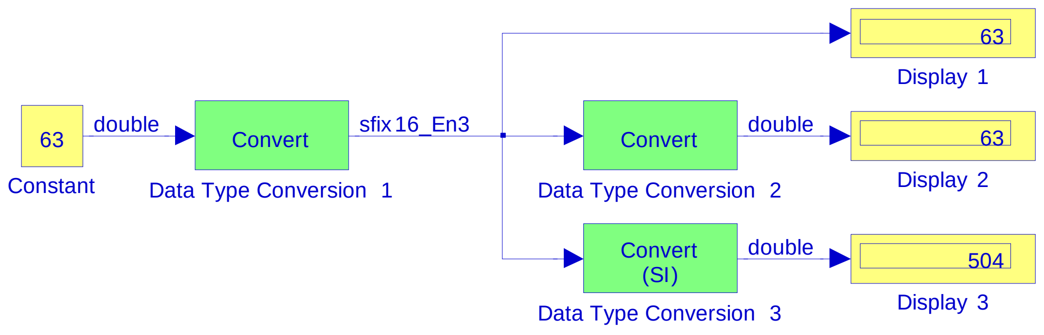
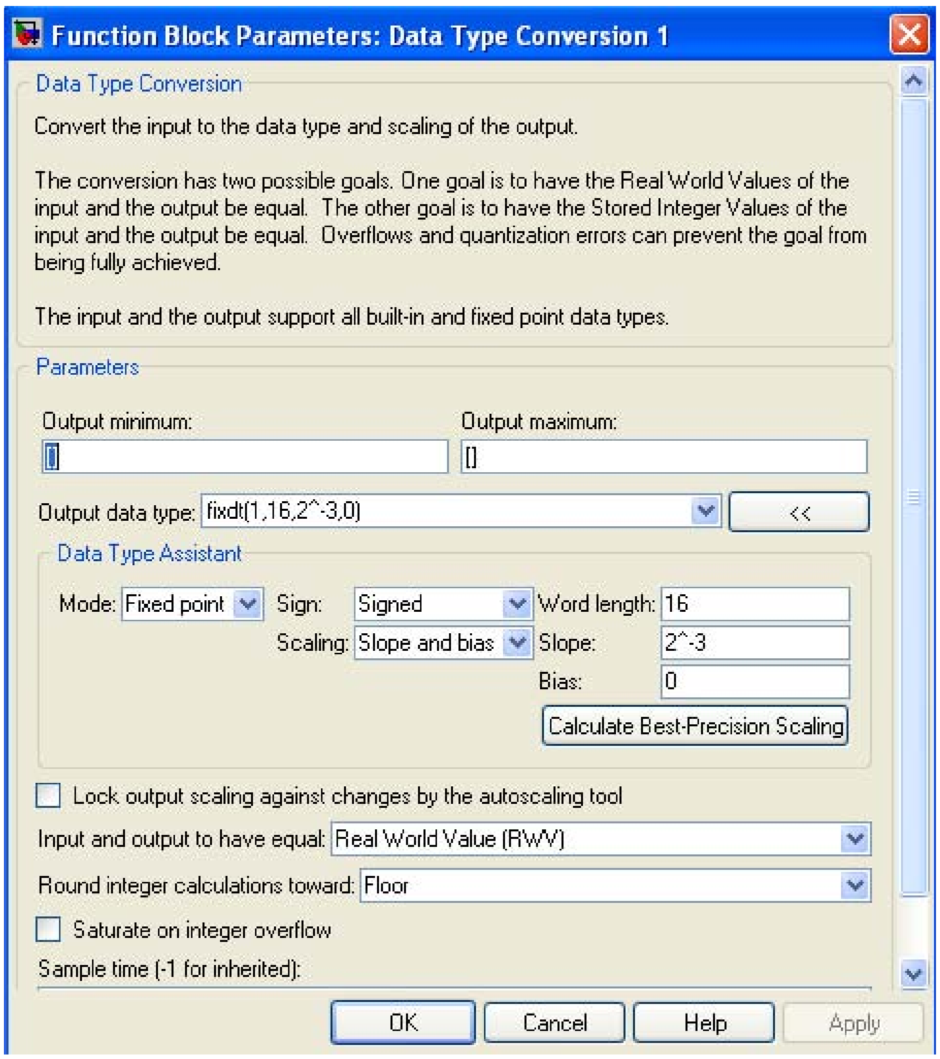


Figure 2.40. Model for Example 2.17



Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: fixdt(1,16,2^-3,0) <<

Data Type Assistant

Mode: Fixed point Sign: Signed Word length: 16

Scaling: Slope and bias Slope: 2^-3

Bias: 0

Calculate Best-Precision Scaling

☐ Lock output scaling against changes by the autoscaling tool

Input and output to have equal: Real World Value (RWV)

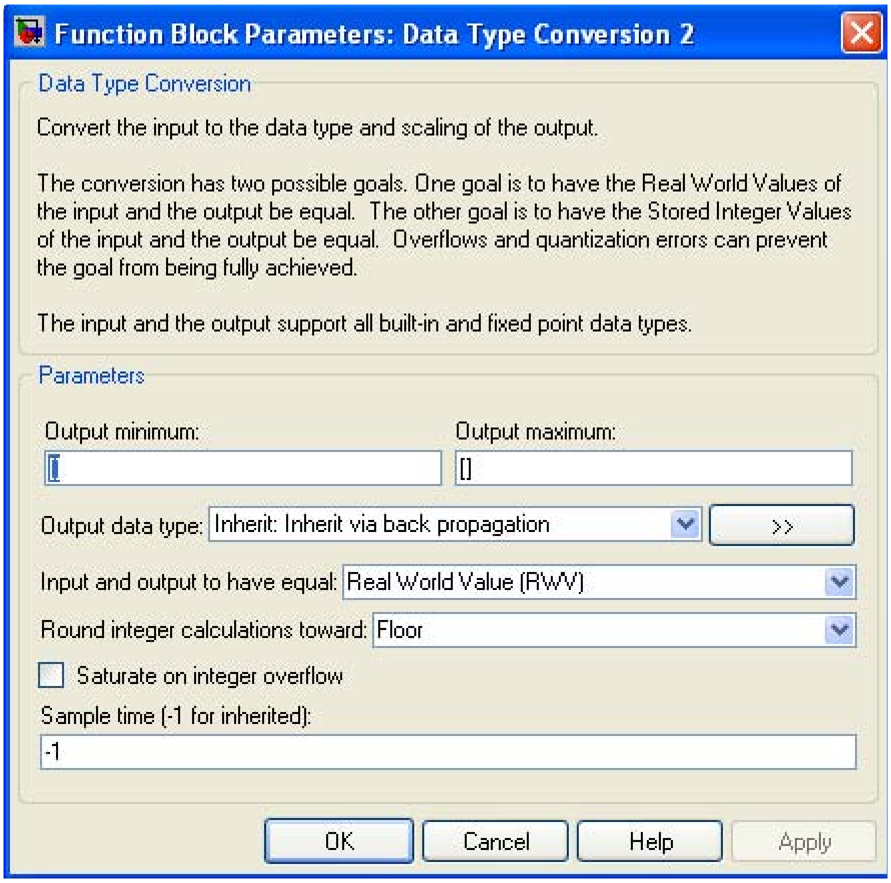
Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited):

Figure 2.41. Function Block Parameters dialog box for the Data Type Conversion 1 block in Figure 2.40

In the **Data Type Conversion 2** block the input is processed as **Real World Value (RWV)** so that the input and output will be equal. The **Function Block Parameters** dialog box for the **Data Type Conversion 2** block is shown in Figure 2.38.



Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Output minimum: []

Output maximum: []

Output data type: Inherit: Inherit via back propagation

Input and output to have equal: Real World Value (RWV)

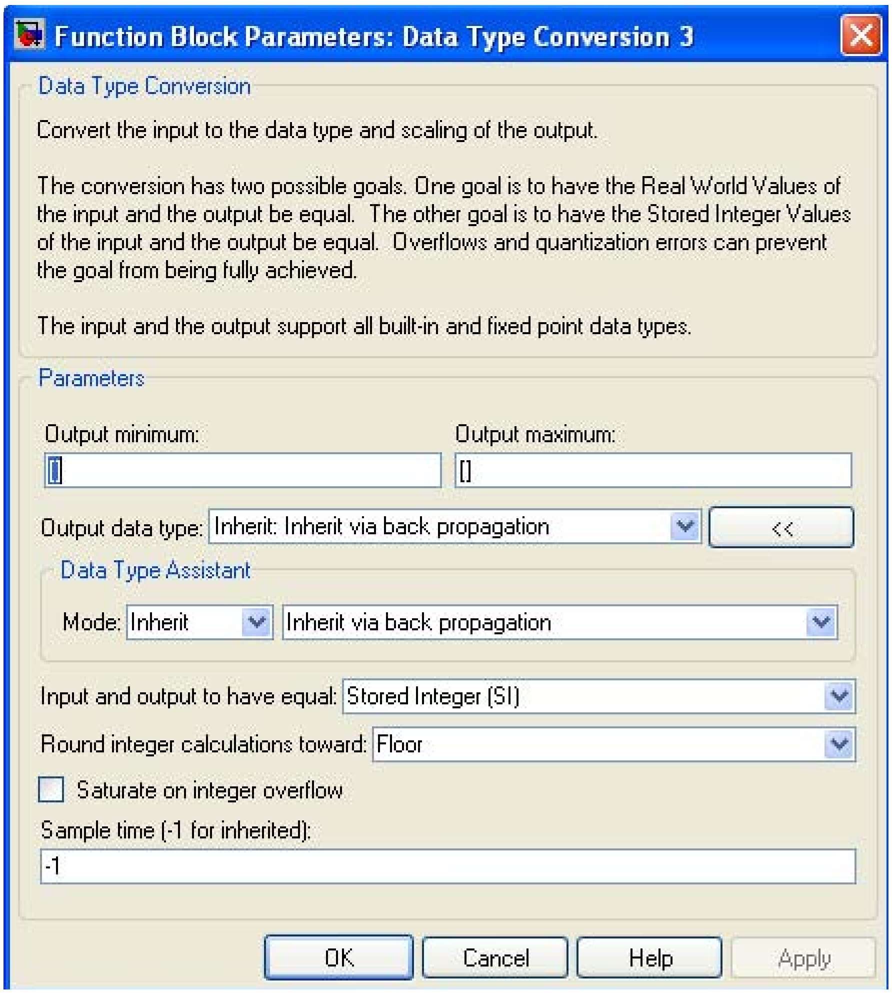
Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1

Figure 2.42. Function Block Parameters dialog box for the Data Type Conversion 2 block in Figure 2.40

In the **Data Type Conversion 3** block the input is processed as **Stored Integer (SI)** so that the input is treated as a raw integer with no scaling information and thus **Display 3** block shows the true value 504 whose binary representation is 0000000111111000. The **Function Block Parameters** dialog box for the **Data Type Conversion 3** block is shown in Figure 2.43.


Function Block Parameters: Data Type Conversion 3

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: Inherit: Inherit via back propagation

Data Type Assistant

Mode: Inherit — Inherit via back propagation

Input and output to have equal: Stored Integer (SI)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1

Figure 2.43. Function Block Parameters dialog box for the Data Type Conversion 3 block in Figure 2.40

Example 2.18

The model shown in Figure 2.44 illustrates how summation is performed with **Real–World Values** and **Stored Integer** data with **Data Type Conversion** blocks. **Display 3** and **Display 4** blocks show the correct result, but **Display 5** block shows an erroneous result because scaling information is not provide for **Data Type Conversion** block 6. This conversion block will provide the correct result if we change Double to sfix16_En5, by specifying sfixdt(1,16,2^–5,0) in the Function Block Parameters dialog box for the **Data Type Conversion 6** block.

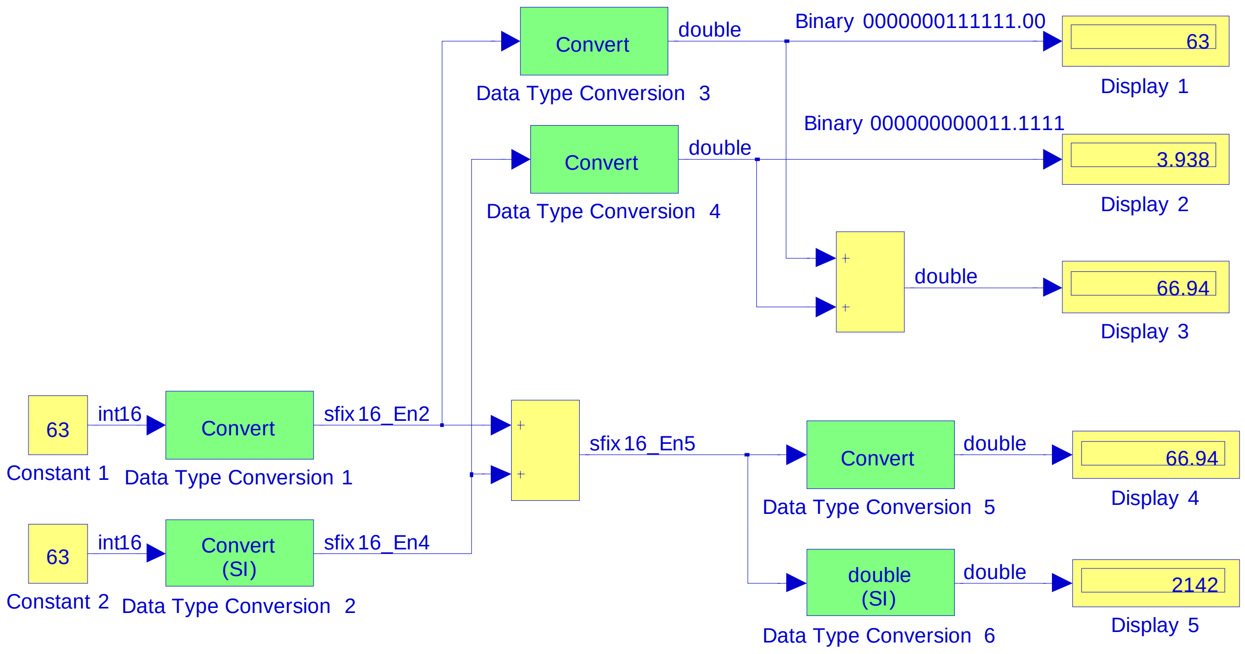


Figure 2.44. Model for Example 2.18

The **Data Type Demonstration** Simulink demo is another model using **Data Type Conversion** blocks. It can be accessed by typing datatypedemo at the MATLAB command prompt.

Note: The MATLAB and Simulink built–in integer data types are limited to 32 bits. If we want to output fixed–point numbers in the range 33 and 53 bits, we can break the number into pieces using Gain blocks. For details please refer to the Simulink Help menu for an example.

2.18 Summary

- A **Subsystem** block represents a subsystem of the system that contains it.
- **Inport** blocks are ports that serve as links from outside a system into the system.
- **Outport** blocks are output ports for a subsystem.
- The **Ground** block can be used to connect blocks whose input ports are not connected to other blocks. If we run a simulation with blocks having unconnected input ports, Simulink issues warning messages. Using Ground blocks to ground those blocks avoids warning messages. The **Ground** block outputs a signal with zero value. The data type of the signal is the same as that of the port to which it is connected.
- The **Terminator** block can be used to cap blocks whose output ports are not connected to other blocks. If we run a simulation with blocks having unconnected output ports, Simulink issues warning messages. Using Terminator blocks to cap those blocks avoids warning messages.
- The **Constant** block generates a real or complex constant value. The block generates scalar (1x1 2–D array), vector (1–D array), or matrix (2–D array) output, depending on the dimensionality of the Constant value parameter and the setting of the Interpret vector parameters as 1–D parameter. By default, the **Constant block** outputs a signal whose data type and complexity are the same as that of the block's Constant value parameter. However, we can specify the output to be any supported data type supported by Simulink, including fixed–point data types.
- The **Product** block performs multiplication or division of its inputs. This block produces outputs using either element–wise or matrix multiplication, depending on the value of the **Multiplication parameter**. We specify the operations with the Number of inputs parameter. Multiply(*) and divide(/) characters indicate the operations to be performed on the inputs.
- The **Scope** block displays waveforms as functions of simulation time. The Scope block can have multiple y–axes with a common time range.
- We use **Bus Creator** blocks to create signal buses and **Bus Selector** blocks to access the components of a bus. Simulink hides the name of a Bus Creator and Bus Selector blocks when we copy them from the Simulink library to a model. However, we can make the names visible by clicking **Show Name** on the **Format** menu.
- The **Bus Editor** allows us to change the properties of the bus types objects. We select the Bus Editor from the model's Tools menu.
- We can add an annotation to any unoccupied area of our model. To insert an annotation, we double–click an unoccupied section of the model, a small rectangle appears, and the cursor changes to an insertion point. We start typing the annotation text and we observe that each line is centered within the rectangle. Then we can move it to the desired location by dragging it. We can choose another Font and Text Alignment from the Format menu. We can delete an

annotation by first selecting it, holding down the Shift key and pressing the Delete or Backspace key.

- The **Mux** block combines its inputs into a single output. An input can be a scalar, vector, or matrix signal. Simulink hides the name of a **Mux block** when we drag it from the Simulink block library to a model. However, we can make the name visible by clicking **Show Name** on the **Format** menu.
- The **Demux** block extracts the components of an input signal and outputs the components as separate signals. The Number of outputs parameter allows us to specify the number and, optionally, the dimensionality of each output port. If we do not specify the dimensionality of the outputs, the block determines the dimensionality of the outputs for us. Simulink hides the name of a Demux block when we drag it from the Simulink library to a model. However, we can make the name visible by clicking **Show Name** on the **Format** menu.
- The **Switch** block outputs the first input or the third input depending on the value of the second input. The first and third inputs are called **data inputs**. The second input is called the **control input** and it is specified on the **Function Block Parameters** for the **Switch block**. The following options are available:

  u2>=Threshold

  u2>Threshold

  u2~=0

  where u2~=0 indicates a non–zero condition.
- The **Divide** block is an implementation of the Product block. It can be used to multiply or divide inputs.
- The **Gain** block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix. We specify the value of the gain in the Gain parameter. The Multiplication parameter lets us specify element–wise or matrix multiplication. For matrix multiplication, this parameter also lets us indicate the order of the multiplicands.
- The **Relational Operator** block performs the specified comparison of its two inputs. We select the relational operator connecting the two inputs with the Relational Operator parameter. The block updates to display the selected operator. The supported operations are given below.

  Operation Description:

  == TRUE if the first input is equal to the second input

  ~= TRUE if the first input is not equal to the second input

  < TRUE if the first input is less than the second input

  <= TRUE if the first input is less than or equal to the second input

>= TRUE if the first input is greater than or equal to the second input

> TRUE if the first input is greater than the second input

- The **Logical Operator** block performs the specified logical operation on its inputs. An input value is TRUE (1) if it is nonzero and FALSE (0) if it is zero. The Boolean operation connecting the inputs is selected with the Operator parameter list in the Function Block Parameters window. The block updates to display the selected operator. The supported operations are given below.

  Operation Description:

  AND – TRUE if all inputs are TRUE

  OR – TRUE if at least one input is TRUE

  NAND – TRUE if at least one input is FALSE

  NOR – TRUE when no inputs are TRUE

  XOR – TRUE if an odd number of inputs are TRUE

  NOT – TRUE if the input is FALSE and vice–versa

  The number of input ports is specified with the Number of input ports parameter. The output type is specified with the Output data type mode and/or the Output data type parameters. An output value is 1 if TRUE and 0 if FALSE.

- The **Saturation** block sets upper and lower bounds on a signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. When the Lower limit and Upper limit parameters are set to the same value, the block outputs that value.

- The **Integrator** block outputs the integral of its input. We can use different numerical integration methods to compute the **Integrator** block's output. The **Integrator** block's state port allows us to avoid creating algebraic loops when creating an integrator that resets itself based on the value of its output. An algebraic loop is formed when two or more blocks with direct feedthrough (the output of the block at time t, is a function of the input at time t) form a feedback loop. The basic problem with algebraic loops is that the output, y, at time, t, is a function of itself.

- The **Unit Delay** block delays its input by the specified sample period. That is, the output equals the input delayed by one sample. This block is equivalent to the z^{-1} discrete–time operator. This block allows for discretization of one or more signals in time, or for resampling the signal at a different rate. If our model contains multirate transitions, then we must add **Unit**

Delay blocks between the slow–to–fast transitions. The sample rate of the **Unit Delay** block must be set to that of the slower block.

- The **Discrete–Time Integrator block** performs discrete–time integration or accumulation of a signal. This block appears also in the **Discrete Library** Browser. We use this block in discrete–time systems instead of the Continuous Integrator block in continuous–time systems. The block can integrate or accumulate using the Forward Euler, Backward Euler, and Trapezoidal methods.
- There are two classes of data types: those defined by MATLAB and Simulink users, and those strictly defined by MATLAB. The latter type is referred to as MATLAB built–in data types. Simulink supports all built–in MATLAB data types except int64 and uint64. Table 2.1 lists the built–in data types supported by Simulink.
- The **Data Type Conversion block** converts an input signal of any Simulink data type to the data type and scaling specified by the block's Output data type mode, Output data type, and/or Output scaling parameters. The input can be any real– or complex–valued signal. If the input is real, the output is real. If the input is complex, the output is complex. This block requires that we specify the data type and/or scaling for the conversion. Also, the Data Type Conversion block handles any data type supported by Simulink, including fixed–point data types. The **Input and output to have equal** parameter is used to select the method by which the input is processed. The possible values are **Real World Value (RWV)** and **Stored Integer (SI)**.

2.19 Exercises

1 Repeat Example 2.6 using the Mux block instead of the Bus Creator block.

2. It is desired to convert a DC signal from 2.5 volts to 5.0 volts, another DC signal from 12 volts to 15 volts, and a third from +15 volts to −15 volts. The conversions are to be performed at a distant location. Create a model that includes a **Bus Creator** block, a Signal bus, and a **Bus Selector** block to accomplish these conversions.

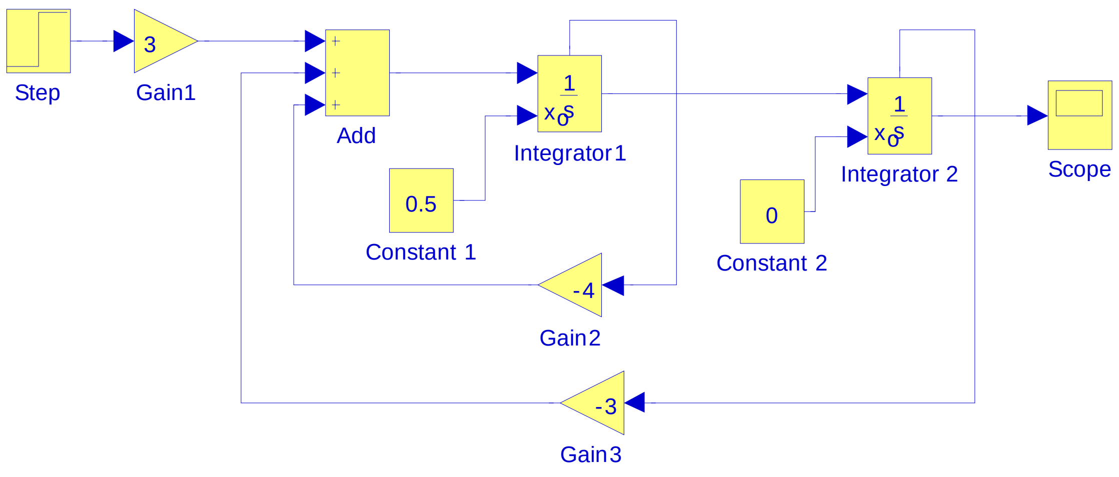
3. Using **Constant** blocks, a **Product** block, and a **Display** block, perform the operation $(3 + j4)/(4 + j3) \times (5 - j8)$.

4. Using a **Constant** block, a **Gain** block, and a **Display** block, perform the matrix multiplication $A \cdot A^*$ where

$$A = \begin{bmatrix} 1+j2 & j \\ 3 & 2-j3 \end{bmatrix} \qquad A^* = \begin{bmatrix} 1-j2 & -j \\ 3 & 2+j3 \end{bmatrix}$$

5. Create a model similar to that of Example 2.5 with the constant 255 as input that will display the true value in one **Display** block and will scale this number by a factor of eight to be shown in another **Display** block.

6. Explain why when the Start simulation command is issued for the model shown below, an error message is displayed.



7. The parameters of a **Pulse Generator** Block found under the **Sources** Simulink Library are set as follows:

Pulse type: Time based

Time (t): Use simulation time

Amplitude: 0.25

Period (secs): 2

Pulse width (% of period): 50

Phase delay (secs): 0

Integrate this pulse using a **Unit Delay** block and the **Backward Euler** integration method. Compare the output with the Forward Euler Integration block in Example 2.15.

8. Create a model to simulate the Boolean expression $D = A(\overline{B} + C) + \overline{A}B$.[*] Display the value of the output variable D for all combinations of the variables A, B, and C.[†]

9. Using a model with a **Relational Operator** block, prove or disprove that the beta function $B(5, 4)$ is equal to the gamma function $\Gamma(5) \cdot \Gamma(4) / \Gamma(5+4)$.[‡]

10. Create a model to display a three–phase power system on a single **Scope** block where the waveforms of three phases are three sine waves $120°$ degrees apart.

11. Create a model to display a sine wave with unity amplitude clipped at points $+0.5$ and -0.5.

12. Prove that relation (2.7), Page 2–27, i.e.,

$$y(n) = y(n-1) + K \cdot (T/2) \cdot [u(n) + u(n-1)]$$

for very small fixed T, the above relation can be approximated by the relation

$$y(n) \approx y(n-1) + K \cdot (T/2) \cdot u(n-1)$$

Hint: Assume that the input has the form

$$x(n) = e^{-naT}$$

.

* *Variables in parentheses have precedence over other operations.*

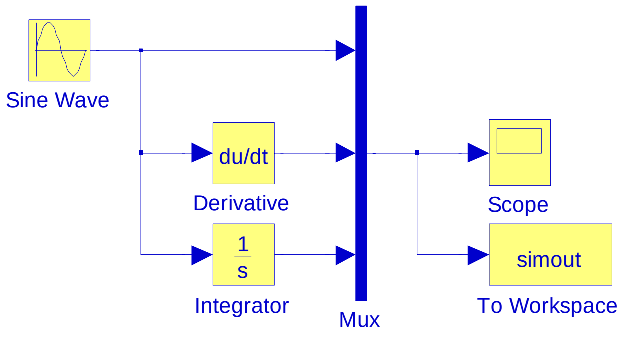
† *In other words, form the truth table for this Boolean expression. For a detailed discussion on truth tables, please refer to Digital Circuit Analysis and Design with Simulink Modeling and Introduction to CPLDs & FPGAs, ISBN 978–1–934404–05–8*

‡ *For a detailed discussion on the beta and gamma functions, please refer to Numerical Analysis Using MAT-LAB and Excel, ISBN 978–1–934404–03–4.*

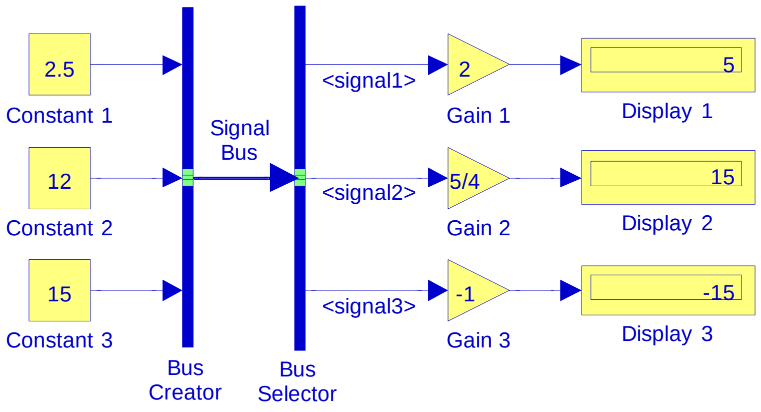
2.20 Solutions to End–of–Chapter Exercises

1.

We substitute the **Bus Creator** block with the **Mux** block, we double click the **Mux** block and in the **Function Block Parameters** dialog box, we change the number of inputs to 3, we assign a name to the simout block, and we save it by that name with the .mat extension



2.

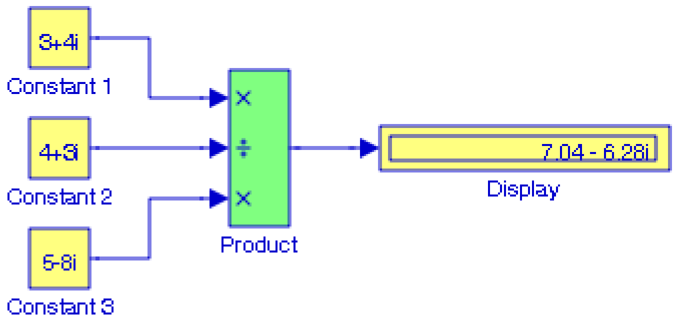


The **Constant** blocks are selected and dragged from the **Sources** Simulink Library Browser, the **Bus Creator** (left bus), **Bus Selector** (right bus), and **Gain** blocks from the **Commonly Used** Simulink Library Browser, and the **Display** blocks from the **Sinks** Simulink Library Browser. The Signal bus is normally shown as a single line arrow. It will change to a three line arrow when we click the **Start simulation** icon.

The “Signal bus” annotation was created by double–clicking a blank space of the model block, and in the small rectangle we entered this annotation. We moved it to location shown by dragging it.

3.

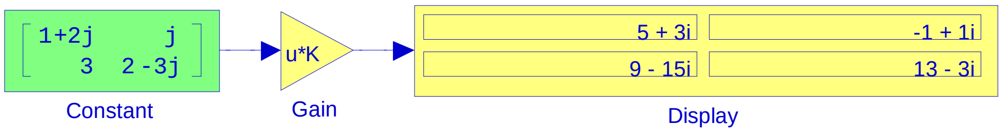
We connect the blocks as shown in the figure below. We double–click the **Constant** blocks and we enter the complex numbers shown. Then, we double click the **Product** block, and on the **Function Blocks Parameters**, in Number of inputs, we type */*. This sequence defines 3 inputs, a multiplication, a division, and another multiplication. After executing the Start simulation command, it may be necessary to stretch the **Display** block to see the result.



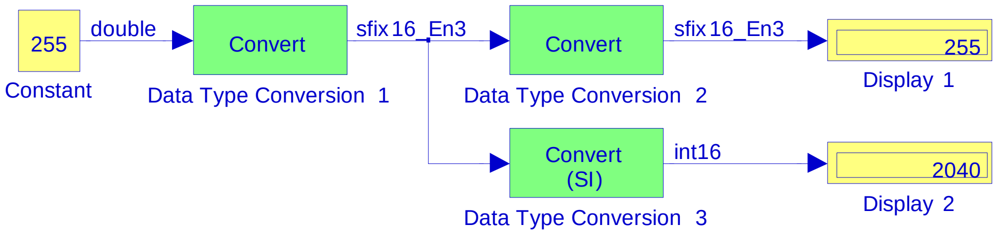
4.

$$A = \begin{bmatrix} 1+j2 & j \\ 3 & 2-j3 \end{bmatrix} \qquad A^* = \begin{bmatrix} 1-j2 & -j \\ 3 & 2+j3 \end{bmatrix}$$

We enter the elements of matrix A in the **Constant block**, and the elements of matrix A^* in the **Gain** block. After the Simulate start command is executed, the product appears in the **Display** block.

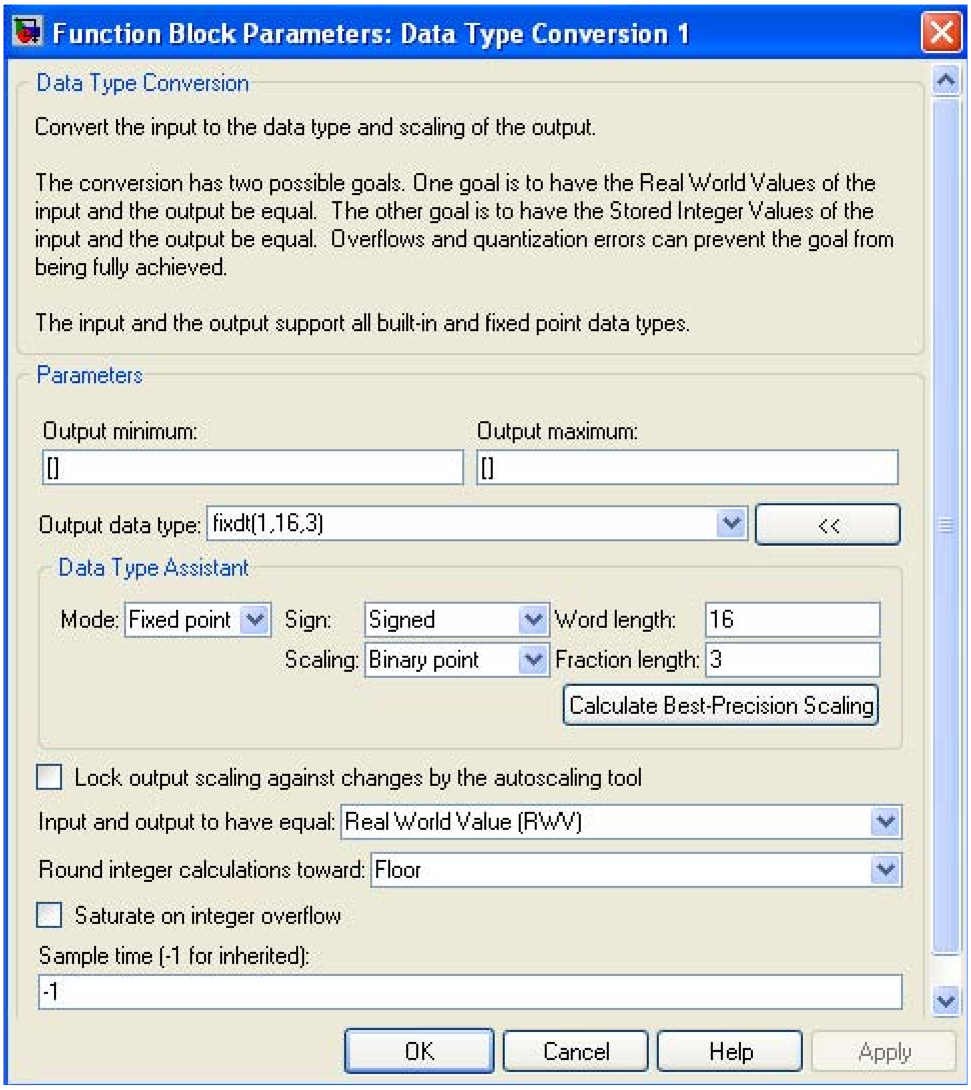


5.



The **Data Type Conversion 1** block treats the input as a real–world value, and maps that value to an 16–bit signed generalized fixed–point data type with a scaling of 2^–3. When the value is then output from the **Data Type Conversion 2** block as a real–world value, the scaling and data type information is retained and the output value is 000011111111.000, or 255.

When the value is output from the **Data Type Conversion 3** block as a stored integer, the scaling and data type information is not retained and the stored integer is interpreted as 000011111111000, or 2040. The settings in the **Function Block Parameters** dialog boxes for the **Data Type Conversion** blocks shown below.


Function Block Parameters: Data Type Conversion 1

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: fixdt(1,16,3)

Data Type Assistant

Mode: Fixed point

Sign: Signed

Word length: 16

Scaling: Binary point

Fraction length: 3

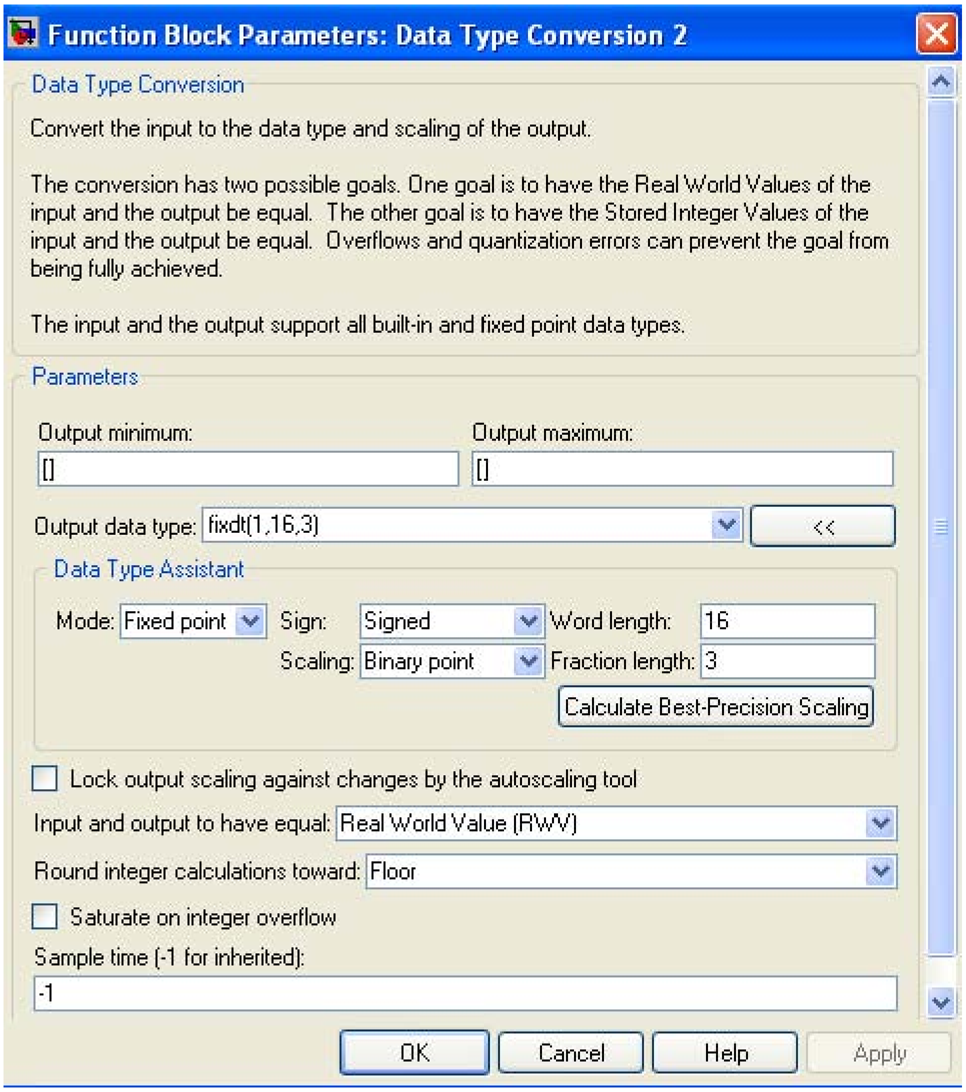
☐ Lock output scaling against changes by the autoscaling tool

Input and output to have equal: Real World Value (RWV)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1



Function Block Parameters: Data Type Conversion 2

Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: fixdt(1,16,3)

Data Type Assistant

Mode: Fixed point Sign: Signed Word length: 16

Scaling: Binary point Fraction length: 3

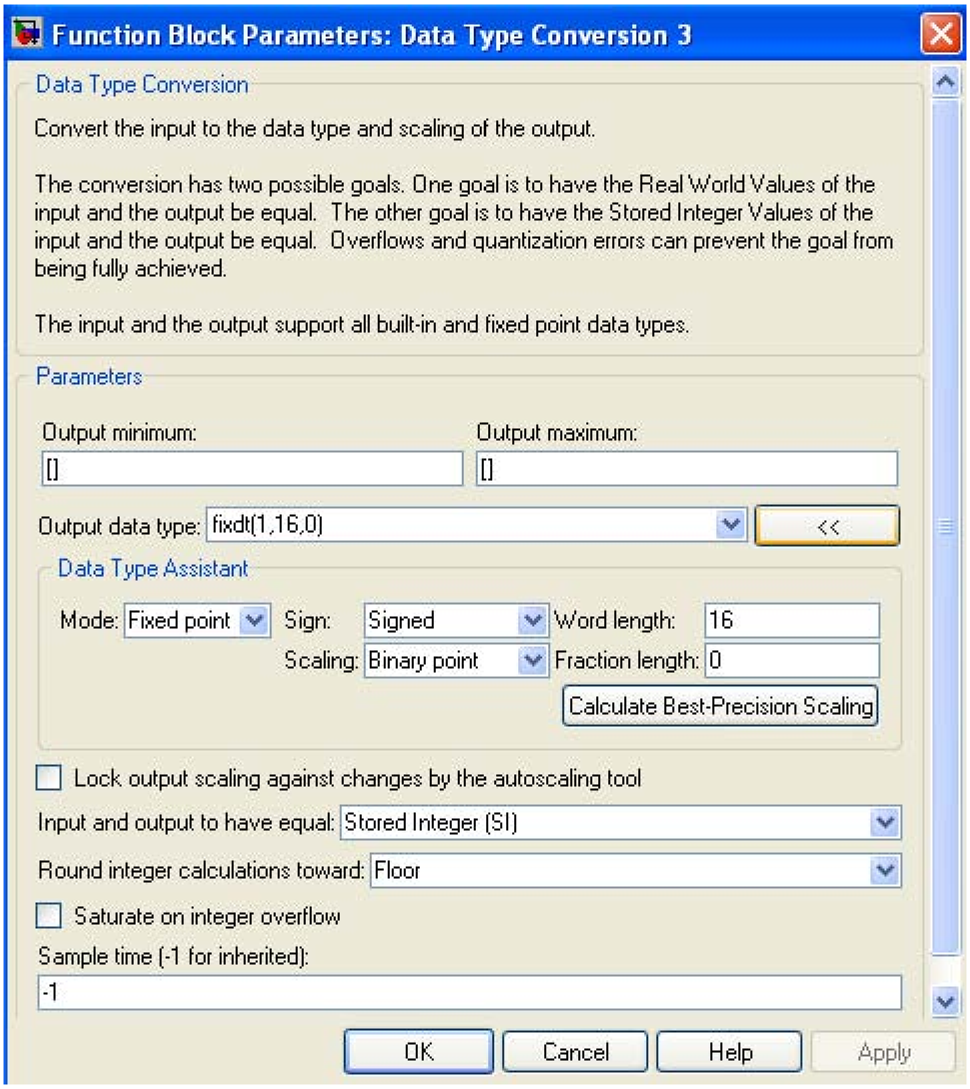
☐ Lock output scaling against changes by the autoscaling tool

Input and output to have equal: Real World Value (RWV)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

Sample time (-1 for inherited): -1



Data Type Conversion

Convert the input to the data type and scaling of the output.

The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved.

The input and the output support all built-in and fixed point data types.

Parameters

Output minimum: []

Output maximum: []

Output data type: fixdt(1,16,0)

Data Type Assistant

Mode: Fixed point Sign: Signed Word length: 16

Scaling: Binary point Fraction length: 0

Calculate Best-Precision Scaling

☐ Lock output scaling against changes by the autoscaling tool

Input and output to have equal: Stored Integer (SI)

Round integer calculations toward: Floor

☐ Saturate on integer overflow

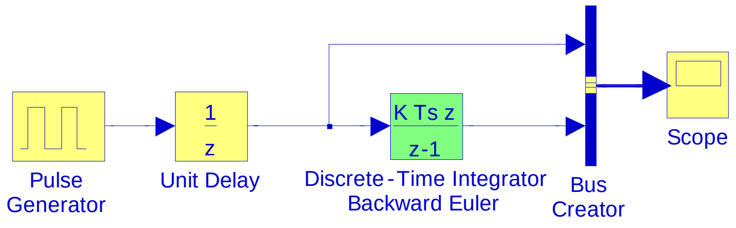
Sample time (-1 for inherited): -1

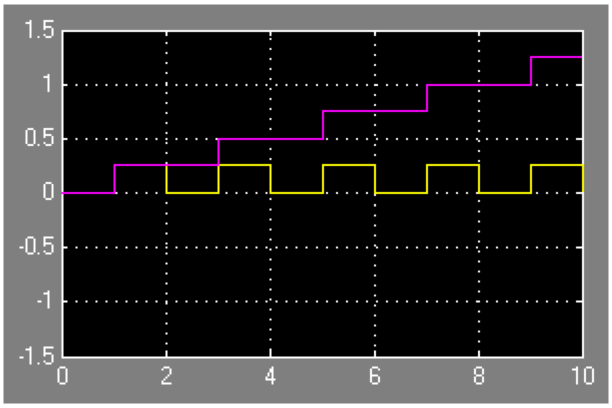
The Inport and Outport labels are displayed by choosing **Format>Port/Signal Displays>Port Data Types**.

6. The state ports are intended to be used specifically for self–resetting integrators (see **Creating Self–Resetting Integrators**), and Handing off a state from one enabled subsystem to another (see **Handing Off States Between Enabled Subsystems**) in Simulink's **Help** menu for the **Integrator** block. The state port should only be used in these two scenarios. When updating a model, Simulink checks to ensure that the state port is being used in one of these two scenarios. If not, Simulink outputs an error warning.

7.

The simulation model and the output of the **Discrete–Time Backward Euler Integrator** are shown below.





A comparison of the waveform above and that of Figure 2.34 in Example 2.15 shows that the accumulation (integration) begins one step *n* earlier. We recall that for the **Forward Euler Discrete–Time Integrator**,

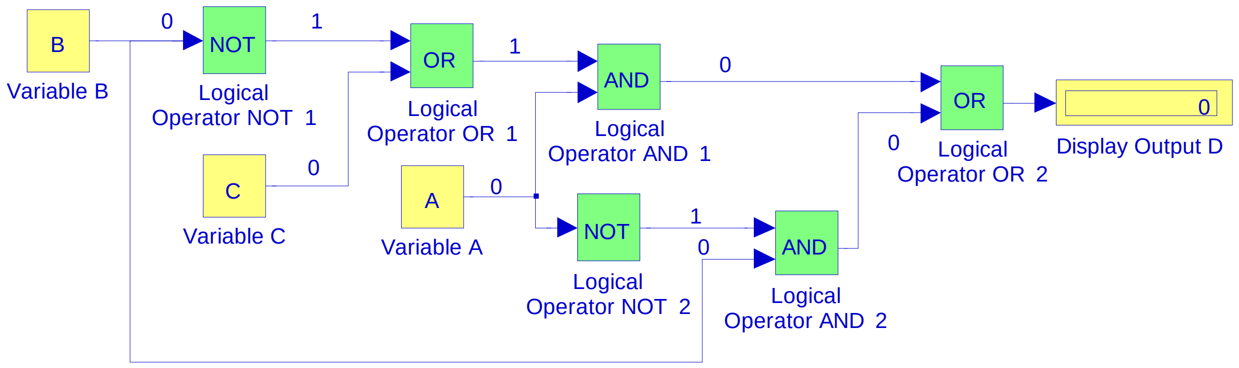
$$y(n) = y(n-1) + K \cdot T \cdot u(n-1)$$

and for the **Backward Euler Discrete–Time Integrator**,

$$y(n) = y(n-1) + K \cdot T \cdot u(n)$$

8.

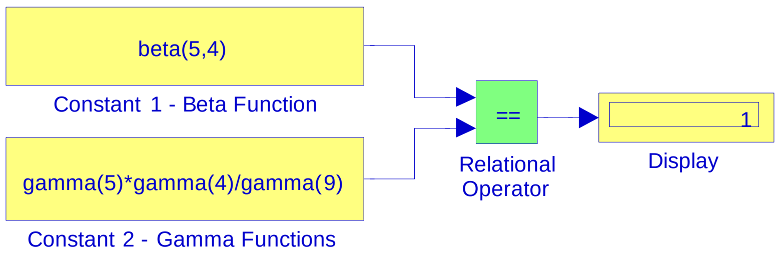
The model is shown below where the blocks indicated as Variable A, Variable B, and Variable C are **Constant** blocks. We begin by specifying the values for the combination `A = 0`, `B = 0`, and `C = 0` at the MATLAB command prompt, and after execution of the Simulation start command we observe the value 0 in **Display Output D** block.



The remaining combinations for the variables A , B , and C and the corresponding value of the output D are shown in the truth table below.

Inputs			Output
A	B	C	D
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	1

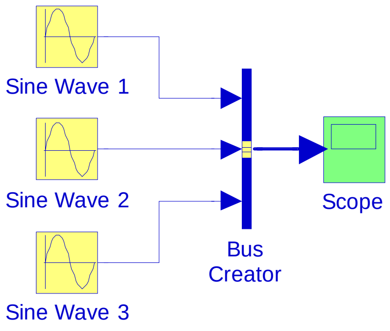
9. The model below proves that $B(5, 4) = \Gamma(5) \cdot \Gamma(4) / \Gamma(5+4)$.


beta(5,4)
Constant 1 - Beta Function
gamma(5)*gamma(4)/gamma(9)
Constant 2 - Gamma Functions
==
Relational Operator
1
Display

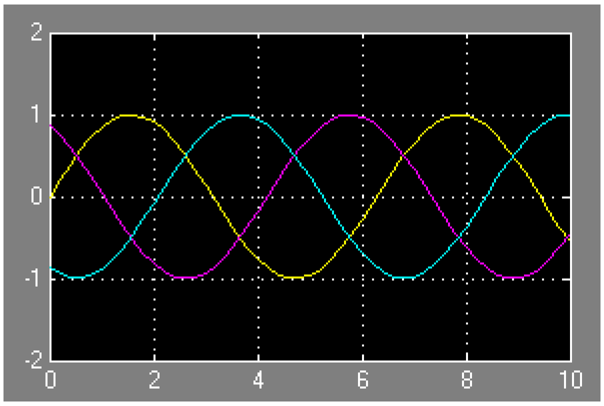
In the **Source Block Parameters** dialog box for the **Constant 1** block we enter beta(5,4), and in the **Source Block Parameters** dialog box for the **Constant 2** block we enter gamma(5)*gamma(4)/gamma(9). For both functions, on the Signal data types we select int8.

10.

The model is shown below where in the **Source Block Parameters** dialog box for the **Sine Wave 1** block the phase is specified as 0 radians, for the **Sine Wave 2** block the phase is specified as $2\pi/3$ radians, and for the **Sine Wave 3** block the phase is specified as $4\pi/3$ radians.

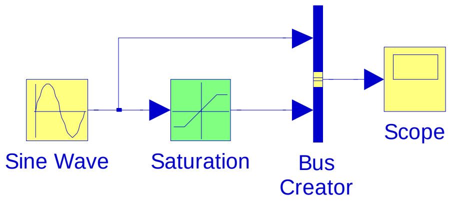


The three–phase waveforms are shown below.

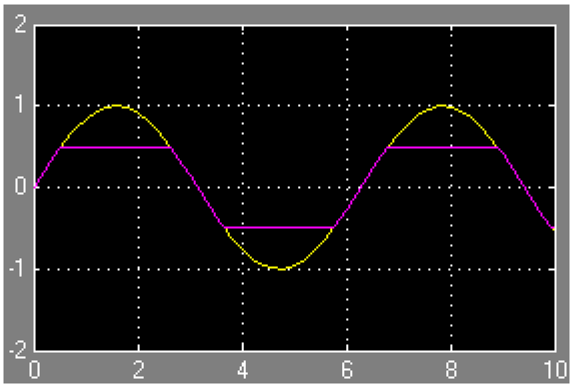


11.

The model is shown below where in the Saturation block's parameters dialog box we have specified Upper and Lower limits at points $+0.5$ and -0.5 respectively.

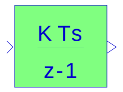


The input and output waveforms are shown below.



12.

Case 1: Forward Euler Discrete–Time Integrator



Discrete -Time Integrator
Forward Euler , K=1, Ts=T

This integrator, with $K = 1$, $T_S = T$, and zero initial conditions (ICs), is described as

$$y(n) = y(n-1) + Tx(n-1) \quad (1)$$

Suppose we want to find the response when the input is the decaying exponential

$$x(n) = e^{-naT} \quad (2)$$

The Z–Transform (ZT) of (1) is

$$H(z) = \frac{T}{z-1} \quad (3)$$

and the ZT of (2) is

$$X(z) = \frac{z}{z-e^{-aT}} \quad (4)$$

Then,

$$Y(z) = H(z)\cdot X(z) = \frac{Tz}{(z-1)(z-e^{-aT})} = \frac{T/(1-e^{-aT})}{z-1} - \frac{T/(1-e^{-aT})}{z-e^{-aT}} \quad (5)$$

from which

$$y(n) = \frac{T}{1-e^{-aT}}(1-e^{-naT}) \quad (6)$$

For the continuous–time case, where

$$x(t) = e^{-at} \quad (7)$$

we obtain

$$\int_0^t e^{-at}dt = \frac{1}{a}(1-e^{-at}) \quad (8)$$

Recalling that

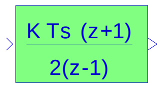
$$e^{-x} = 1 - x + \frac{x^2}{2!} - \ldots + \ldots$$

for $aT \ll 1$, (6) above reduces to

$$y(n) \approx \frac{T}{1-1+aT}(1-e^{-naT}) \approx \frac{1}{a}(1-e^{-naT}) \quad (9)$$

and thus (8) and (9) are almost identical.

Case 2: Trapezoidal Discrete–Time Integrator



Discrete -Time Integrator
Trapezoidal, K=1, Ts=T

This integrator, with $K = 1$, $T_S = T$, and zero initial conditions (ICs), is described as

$$y(n) = y(n-1) + \frac{T}{2}[x(n) + x(n-1)] \quad (10)$$

Suppose we want to find the response when the input is the decaying exponential

$$x(n) = e^{-naT} \quad (11)$$

The ZT of (10) is

$$H(z) = \frac{T}{2} \cdot \frac{z+1}{z-1} \quad (12)$$

and the ZT of (11) is

$$X(z) = \frac{z}{z-e^{-aT}} \quad (13)$$

Then,

$$Y(z) = H(z) \cdot X(z) = \frac{Tz(z+1)}{2(z-1)(z-e^{-aT})} = \frac{T/(1-e^{-aT})}{z-1} - \frac{Te^{-aT}(1+e^{-aT})/2(1-e^{-aT})}{z-e^{-aT}} \quad (14)$$

from which

$$y(n) = \frac{T}{(1-e^{-aT})}\left[1 - \frac{e^{-aT}}{2}(1+e^{-aT})e^{-naT}\right] \quad (15)$$

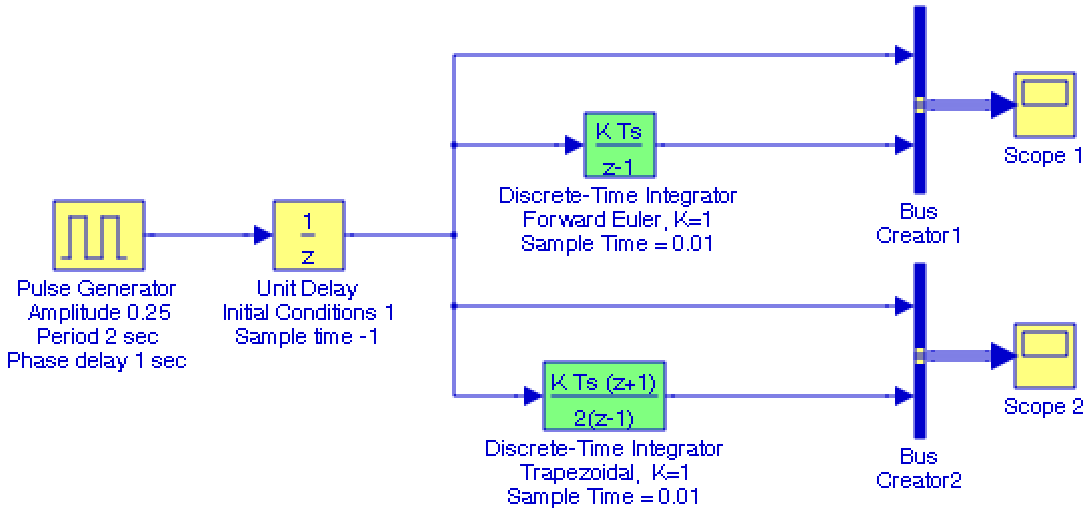
For $aT \ll 1$, (15) reduces to

$$y(n) \approx \frac{T}{1-1+aT}\left[1 - \frac{1-\overset{0}{\cancel{aT}}}{2}(1+1-\overset{0}{\cancel{aT}})e^{-naT}\right] \approx \frac{1}{a}[1-e^{-naT}] \quad (16)$$

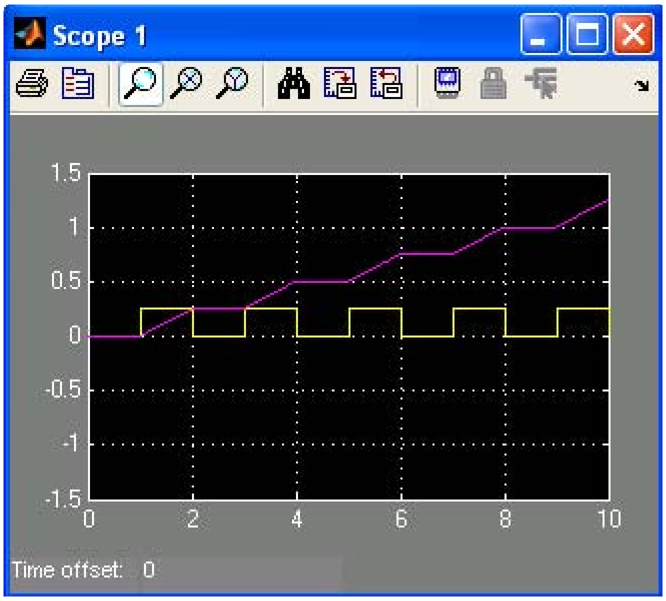
and (16) is almost identical to (9).

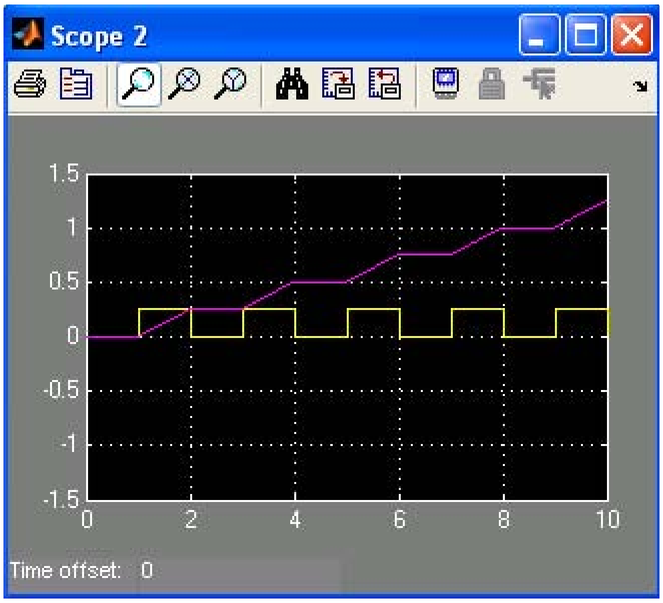
In both cases, we have assumed that the input is an exponential function. What about if the input is the discrete unit step function $u(n)$ or a sinusoid? It is reasonable to assume that the same results will be obtained considering that for $aT \approx 0$, $e^{-naT} \approx 1$, and for the discrete sinusoids using Euler's identity.

Let's try using the Forward Euler Discrete–Time Integrator and the Trapezoidal Discrete–Time Integrator with a pulse signal as the input shown below.



Scope 1 and **Scope 2** blocks display the same outputs as shown below.

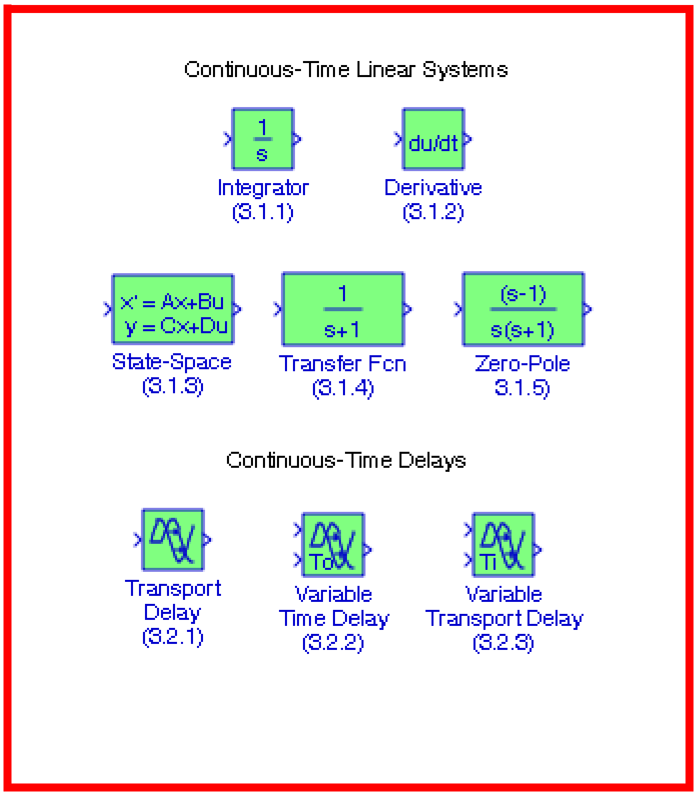

Scope 1
1.5
1
0.5
0
-0.5
-1
-1.5
0
2
4
6
8
10
Time offset: 0


Scope 2
1.5
1
0.5
0
-0.5
-1
-1.5
0
2
4
6
8
10
Time offset: 0

Chapter 3

The Continuous-Time Blocks Library

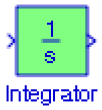
This chapter is an introduction to the **Continuous–Time Blocks** library. This is the second library in the Simulink group of libraries and contains the **Continuous–Time Linear Systems Sub–Library**, and the **Continuous–Time Delays Sub–Library** blocks shown below. We will describe the function of each block included, and their application will be illustrated with examples.



3.1 The Continuous–Time Linear Systems Sub–Library

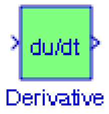
The **Continuous–Time Linear Systems Sub–Library** contains the blocks described in Subsections 3.1.1 through 3.1.5 below.

3.1.1 The Integrator Block



The **Integrator** block is described in Section 2.14, Chapter 2, Page 2–22.

3.1.2 The Derivative Block



The **Derivative block** approximates the derivative of its input. The initial output for the block is zero. The accuracy of the results depends on the size of the time steps taken in the simulation. Smaller steps allow a smoother and more accurate output curve from this block. Unlike blocks that have continuous states, the solver does not take smaller steps when the input changes rapidly. Let us consider the following simple example.

Example 3.1

We will create a model that will compute and display the waveform of the derivative of the function $y = \cos x$.

The model is shown in Figure 3.1, and the input and output waveforms are shown in Figure 3.2.

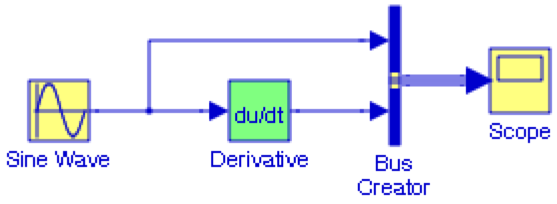


Figure 3.1. Model for Example 3.1

To convert the sine function in the Sine Wave block to a cosine function, in the **Source Block Parameters** dialog box we specify $\text{Phase} = \pi/2$. As we know, the derivative of the cosine function is the negative of the sine function and this is shown in Figure 3.2.

To scale the vertical axis in Figure 3.2, we move the cursor near that axis, we right–click, and we set the values as indicated. We will follow this practice in subsequent illustrations.

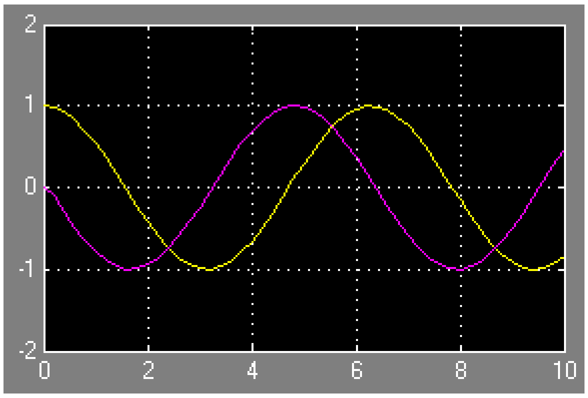


Figure 3.2. Input and output waveforms for the model of Figure 3.1

The Simulink Help for the derivative block states that using the MATLAB function **linmod** to linearize a model[*] that contains a **Derivative** block can be troublesome. Let us elaborate on linearization.

We prefer to work with linear functions since the slope is constant and thus we can find the output for any input. Unfortunately, the equations that describe the behavior of most physical phenomena are non–linear. If we are interested in values of the function close to some point (a,b), we can replace the given function by its first Taylor polynomial, which is a linear function.[†] We recall that the Taylor series are defined as in relation (3.1) below.

$$\boxed{f(x) = f(x_0) + f'(x_0)(x-x_0) + \frac{f''(x_0)}{2!}(x-x_0)^2 + \ldots + \frac{f^{(n)}(x_0)}{n!}(x-x_0)^n} \tag{3.1}$$

In (3.1), the first two terms on the right side define an equation of a straight line, i.e., $y = mx + b$, a linear function. For example, if $y = f(x) = x^2$, the first two terms on the right side of (3.1) at point x=3 are represented by $9 + 6(x-3) = 6x - 9$. The same is true for a function f of two variables, say x and y, i.e., $f(x, y)$, where if we let L denote the local linearization at the point (a, b), we obtain

* *One of the Simulink models provided by The MathWorks, is named **Airframe Trim and Linearize**. Simulink defines a **trim point**, also known as an equilibrium point, as a point in the parameter space of a dynamic system at which the system is in a steady state. For example, a trim point of an aircraft is a setting of its controls that causes the aircraft to fly straight and level. Mathematically, a trim point is a point where the system's state derivatives equal zero. Linearization is discussed in this section.*

† *The first Taylor polynomial is often called the local linearization.*

$$L(x, y) = f(a, b) + \frac{\partial f}{\partial x}(a, b)(x-a) + \frac{\partial f}{\partial y}(a, b)(y-b) \tag{3.2}$$

Relation (3.2) yields the three numbers required to define the local linearization. The first number is the value of f at point (a, b), the second is the value of the partial derivative with respect to x at point (a, b), and the third is the value of the partial derivative with respect to y at point (a, b).

Taking the partial derivative of $z = f(x, y) = x^2 + y^2$ and evaluating it at the point $(1, 2)$ we find that the local linearization is $w = L(1, 2) = 5 + 2(x-1) + 4(y-2)$. We observe that this local linearization contains x and y terms of first degree. We can plot these functions with the following MATLAB script. The plot is shown in Figure 3.3.

```
x=–3:0.01:3; y=x; z=x.^2+y.^2; w=5+2.*(x–1)+4.*(y–2); plot(x,z,x,w); grid
```

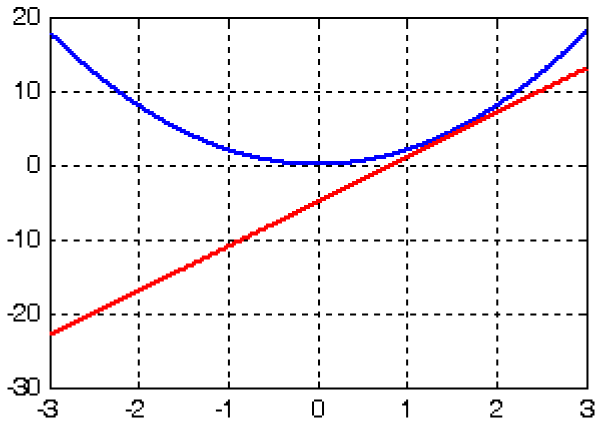


Figure 3.3. An example of linearization at a specified point

Example 3.2

A trivial solution of the non–linear differential equation

$$\frac{d^2y}{dt^2} + y\cos y = x \tag{3.3}$$

is $y = 0$ if $x = 0$

We can linearize this equation using a Taylor series expansion of the function

$$\frac{d^2y}{dt^2} + y\cos y - x$$

about the point $x = 0,\ y = 0$.

From (3.1) with $y = 0$

$$\cos y = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!} y^{2n} = 1 - \frac{1}{2!} y^2 + \ldots$$

Thus

$$\frac{d^2y}{dt^2} + y\cos y - x = \frac{d^2y}{dt^2} + y\left(1 - \frac{1}{2!}y^2 + \ldots\right) - x$$

and discarding all second and higher degree terms, we obtain the linearized differential equation

$$\frac{d^2y}{dt^2} + y = x$$

Of course, this equation is valid for small deviations about the operating point $x = 0$, $y = 0$

MATLAB provides three functions to extract linear functions in the form of state–space matrices A, B, C, and D. We recall that the input–output relationship in terms of these matrices is

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{3.4}$$

where x represents the state(s), u the input, and y the output, and the inputs and outputs must be **Inport** and **Outport** blocks. Other blocks cannot be used as inputs and outputs.

Example 3.3

We will use the MATLAB **linmod('x')** function to extract the linear model for the model shown in Figure 3.4.

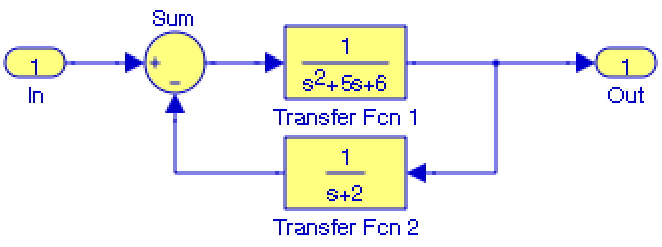


Figure 3.4. Model for Example 3.3

We save the given model as Figure_3_4, and at the MATLAB command prompt we execute the command [A,B,C,D]=linmod('Figure_3_4'). MATLAB displays the four matrices as

```
A =
    -5      -6     -1
     1       0      0
     0       1     -2

B =
      1
      0
      0

C =
      0      1      0

D =
      0
```

and thus the model of Figure 3.4 can be represented as

$$\dot{x} = \begin{bmatrix} -5 & -6 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & -2 \end{bmatrix} x + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \end{bmatrix} u$$

The **Simulink Extras** library described in Chapter 19, contains the **Switched derivative for linearization** block and the **Switched transport delay for linearization** block. The former should be used in place of the derivative when we are linearizing the model. It approximates the derivative with a proper transfer function. The latter delays the input by a specified amount of time. It can be used to simulate a time delay.

To avoid possible problems with derivatives we can incorporate the derivative block in other blocks.

Example 3.4

Let us consider the model of Figure 3.5.

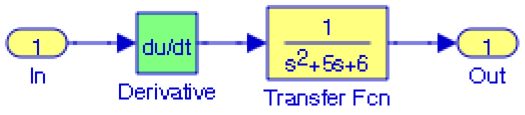


Figure 3.5. Model with derivative block

Recalling that differentiation in the time domain corresponds to multiplication by s in the complex frequency domain minus the initial value of $f(t)$ at $t = 0^-$, that is,

$$f'(t) = \frac{d}{dt} f(t) \Leftrightarrow sF(s) - f(0^-)$$

and assuming that the initial value is zero, we can replace the model of Figure 3.5 with that of Figure 3.6.

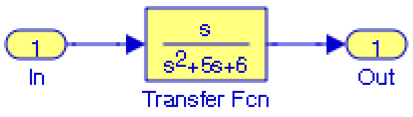
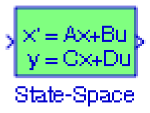


Figure 3.6. Model equivalent to the model in Figure 3.5

3.1.3 The State–Space Block



The **State–Space** block implements a system defined by the state–space equations

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \qquad (3.5)$$

where x and u are column vectors, matrix A must be an $n \times n$ square matrix where n represents the number of the states, matrix B must have dimension $n \times m$ where m represents the number of inputs, matrix C must have dimension $r \times n$ where r represents the number of outputs, and matrix D must have dimension $r \times m$.

For examples with the state–space block please refer to Chapter 1, Examples 1.1 and 1.2.

3.1.4 The Transfer Fcn Block

1
s+1
Transfer Fcn

The **Transfer Fcn** block implements a transfer function where the input $V_{in}(s)$ and output $V_{out}(s)$ can be expressed in transfer function form as the following equation

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} \qquad (3.6)$$

Example 3.5

Let us consider the op amp circuit of Figure 3.7.

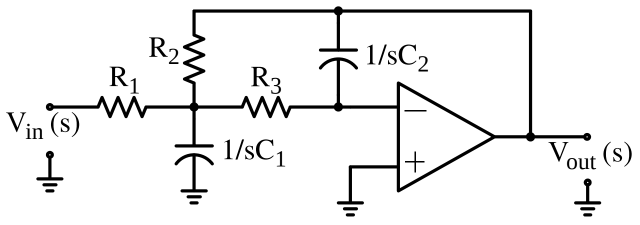


Figure 3.7. Circuit for Example 3.4 to be simulated.

It can be shown* that the transfer function of the op amp circuit of Figure 3.7 is given by

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{-1}{R_1[(1/R_1 + 1/R_2 + 1/R_3 + sC_1)(sR_3C_2) + 1/R_2]} \tag{3.7}$$

and this transfer function describes a second order lowpass filter. For simplicity, we let

$$R_1 = R_2 = R_3 = 1\ \Omega$$

$$C_1 = C_2 = 1\ F$$

and by substitution of these values into (3.7) we obtain

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{-1}{s^2 + 3s + 1} \tag{3.8}$$

Assuming that the input $V_{in}(s)$ is the unit step function, we will create a model using the **Transfer Fcn** block to simulate the output $V_{out}(s)$.

The model is shown in Figure 3.8 where in the Function Block Parameters dialog box for the Transfer Fcn block we have entered −1 for the numerator and [1 3 1] for the denominator.

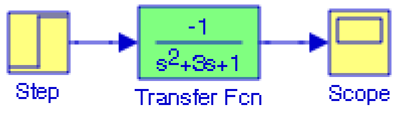


Figure 3.8. Model for Example 3.4

Upon execution of the Simulation start command, the **Scope** block displays the waveform shown in Figure 3.9.

* *The derivation of this transfer function is shown in Chapter 4, Signals and Systems with MATLAB Computing and Simulink modeling, ISBN 978–0–9744239–9–9.*

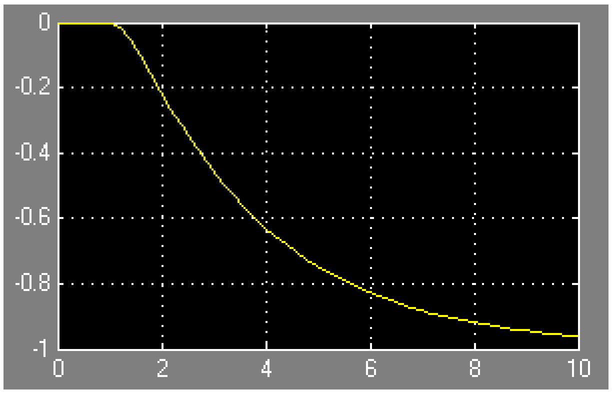
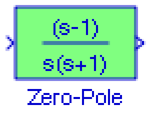


Figure 3.9. Output waveform for the model in Figure 3.8

3.1.5 The Zero–Pole Block



The **Zero–Pole** block implements a system with the specified zeros, poles, and gain in the s–domain. This block displays the transfer function depending on how the parameters are specified:

1. If each is specified as an expression or a vector, the icon shows the transfer function with the specified zeros, poles, and gain. If we specify a variable in parentheses, the variable is evaluated. For example, if in the **Function Block Parameters** dialog box we specify **Zeros** as [2 4 6 8], **Poles** as [1 3 5 7 9], and **Gain** as 25, the block looks like as shown in Figure 3.10.*

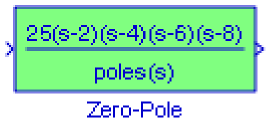


Figure 3.10. The Zero–Pole block specified in vector form

2. If each is specified as a variable, e.g., zeros, poles, Gain, at the MATLAB command prompt we enter

```
zeros=[2 4 6 8]; poles=[1 3 5 7 9]; Gain=25;
```

then the block shows the variable name followed by (s) if appropriate. For this example the block appearance will be as shown in Figure 3.11.

* *We may need to stretch the block to see the entire block shown above.*

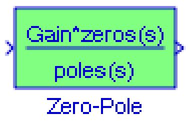


Figure 3.11. The Zero–Pole block specified as variables

Example 3.6

The system transfer function of a system has a gain factor of 1.5, zeros at $-2 \pm j$, and poles at -3 and at $-1 \pm j$. We will create a model to display the step response of this system.

The model and the input and output waveforms are shown in Figures 3.12 and 3.13 respectively.

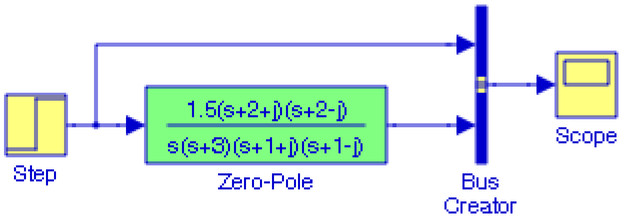


Figure 3.12. Model for Example 3.6

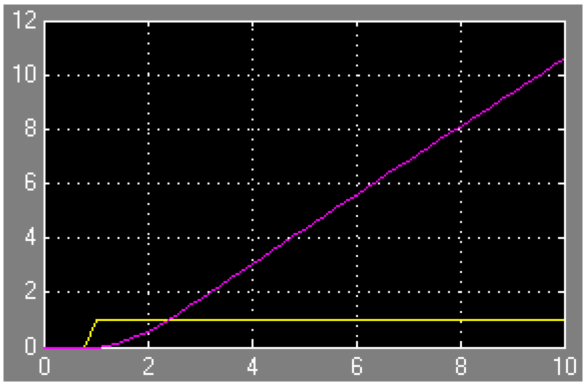


Figure 3.13. Input and output waveforms for the model in Figure 3.12

3.2 The Continuous–Time Delays Sub–Library

The **Continuous–Time Delays Sub–Library** contains the blocks described in Subsections 3.2.1 through 3.2.3 below.

3.2.1 The Transport Delay Block

The **Transport Delay** block delays the input by a specified amount of time. It can be used to simulate a time delay. At the start of the simulation, the block outputs the Initial input parameter until the simulation time exceeds the Time delay parameter. The Time delay parameter must be nonnegative. Best accuracy is achieved when the delay is larger than the simulation step size.

Example 3.7

For the model shown in Figure 3.14, the Time delay in the **Function Block Parameters** dialog box is specified as 2, and this delay is shown in Figure 3.15.

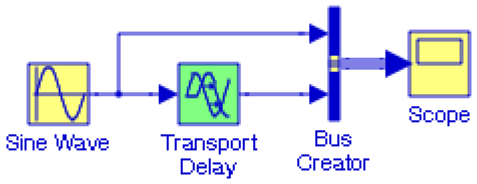


Figure 3.14. Model to illustrate the use of the Transport Delay block

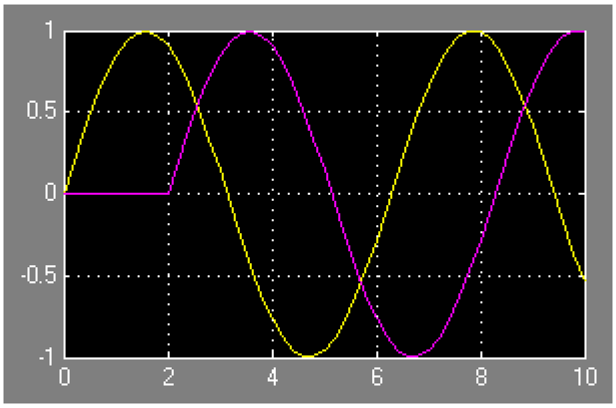


Figure 3.15. Input and output waveforms for the model in Figure 3.14

When an output is required at a time that does not correspond to the times of the stored input values, the **Transport Delay** block interpolates linearly between points. For a more detailed discussion please refer to the Simulink Help menu for this block.

The **Transport Delay** block does not interpolate discrete signals. Instead, it returns the discrete value at the required time.

Refer also to the **Switched Transport Delay for Linearization** block, Section 19.5.2, Chapter 19. This block delays the input by a specified amount of time. It can be used to simulate a time delay.

3.2.2 The Variable Time Delay Block

The **Variable Time Delay** block and the **Variable Transport Delay** block appear as two blocks in the Simulink block library. However, they are actually the same built–in Simulink block with different settings of a Select delay type parameter. In the Variable Time Delay mode, the block has a data input, a time delay input, and a data output. The block's output at the current time step equals the value of its data input at a previous time which is equal to the current simulation time minus a delay time specified by the block's time delay input.

Example 3.8

The model in Figure 3.16 shows a **Variable Time Delay** block where the **Signal Generator** block output is a square wave and the **Constant** block is set to the value 0.5 to introduce a delay of 0.5 second. The input and output waveforms of the **Variable Time Delay** block are shown in Figure 3.17.

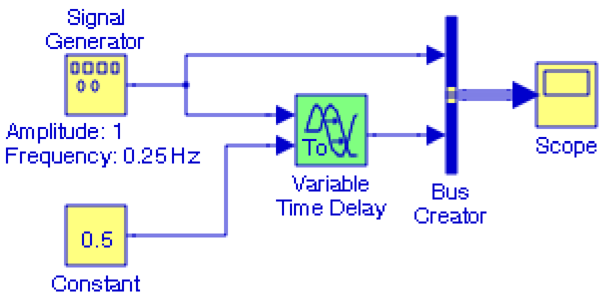


Figure 3.16. Model with Variable Time Delay

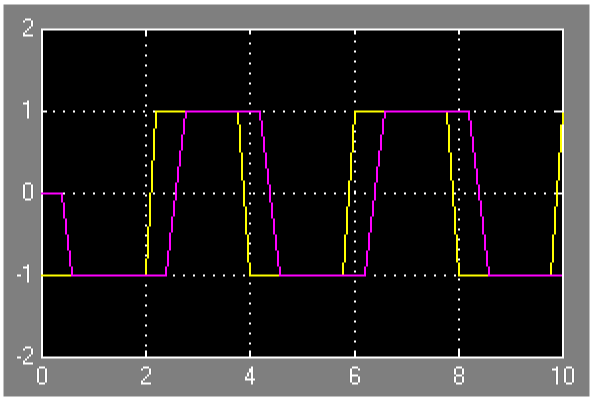
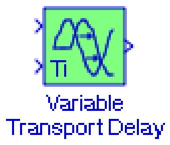


Figure 3.17. Signal Generator and Variable Time Delay output waveforms for the model in Figure 3.16

3.2.3 The Variable Transport Delay Block



In the **Variable Transport Delay** block the output is equal to the value of its data input at an earlier time which is equal to the current time minus a transportation delay. If we let $u(t)$ be the input, $t_d(t)$ the transportation delay, and $y(t)$ the output, then

$$y = u(t - t_d(t)) \tag{3.9}$$

Example 3.9

From electric circuit theory, we know that an alternating current i_C through a capacitor C leads the voltage v_C by $90°$. Using a **Variable Transport Delay** block, we will create a model that will display the current and voltage waveforms.

The model and the input and output waveforms are shown in Figures 3.18 and 3.19 respectively.

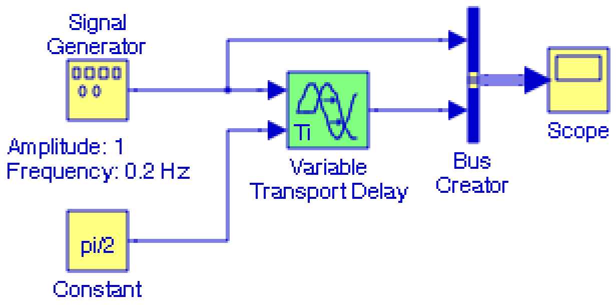


Figure 3.18. Model for Example 3.9

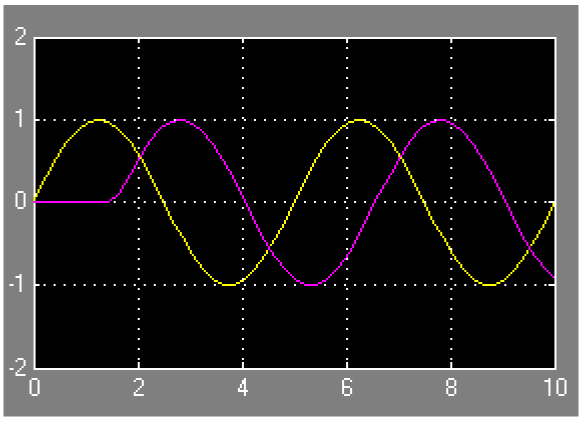


Figure 3.19. Input and output waveforms for the model in Figure 3.18

For another model using the **Variable Transport Delay** block, refer to the Simulink **Vertical Displacement of the Wheels of One Dimensional Car** demo by typing

```
sldemo_VariableTransportDelay
```

at the MATLAB command prompt.

3.3 Summary

- The **Integrator** block outputs the integral of its input at the current time step.
- The **Derivative** block approximates the derivative of its input. The block accepts one input and generates one output. The initial output for the block is zero. For nonlinear models, we can use the MATLAB function **linmod** to linearize a model that contains a Derivative block. To avoid problems, it is recommended that before linearizing we replace troublesome blocks with blocks found in the Simulink Extras library in the Linearization sublibrary. To avoid possible problems with derivatives we can incorporate the derivative block in other blocks.
- MATLAB provides three functions to extract linear functions in the form of state–space matrices A, B, C, and D. The input–output relationship in terms of these matrices is

  $$\begin{aligned}\dot{x} &= Ax + Bu\\ y &= Cx + Du\end{aligned}$$

  where x represents the state(s), u the input, and y the output, and the inputs and outputs must be Inport and Outport blocks. Source and Sink blocks cannot be used as inputs and outputs.
- The **Simulink Extras** library contains the Derivative for linearization block and the Transport Delay block. The former should be used in place of the derivative when we are linearizing the model. It approximates the derivative with a proper transfer function. The latter delays the input by a specified amount of time. It can be used to simulate a time delay.
- The **State–Space** block implements a system defined by the state–space equations

  $$\begin{aligned}\dot{x} &= Ax + Bu\\ y &= Cx + Du\end{aligned}$$

  where x and u are column vectors, A and C must be matrices conformable for multiplication with x, and B and D must be matrices conformable for multiplication with u.
- The **Transfer Fcn** block implements a transfer function where the input $V_{in}(s)$ and output (y) can be expressed in transfer function form as the following equation

  $$G(s) = \frac{V_{out}(s)}{V_{in}(s)}$$

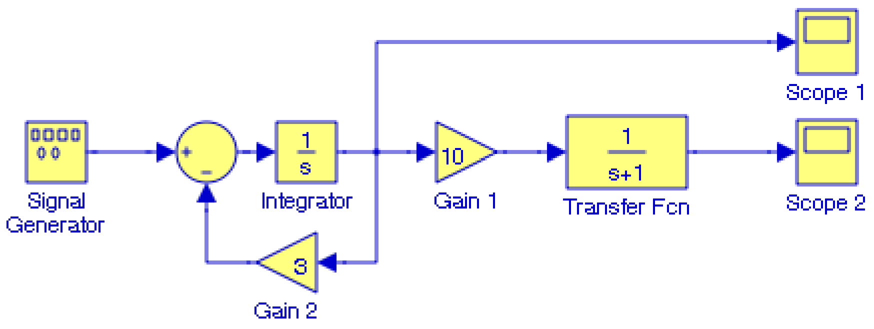
- The **Zero–Pole** block implements a system with the specified zeros, poles, and gain in the s–domain. The Zero–Pole block displays the transfer function depending on how the parameters are specified. If each is specified as an expression or a vector, the icon shows the transfer function with the specified zeros, poles, and gain. If we specify a variable in parentheses, the variable is evaluated.

- The **Transport Delay** block delays the input by a specified amount of time. It can be used to simulate a time delay. At the start of the simulation, the block outputs the Initial input parameter until the simulation time exceeds the Time delay parameter, when the block begins generating the delayed input. The Time delay parameter must be nonnegative. Best accuracy is achieved when the delay is larger than the simulation step size.
- The **Variable Time Delay** block and the Variable Transport Delay block appear as two blocks in the Simulink block library. However, they are actually the same built–in Simulink block with different settings of a Select delay type parameter. In the Variable Time Delay mode, the block has a data input, a time delay input, and a data output. The block's output at the current time step equals the value of its data input at a previous time equal to the current simulation time minus a delay time specified by the block's time delay input.
- In the **Variable Transport Delay** block the output at the current time step is equal to the value of its data input at an earlier time equal to the current time minus a transportation delay. If we let $u(t)$ be the input, $t_d(t)$ the transportation delay, and $y(t)$ the output, then

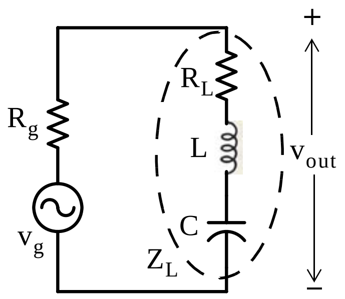
$$y = u(t - t_d(t))$$

3.4 Exercises

1. Using MATLAB's **linmod('x')** function, express the model below in state–space form.



2. Create a model that includes a **Transfer Fcn** block to simulate the output v_{out} of the electric circuit below where R_g represents the internal resistance of the applied (source) voltage v_g, and Z_L represents the impedance of the load that consists of R_L, L, and C. The values of the circuit constants are $R_g = 100\ \Omega$, $R_L = 1\ K\Omega$, $L = 10\ mH$, and $C = 500\ \mu F$.



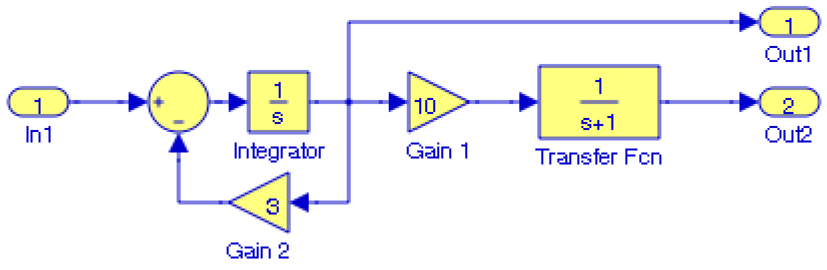
3. From electric circuit theory, it is known that charging a capacitor with a constant current produces a linear voltage across it, that is,

$$V_C = \frac{I}{C}t$$

where C is the capacitance in farads, I is the constant current through the capacitor in amperes, and V_C is the linear voltage across the capacitor in volts. Using a **Variable Transport Delay** block create a model to display the output if $I = 2\ mA$, $C = 1000\ \mu F$, and the voltage across the capacitor at some time t_0 is $V_0 = 2\ v$.

3.5 Solutions to End–of–Chapter Exercises

1. The first step is to replace the source and sink blocks with Inport and Outport blocks as shown below. This model is saved as Exercise_3_1A.



At the MATLAB command prompt we execute the statement

```
[A,B,C,D]=linmod('Exercise_3_1A')
```

and MATLAB displays

```
A =
    -3      0

    10     -1

B =
     1

     0

C =
     1      0

     0      1

D =
     0

     0
```

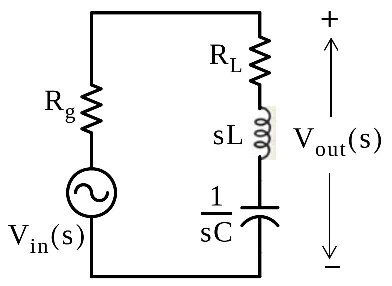
Therefore, the linear model of the given model in state–space form is expressed as

$$\dot{x} = \begin{bmatrix} -3 & 0 \\ 10 & -1 \end{bmatrix} x + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u$$

2.

The s – domain equivalent circuit is shown below.



The transfer function $G(s)$ is readily found by application of the voltage division expression

$$V_{out}(s) = \frac{R_L + sL + 1/sC}{R_g + R_L + sL + 1/sC} V_{in}(s)$$

Then,

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{R_L + Ls + 1/sC}{R_g + R_L + Ls + 1/sC}$$

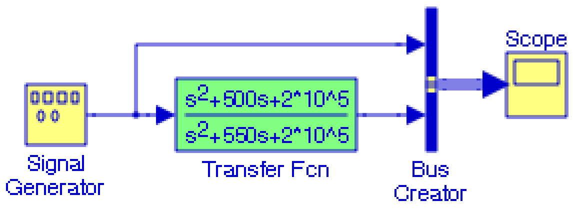
$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{LCs^2 + R_LCs + 1}{LCs^2 + (R_g + R_L)Cs + 1}$$

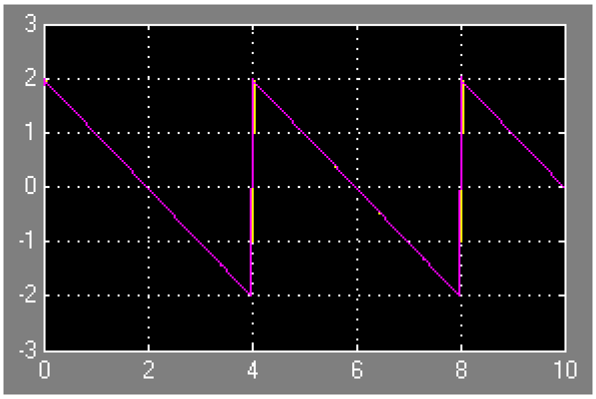
With $R_g = 100\ \Omega$, $R_L = 1\ K\Omega$, $L = 10\ mH$, and $C = 500\ \mu F$, the transfer function becomes

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{5 \times 10^{-6}s^2 + 5 \times 10^{-4}s + 1}{5 \times 10^{-6}s^2 + 5.5 \times 10^{-4}s + 1}$$

$$G(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{s^2 + 500s + 2 \times 10^5}{s^2 + 550s + 2 \times 10^5}$$

This transfer function is very nearly unity for all values of the variable s and thus we expect the output to be the same as the input. In the model shown below, the Signal Generator's waveform was chosen as sawtooth with amplitude 2 and frequency 0.25 Hz.





3.

$$V_C = \frac{I}{C}t = 2\times 10^3 t$$

Slope $= m = I/C$. Then

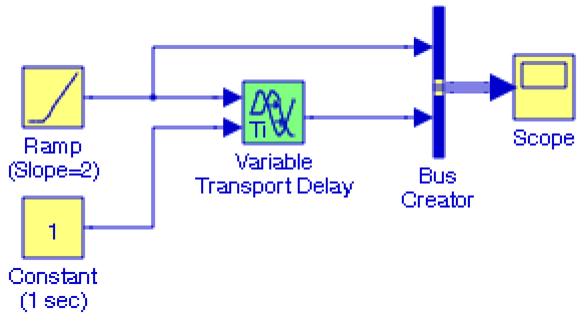
$$m = \frac{I}{C} = \frac{2\times 10^{-3}}{10^{-3}} = 2$$

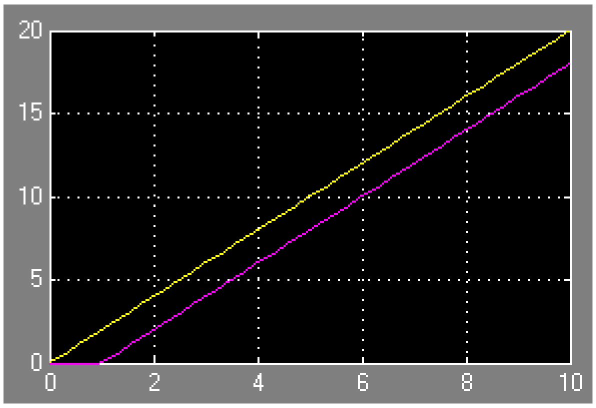
$$V_C = \frac{I}{C}t = 2t$$

For $V_C = V_0 = 2$ v

$$t = t_0 = \frac{2}{2} = 1 \text{ s}$$

The model and the input and output are shown below where the slope for the **Ramp** block is set to 2 and the time delay of 1 second is specified by the **Constant** block.


Ramp
(Slope=2)
1
Constant
(1 sec)
Variable
Transport Delay
Ti
Bus
Creator
Scope


20
15
10
5
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2
4
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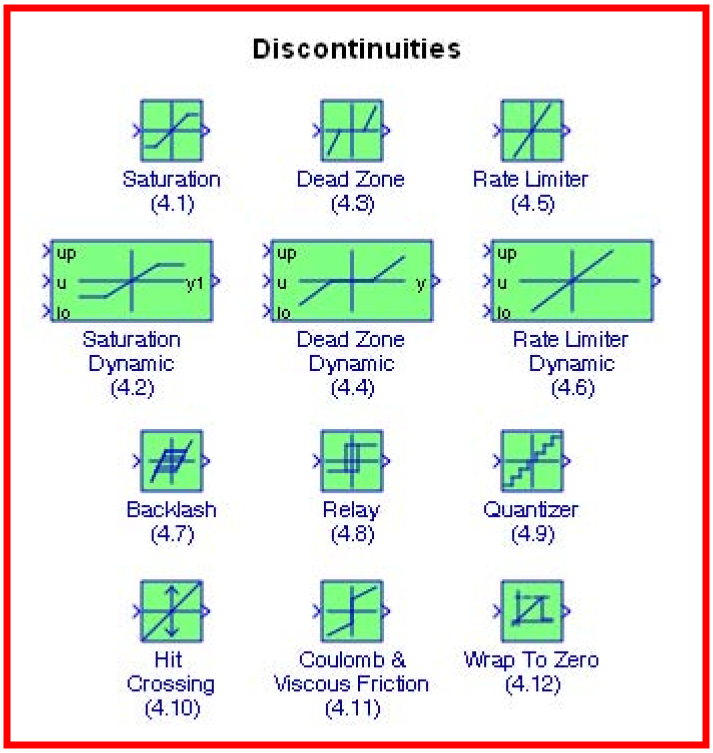
8
10

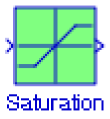
Chapter 4

The Discontinuities Blocks Library

This chapter is an introduction to the **Discontinuities Blocks** library. This is the third library in the Simulink group of libraries and contains the blocks shown below. Their functions are illustrated with examples.



4.1 The Saturation Block



The **Saturation** block sets upper and lower bounds on a signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. When the Lower limit and Upper limit parameters are set to the same value, the block outputs that value. This block is also described in Section 2.13, Chapter 2, Page 2−21.

Example 4.1 *

We will create a model with a Saturation block where the upper limit is clipped at $+0.5$ and the lower limit is clipped at -0.5. The input will be a sine function with amplitude 1 and frequency $0.25\ \mathrm{Hz}$.

The model is shown in Figure 4.1 and the input and output waveforms are shown in Figure 4.2.

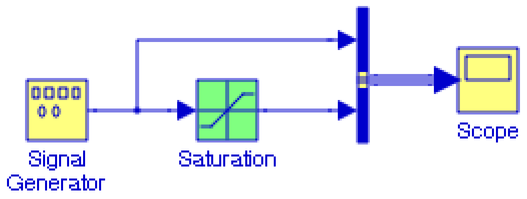


Figure 4.1. Model for Example 4.1

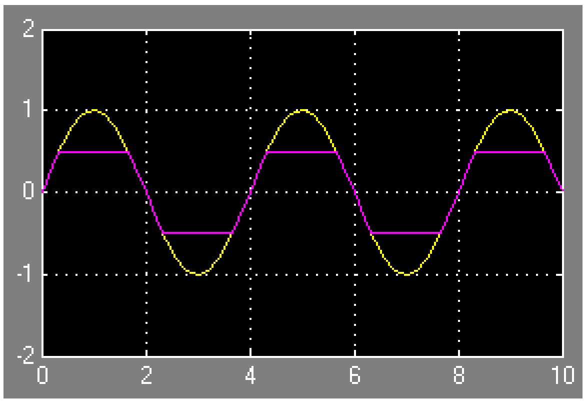
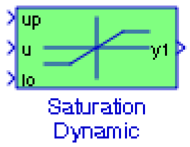


Figure 4.2. Input and output waveforms for the model in Figure 4.1

* *Another example with the Saturation block is presented as Example 2.13, Chapter 2, Page 2−21.*

4.2 The Saturation Dynamic Block



The **Saturation Dynamic** block bounds the range of the input signal to upper and lower saturation values. The input signal outside of these limits saturates to one of the bounds where the input below the lower limit is set to the lower limit, the input above the upper limit is set to the upper limit. The input for the upper limit is the up port, and the input for the lower limit is the lo port.

Example 4.2

We will create a model with a **Saturation Dynamic** block where the upper limit is clipped at $+1$ and the lower limit is clipped at 0. The **Signal Generator** block is specified in the **Block Parameters** dialog box as a sine function with amplitude 1 and frequency $0.25\ \mathrm{Hz}$.

The values of the **Constant** blocks are entered at the MATLAB command prompt as:

```
a=1; b=0;
```

The model is shown in Figure 4.3 and the input and output waveforms are shown in Figure 4.4.

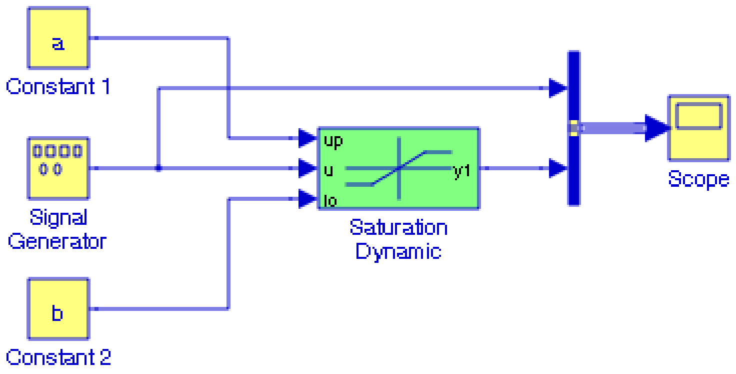


Figure 4.3. Model for Example 4.2

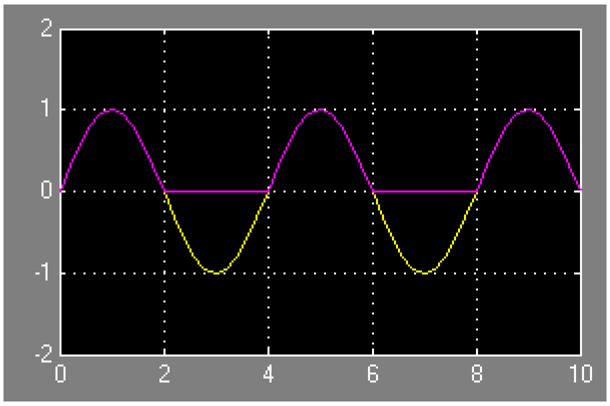
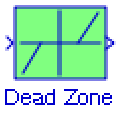


Figure 4.4. Input and output waveforms for the model in Figure 4.3

4.3 The Dead Zone Block



The **Dead Zone** block generates zero output within a specified region, called its **dead zone**. The lower and upper limits of the dead zone are specified as the Start of dead zone and End of dead zone parameters. The block output depends on the input and dead zone:

1. If the input is within the dead zone (greater than the lower limit and less than the upper limit), the output is zero.

2. If the input is greater than or equal to the upper limit, the output is the input minus the upper limit.

3. If the input is less than or equal to the lower limit, the output is the input minus the lower limit.

Example 4.3

We will create a model with the **Dead Zone** block where the **Function Block Parameters** dialog box for this block the start of the dead zone is -0.25, and the end of the dead zone is $+0.25$. The input will be a sine waveform with amplitude 1 and frequency $0.2\ \mathrm{Hz}$.

The model is shown in Figure 4.5 and the input and output waveforms are shown in Figure 4.6. This model uses lower and upper limits of -0.25 and $+0.25$ with the **Signal Generator** block specified in the **Block Parameters** dialog box as a sine wave of unity amplitude. Since the input is greater than he upper limit, the output is the input minus the upper limit, i.e., $1.00 - 0.25 = 0.75$. Likewise, for the negative half–cycle the output is $-1.00 - (-0.25) = -0.75$.

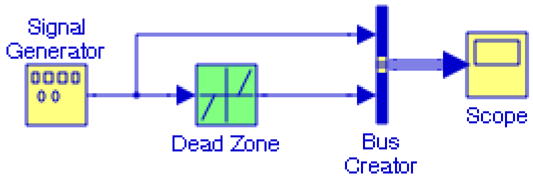


Figure 4.5. Model for Example 4.3

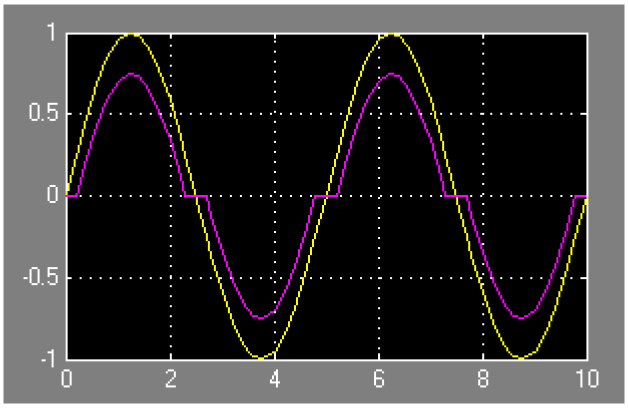
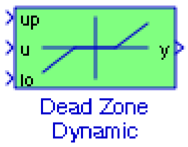


Figure 4.6. Input and output waveforms for the model in Figure 4.5

4.4 The Dead Zone Dynamic Block



The **Dead Zone Dynamic** block dynamically bounds the range of the input signal, providing a region of zero output. The bounds change according to the upper and lower limit input signals where:

1. The input within the bounds is set to zero.

2. The input below the lower limit is shifted down by the lower limit.

3. The input above the upper limit is shifted down by the upper limit.

The input for the upper limit is the up port, and the input for the lower limit is the lo port.

Example 4.4

We will create a model with the **Dead Zone Dynamic** block where the input for the upper limit is $+1.0$, and the input for the lower limit is -1.5. The input will be a sine waveform with amplitude 2 and frequency $0.2\ \mathrm{Hz}$.

The model is shown in Figure 4.7 and the input and output waveforms are shown in Figure 4.8.

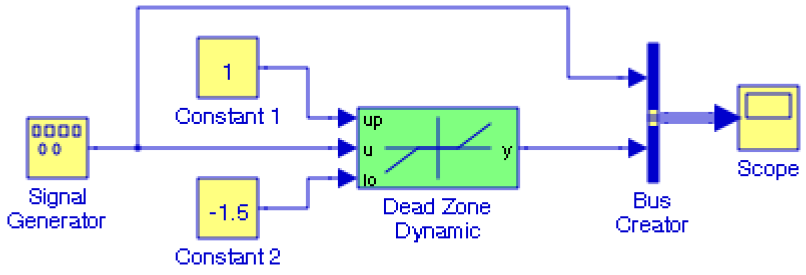


Figure 4.7. Model for Example 4.4

In Figure 4.8, the positive half–cycle of the output has a maximum value of $2.0 - 1.0 = 1.0$; that is, the input above the upper limit at the up port is shifted down by the upper limit whose value is $+1.0$. The input for the lower limit at the lo port is -1.5. The negative half–cycle of the output has a minimum value of $-2.0 - (-1.5) = -0.5$; that is, the input below the lower limit is shifted down by the lower limit.

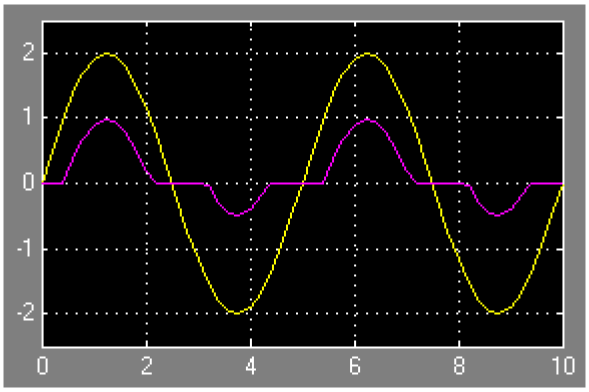
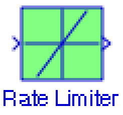


Figure 4.8. Input and output waveforms for the model in Figure 4.7

4.5 The Rate Limiter Block



The **Rate Limiter** block limits the first derivative of the signal passing through it. The equation and parameters used with this block are described in the Help menu for this block. The Function Block Parameters window for the Rate Limiter indicates that we can specify rising and falling slew rates where the default values are $+1$ and -1 respectively.

To understand the meaning of the slew rate, let us consider a typical operational amplifier,* or op amp for short. There is a limit to the rate at which the output voltage of an op amp can change. Therefore, manufacturers specify a new parameter referred to as the *slew rate*. By definition, the slew rate (SR) is the maximum rate of change of an output voltage produced in response to a large input step function and it is normally expressed in volts per microsecond, that is,

$$\text{Slew Rate} = SR = \frac{dv_{out}}{dt_{max}} \tag{4.1}$$

Of course, relation (4.1) is the slope of the output voltage under maximum rate of change conditions. Typical slew rates range from $0.1\ V/\mu s$ to $100\ V/\mu s$, and most internally compensated op amps have slew rates in the order of $1\ V/\mu s$. Figure 4.9 shows a step function of amplitude $10\ V$ applied to the input of a unity gain op amp, and the waveform at the output of this op amp.

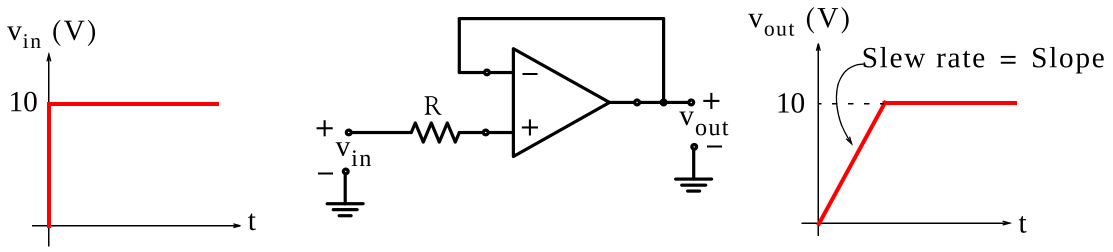


Figure 4.9. The resultant slew rate when a step function is applied to a unity gain op amp

The linearly rising slew rate shown in Figure 4.9 will not be produced if the input voltage is smaller than that specified by the manufacturer. In this case, the slew rate will be a rising exponential such as the rising voltage across a capacitor. In most op amps the slew rate is set by the charging rate of the frequency compensating capacitor and the output voltage is

$$v_{out} = V_f(1 - e^{-\omega_{ug}t}) \tag{4.2}$$

Example 4.5

We will create a model with a **Rate Limiter** block where the rising and falling slew rates will be the default values and the input will be the unit step function with **Step time** equal to 1.

* *For a detailed discussion on operational amplifiers, or op amps for short, please refer to Chapter 5, Electronic Devices and Amplifier Circuits with MATLAB Applications, ISBN 978−0−9709511−7−5.*

The model is shown in Figure 4.10 and the input and output waveforms are shown in Figure 4.11.

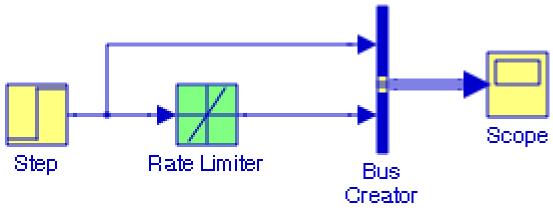


Figure 4.10. Model for Example 4.5

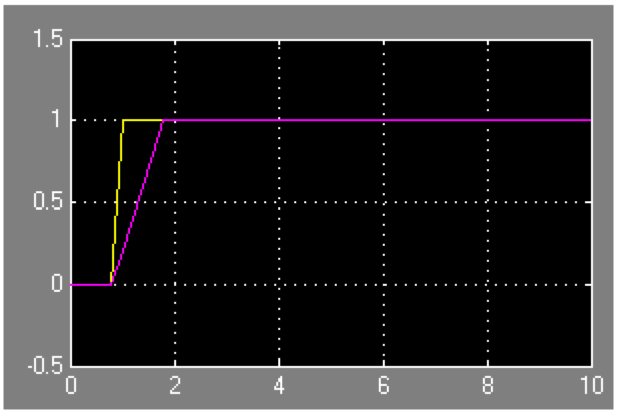
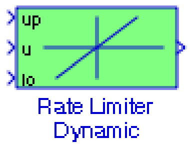


Figure 4.11. Input and output waveforms for the model in Figure 4.10

4.6 The Rate Limiter Dynamic Block



The **Rate Limiter Dynamic** block limits the rising and falling rates of the signal. The external signal up sets the upper limit on the rising rate of the signal. The external signal lo sets the lower limit on the falling rate of the signal.

Example 4.6

We will create a model with a **Rate Limiter Dynamic** block where the upper limit on the rising rate of the signal will be $+1$ and the lower limit on the falling rate of the signal will be -1. The input will be a sine function with amplitude 2 and frequency $2\ \mathrm{Hz}$.

The model is shown in Figure 4.12 and the input and output waveforms are shown in Figure 4.13.

For this example, the input is specified as a sine wave, and since the rate of change (slope or derivative) of the sine is the cosine, for the **Sine Wave** block we specified Amplitude 2, Frequency $2\ \mathrm{Hz}$, and Phase $\pi/2$. The values $+1$ and -1 assigned to the **Constant** blocks represent the rising and falling rates, that is, the slopes defined as the upper and lower limits respectively.

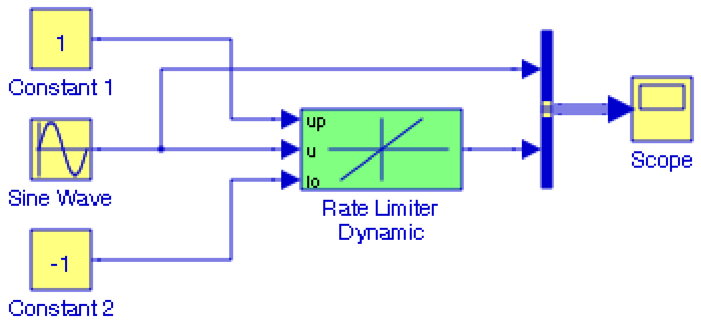


Figure 4.12. Model for Example 4.6

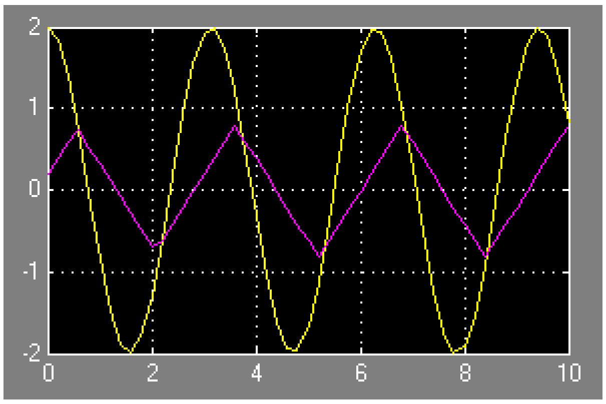


Figure 4.13. Input and output waveforms for the model in Figure 4.12

4.7 The Backlash* Block

* *In engineering,* ***backlash*** *is the amount of clearance between mated* ***gear*** *teeth in a* ***gear pair****. Some backlash is required to allow for lubrication, manufacturing errors,* ***deflection*** *under load and differential expansion between the gears and the housing. Backlash is created when the* ***tooth thickness*** *of either gear is less than the tooth thickness of an ideal gear, or the zero backlash tooth thickness. Additional backlash is created when the operating center distance of the gear pair is less than that for two ideal gears. Standard practice is to make allowance for half the backlash in the tooth thickness of each gear.*

The **Backlash** block implements a system in which a change in input causes an equal change in output. However, when the input changes direction, an initial change in input has no effect on the output. The amount of side–to–side play in the system is referred to as the **deadband**. The deadband is centered about the output. A system can be in one of three modes:

- Disengaged – In this mode, the input does not drive the output and the output remains constant.
- Engaged in a positive direction – In this mode, the input is increasing (has a positive slope) and the output is equal to the input minus half the deadband width.
- Engaged in a negative direction – In this mode, the input is decreasing (has a negative slope) and the output is equal to the input plus half the deadband width.

For illustrations and examples please refer to the Simulink Help menu for this block.

Example 4.7

We will create a model with a **Backlash** block with deadband width of unity and initial output zero whose input will be a square waveform with amplitude 1 and frequency $0.25\ \mathrm{Hz}$.

The model is shown in Figure 4.14, and the input and output are shown in Figure 4.15.

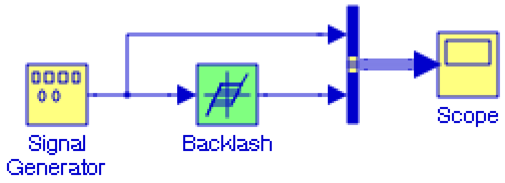


Figure 4.14. Model for Example 4.7

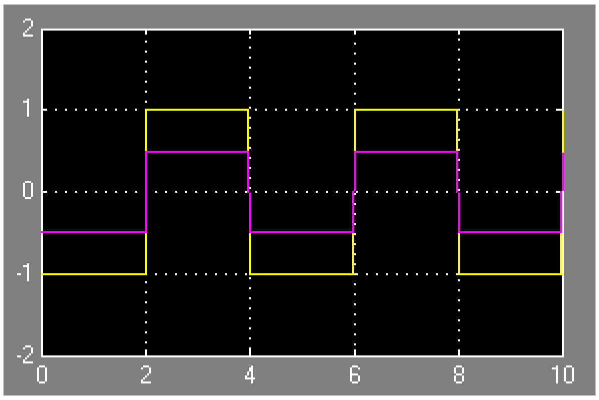
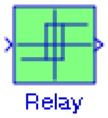


Figure 4.15. Input and output for the model in Figure 4.14

In the **Function Block Parameters** dialog box for the **Signal Generator** block we have specified a square waveform with amplitude 1 and frequency at 0.25 Hz. In the **Function Block Parameters** dialog box for the **Backlash** block we have specified the deadband width at 1 and initial output at 0. In Figure 4.15, we observe that the deadband extends from –0.5 to +0.5 .

4.8 The Relay Block



The **Relay** block output can switch between two specified values. When the relay is on, it remains on until the input drops below the value of the Switch off point parameter. When the relay is off, it remains off until the input exceeds the value of the Switch on point parameter. The block accepts one input and generates one output. The Switch on point value must be greater than or equal to the Switch off point. Specifying a Switch on point value greater than the Switch off point value models hysteresis, whereas specifying equal values models a switch with a threshold at that value.

Example 4.8

In the **Function Block Parameters** dialog box for the **Relay** block in Figure 4.16 we have entered:

a. Switch on point: 10

b. Switch off point: 0

c. Output when on: 1

d. Output when off: 0

We will choose appropriate values for blocks a and b so that the Relay block output will be on.

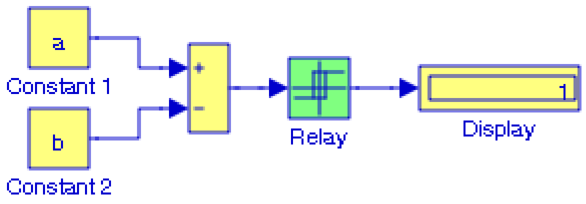


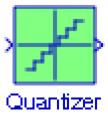
Figure 4.16. Model for Example 4.8

Two appropriate values would be a = 11 and b = 1 . Thus at the MATLAB command prompt we have entered:

```
a=11; b=1;
```

The Simulink **Thermal Model of a House** demo includes a **Relay** block inside the Thermostat Subsystem block. It can be accessed by typing sldemo_househeat at the MATLAB command prompt.

4.9 The Quantizer Block



The **Quantizer** block passes its input signal through a stair–step function so that many neighboring points on the input axis are mapped to one point on the output axis. The effect is to quantize a smooth signal into a stair–step output. The output is computed using the round–to–nearest method, which produces an output that is symmetric about zero. That is,

$$y = q \times \text{round}(u/q) \tag{4.3}$$

where y is the output, u is the input, and q is the quantization interval.

Example 4.9

We will create a model with a **Quantizer** block with Quantization Interval 0.25. The input will be a sine waveform with amplitude 1 and frequency $0.25\ \text{Hz}$.

The model is shown in Figure 4.17 and the input and output waveforms are shown in Figure 4.18.

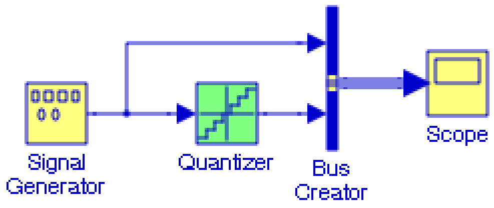


Figure 4.17. Model for Example 4.9

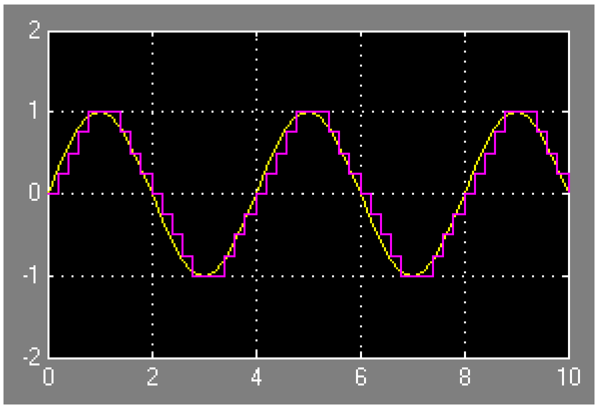
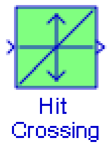


Figure 4.18. Input and output waveforms for the model in Figure 4.17

4.10 The Hit Crossing Block



The **Hit Crossing** block detects when the input reaches the Hit crossing offset parameter value in the direction specified by the Hit crossing direction (rising, falling, or either) parameter. To see where the crossing occurs, we click the Show output port check box. If the Show output port check box is not selected, the block ensures that the simulation finds the crossing point but does not generate an output.

Example 4.10

We will create a model with the **Hit Crossing** block where the Hit crossing offset is set at -1. The input is a sine waveform with amplitude 1 and frequency $0.25\ \mathrm{Hz}$.

The model is shown in Figure 4.19, and the input and output waveform in Figure 4.20. The **Data Type Conversion** block converts the output of the **Hit Crossing** block which is Boolean, i.e., logical 0 or logical 1, to double so that both inputs to the **Bus Creator** block are of the same type.

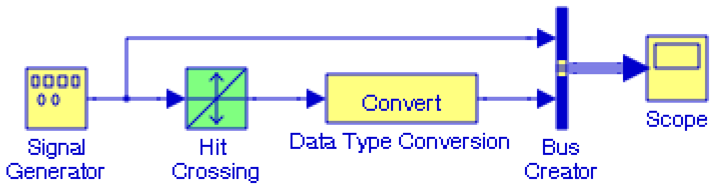


Figure 4.19. Model for Example 4.10

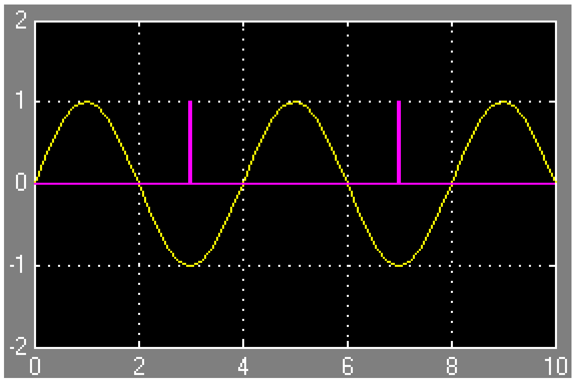
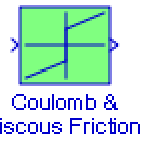


Figure 4.20. Input and output waveforms for the model in Figure 4.19

As stated in the Simulink Help menu, the use of the **Hit Crossing** block is illustrated in the hardstop and clutch demos. In the hardstop demo, the **Hit Crossing** block is in the Friction Model subsystem. In the clutch demo, the **Hit Crossing** block is in the Lockup Detection subsystem. These demos can be accessed by typing sldemo_hardstop and sldemo_clutch at the MATLAB command prompt respectively.

4.11 The Coulomb and Viscous Friction Block



The **Coulomb and Viscous Friction** block models Coulomb (static) and Viscous (dynamic) friction. The block produces an offset at zero and a linear gain elsewhere. The offset corresponds to the Coulombic friction; the gain corresponds to the viscous friction.

As we know from physics, friction is a force that resists the relative motion or tendency to such motion of two bodies in contact. Friction is undesirable in some parts of rotating machinery such as bearings and cylinders, but very beneficial in the automotive industry such as the design of brakes and tires. Theoretically, there should be no friction in a motor with zero velocity, but in reality, a small amount of "static" (no velocity) friction known as Coulomb friction, is always present even in roller or ball type anti–friction bearings. Viscous friction, on the other hand, is friction force caused by the viscosity of lubricants.

The Coulomb friction function, the Viscous friction function, and the combined Coulomb plus Viscous friction functions are illustrated in Figure 4.21.

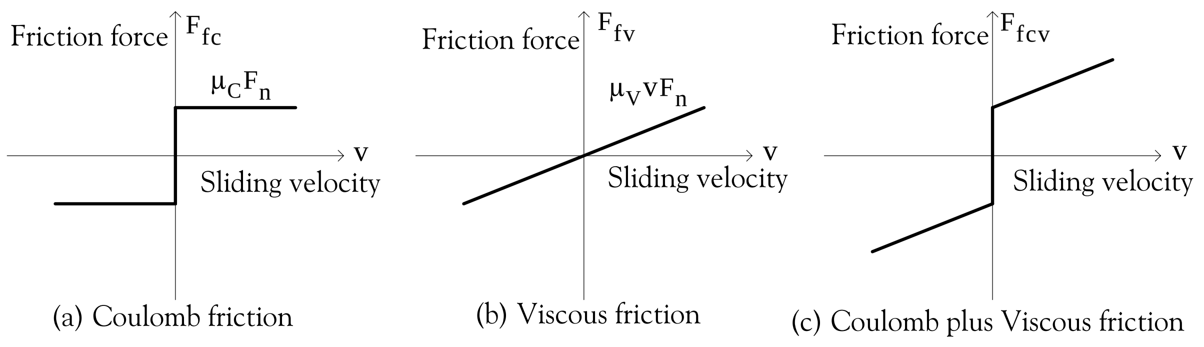


Figure 4.21. Coulomb friction and Viscous friction functions

The Coulomb friction function is defined as

$$F_{fc} = \pm\mu_C F_n \tag{4.4}$$

where μ_C is the Coulomb friction coefficient.

The Viscous friction function is defined as

$$F_{fv} = \mu_v v F_n \tag{4.5}$$

and the Coulomb plus Viscous friction is defined as

$$F_{fc+fv} = \mu_v v F_n \pm \mu_C F_n \tag{4.6}$$

Coulomb friction force can be represented by at least four different continuous functions. Each of these functions involves one constant that controls the level of accuracy of that function's representation of the friction force. Simulink uses the default values [1 3 2 0] for the offset (Coulomb friction value). For the signal gain (coefficient of viscous friction) at nonzero input points the default is 1.

Example 4.11

We will create a model with the **Coulomb and Viscous Friction** block where in the Function Block Parameters for this block the offset are the default values, the gain is 2, and the input is the Step function where the Step time is specified as 1.

The model is shown in Figure 4.22 and the input and output waveforms are shown in Figure 4.23.

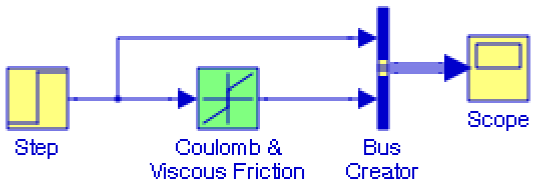


Figure 4.22. Model for Example 4.11

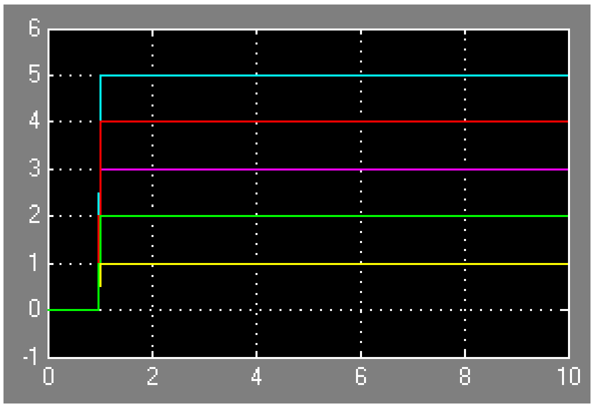
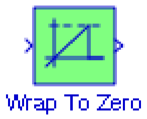


Figure 4.23. Input and output waveforms for the model in Figure 4.22

4.12 The Wrap to Zero Block



The **Wrap To Zero** block sets the output to zero if the input is above the value set by the Threshold parameter, and outputs the input if the input is less than or equal to the Threshold.

Example 4.12

We will create a model with a **Wrap to Zero** block where the Threshold in the **Function Block Parameters** is specified as 75. We will choose an appropriate value for the input to this block so that the output will display the input value. The model is shown in Figure 4.24. Any input value equal of less than 75 will cause the **Wrap to Zero** block to display the input value.

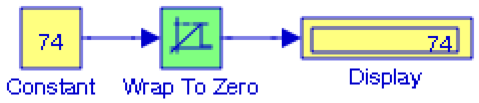


Figure 4.24. Model for Example 4.12

4.13 Summary

- The **Saturation** block sets upper and lower bounds on a signal. When the input signal is within the range specified by the Lower limit and Upper limit parameters, the input signal passes through unchanged. When the input signal is outside these bounds, the signal is clipped to the upper or lower bound. When the Lower limit and Upper limit parameters are set to the same value, the block outputs that value.
- The **Saturation Dynamic** block bounds the range of the input signal to upper and lower saturation values. The input signal outside of these limits saturates to one of the bounds where the input below the lower limit is set to the lower limit, the input above the upper limit is set to the upper limit. The input for the upper limit is the up port, and the input for the lower limit is the lo port.
- The **Dead Zone** block generates zero output within a specified region, called its dead zone. The lower and upper limits of the dead zone are specified as the Start of dead zone and End of dead zone parameters. The block output depends on the input and dead zone.
- The **Dead Zone Dynamic** block dynamically bounds the range of the input signal, providing a region of zero output. The bounds change according to the upper and lower limit input signals.
- The **Rate Limiter** block limits the first derivative of the signal passing through it. We can specify rising and falling slew rates.
- The **Rate Limiter Dynamic** block limits the rising and falling rates of the signal. The external signal up sets the upper limit on the rising rate of the signal. The external signal lo sets the lower limit on the falling rate of the signal.
- The **Backlash** block implements a system in which a change in input causes an equal change in output. However, when the input changes direction, an initial change in input has no effect on the output. The amount of side–to–side play in the system is referred to as the deadband. The deadband is centered about the output.
- The **Relay** block allows its output to switch between two specified values. When the relay is on, it remains on until the input drops below the value of the Switch off point parameter. When the relay is off, it remains off until the input exceeds the value of the Switch on point parameter. The block accepts one input and generates one output. The Switch on point value must be greater than or equal to the Switch off point. Specifying a Switch on point value greater than the Switch off point value models hysteresis, whereas specifying equal values models a switch with a threshold at that value.
- The **Quantizer** block passes its input signal through a stair–step function so that many neighboring points on the input axis are mapped to one point on the output axis. The effect is to quantize a smooth signal into a stair–step output. The output is computed using the round–to–nearest method, which produces an output that is symmetric about zero.

- The **Hit Crossing** block detects when the input reaches the Hit crossing offset parameter value in the direction specified by the Hit crossing direction (rising, falling, or either) parameter. To see where the crossing occurs, we click on the Show output port check box. If the Show output port check box is not selected, the block ensures that the simulation finds the crossing point but does not generate output.
- The **Coulomb and Viscous Friction** block models Coulomb (static) and viscous (dynamic) friction. The block models a discontinuity at zero and a linear gain otherwise. The offset corresponds to the Coulombic friction; the gain corresponds to the viscous friction.
- The **Wrap To Zero** block sets the output to zero if the input is above the value set by the Threshold parameter, and outputs the input if the input is less than or equal to the Threshold.

4.14 Exercises

1. Create a model with a **Backlash** block whose input is the Step block and the Function Block Parameters for both blocks are the default values.

2. Create a model with the **Coulomb and Viscous Friction** block where in the Function Block Parameters for this block the offset are the default values, the gain is 0.5, and the input is the Ramp function with unity slope.

3. Using the **Dead Zone** block, create a model that will display the following input (yellow) and output (magenta) waveforms.

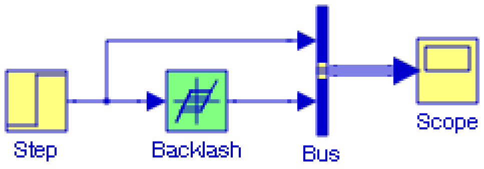
4. Using the **Hit Crossing** block, create a model with the Hit crossing offset set at 1 and the input is a square waveform with amplitude 1 and frequency $0.25\ \mathrm{Hz}$.

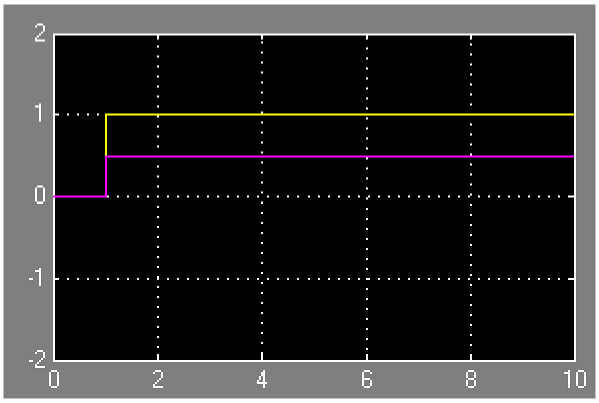
5. Create a model with a **Quantizer** block with Quantization Interval 0.2. The input is a straight line passing through the origin with slope 0.25.

6. Create a model with a **Relay** block and choose appropriate values so that the relay will be in the off condition.

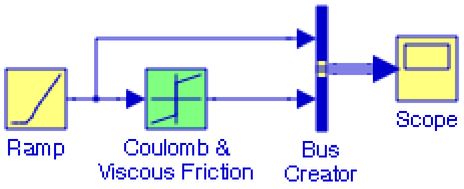
4.15 Solutions to End–of–Chapter Exercises

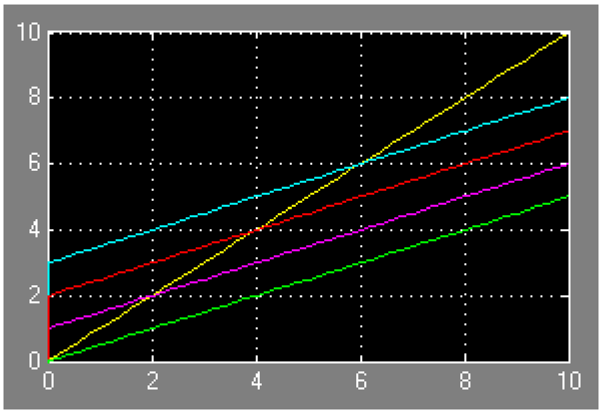
1.





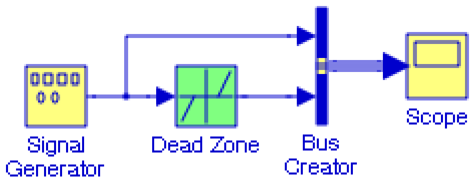
2.

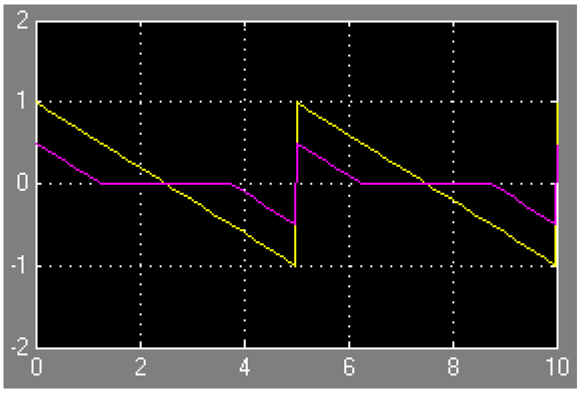




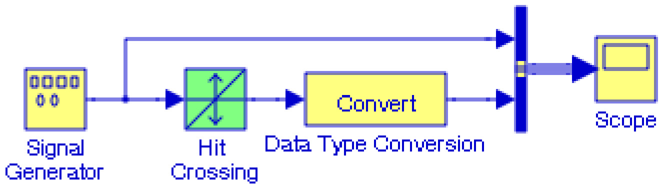
3.

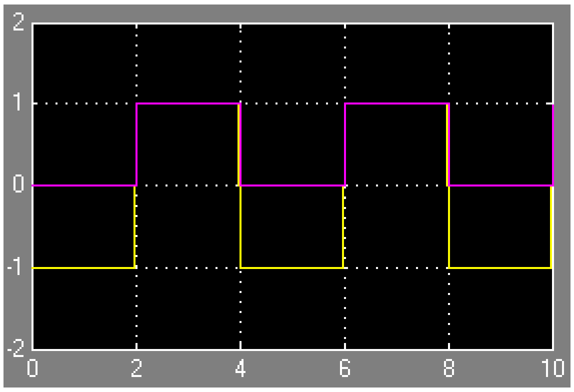
The model is shown below where the waveform for the **Signal Generator** block is chosen as Saw Tooth, unity amplitude, and 0.2 Hz frequency. The **Dead Zone** block parameters are set for lower limit of -0.5 and upper limit $+0.5$





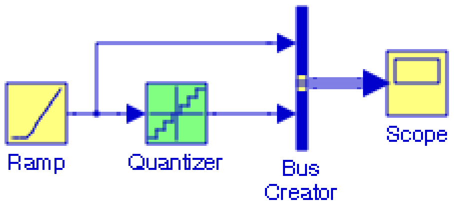
4.

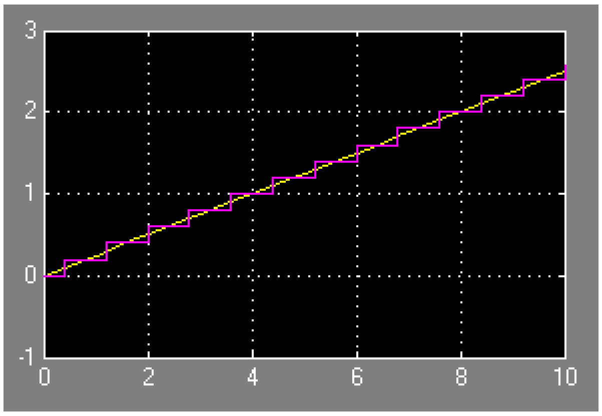




The output of the **Hit Crossing** block is shown as a pulse with 50% duty cycle. Since the input signal reaches the offset value and remains at this value, the block outputs 1 from the hit time till the time when the input signal leaves the offset value.

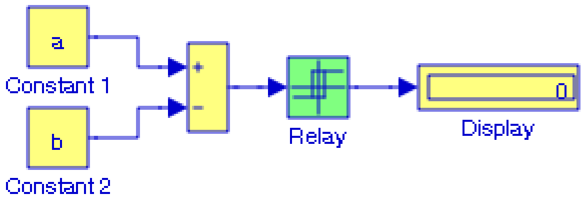
5.





The **Ramp** block slope is set at 0.25. The **Quantizer** block is set for Quantization Interval 0.2.

6.



The Function Block Parameters for the Relay block in the above model are specified as:

a. Switch on point: 4

b. Switch off point: 0

c. Output when on: 1

d. Output when off: 0

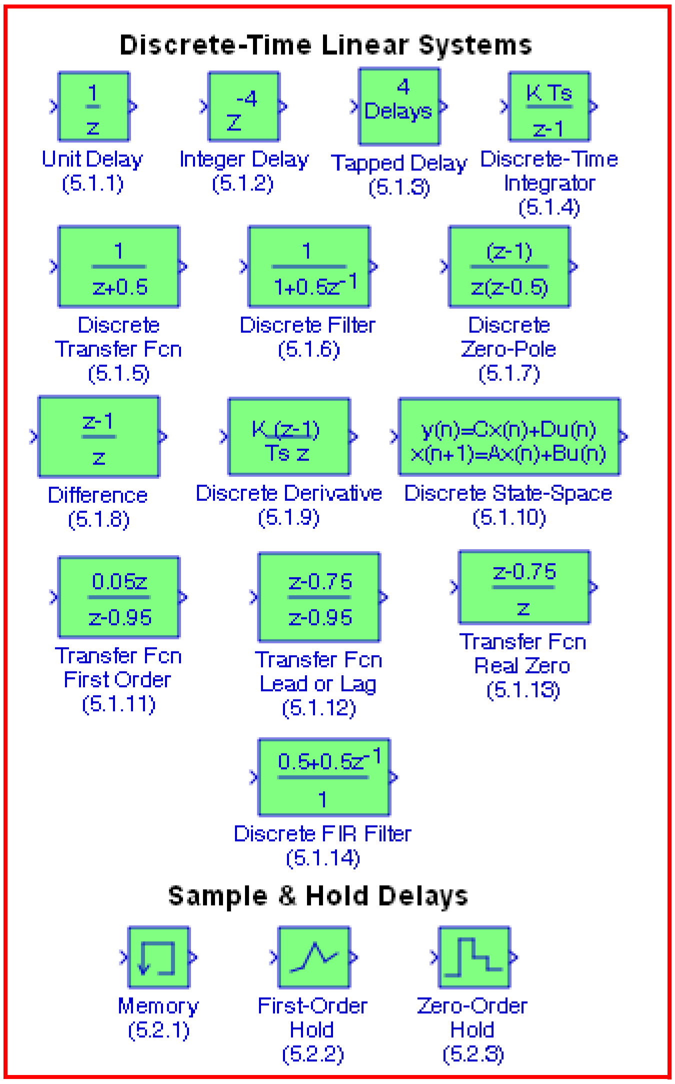
Two appropriate values would be `a = 5` and `b = 4`. Thus, at the MATLAB command prompt we enter:

```
a=5; b=4;
```

Chapter 5

The Discrete Blocks Library

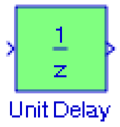
This chapter is an introduction to the **Discrete Blocks** library. This is the fourth library in the Simulink group of libraries and contains the **Discrete–Time Linear Systems Sub–Library**, and the **Sample & Hold Delays Sub–Library** blocks shown below. Their functions are illustrated with examples.


Discrete-Time Linear Systems
1/z
Unit Delay (5.1.1)
-4 z
Integer Delay (5.1.2)
4 Delays
Tapped Delay (5.1.3)
K Ts / z-1
Discrete-Time Integrator (5.1.4)
1 / z+0.5
Discrete Transfer Fcn (5.1.5)
1 / 1+0.5z-1
Discrete Filter (5.1.6)
(z-1) / z(z-0.5)
Discrete Zero-Pole (5.1.7)
z-1 / z
Difference (5.1.8)
K (z-1) / Ts z
Discrete Derivative (5.1.9)
y(n)=Cx(n)+Du(n) x(n+1)=Ax(n)+Bu(n)
Discrete State-Space (5.1.10)
0.05z / z-0.95
Transfer Fcn First Order (5.1.11)
z-0.75 / z-0.95
Transfer Fcn Lead or Lag (5.1.12)
z-0.75 / z
Transfer Fcn Real Zero (5.1.13)
0.5+0.5z-1 / 1
Discrete FIR Filter (5.1.14)
Sample & Hold Delays
Memory (5.2.1)
First-Order Hold (5.2.2)
Zero-Order Hold (5.2.3)

5.1 The Discrete–Time Linear Systems Sub–Library

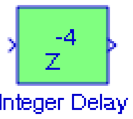
The **Discrete–Time Linear Systems Sub–Library** contains the blocks described in Subsections 5.1.1 through 5.1.14 below.

5.1.1 The Unit Delay Block



The **Unit Delay** block is described in Chapter 2, Section 2.15, Chapter 2, Page 2–27.

5.1.2 The Integer Delay Block



The **Integer Delay** block delays its input by N sample periods. Both the input and the output can be scalar or vector.

Example 5.1

We will create a model using an **Integer Delay** block with five delays $(N = 5)$ where the input will be a discrete sine wave with amplitude 1, frequency $1\ Hz$, and sample time $0.1\ s$.

The model is shown in Figure 5.1 and the input and output waveforms are shown in Figure 5.2.

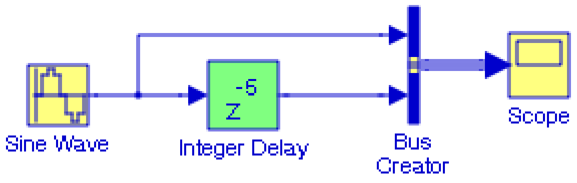


Figure 5.1. Model for Example 5.1

For the **Sine Wave** block, in the **Block Parameters** dialog box we specified:

Sine type: Time based

Sample time: 0.1

For the **Integer Delay** block, in the **Block Parameters** dialog box we specified:

Initial condition: 0.0

Number of delays: 5

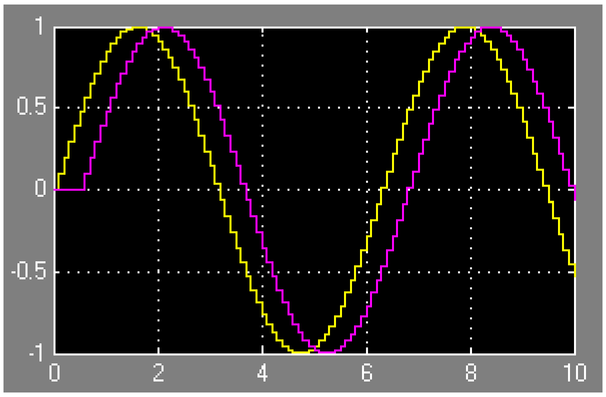


Figure 5.2. Input and output waveforms for the model in Figure 5.1

5.1.3 The Tapped Delay Block

The **Tapped Delay** block delays its input by the specified number of sample periods, and outputs all the delayed versions. Each delay is equivalent to the z^{-1} discrete−time operator, which is represented by the **Unit Delay** block.

Example 5.2

We will create a model using a **Tapped Delay** block with five delays $(N = 5)$ where the input is a a discrete sine wave with amplitude 1, frequency $0.5\ Hz$, and sample time $0.25\ s$.

The model is shown in Figure 5.3 and the input and output waveforms are shown in Figure 5.4. We observe that unlike the **Integer Delay** block in Subsection 5.1.2, the **Tapped Delay** block outputs all the delayed versions.

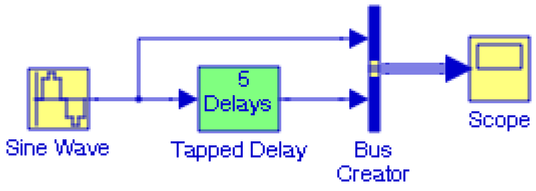


Figure 5.3. Model for Example 5.2

For the **Sine Wave** block, in the **Block Parameters** dialog box we specified Sine type: Time based, Frequency: 0.5, Sample time: 0.25. For the **Tapped Delay** block, in the Block Parameters dialog box we specified Initial condition: 0.0, Number of delays: 5

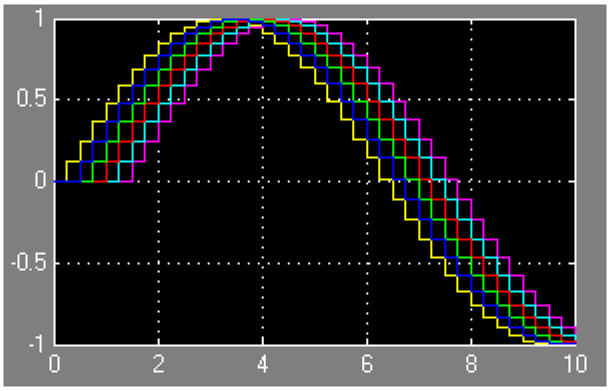
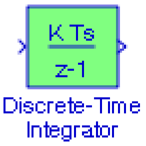


Figure 5.4. Input and output waveforms for the model in Figure 5.3

5.1.4 The Discrete–Time Integrator Block



The **Discrete–Time Integrator** block is described in Section 2.16, Chapter 2, Page 2–29.

5.1.5 The Discrete Transfer Fcn Block

The **Discrete Transfer Fcn** block implements the $\mathcal{Z}$–transform transfer function described by the following equation:

$$G(z) = \frac{N(z)}{D(z)} = \frac{a_0 z^n + a_1 z^{n-1} + \ldots + a_m z^{n-m}}{b_0 z^n + b_1 z^{n-1} + \ldots + b_m z^{n-m}} \tag{5.1}$$

The order of the denominator must be greater than or equal to the order of the numerator.

Example 5.3

It is known that the discrete transfer function of a system is

$$G(z) = \frac{0.951z}{z^2 + 0.618z + 1}$$

We will create a model to display the input and output waveforms when the input is the discrete sine wave with amplitude 1, frequency 1 r/s, and sample time 0.1 s.

The model is shown in Figure 5.5 and the input and output waveforms are shown in Figure 5.6 where in the **Function Block** Parameters for the **Discrete Transfer Fcn** block we have entered:

Numerator coefficient: [0.951 0]

Denominator coefficient: [1 0.618 1]

Sample time: 0.1

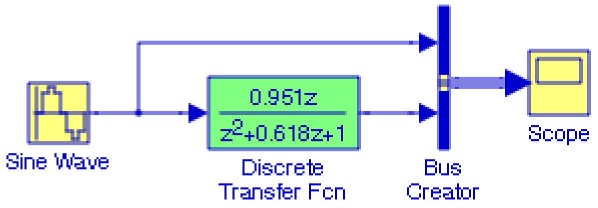


Figure 5.5. Model for Example 5.3

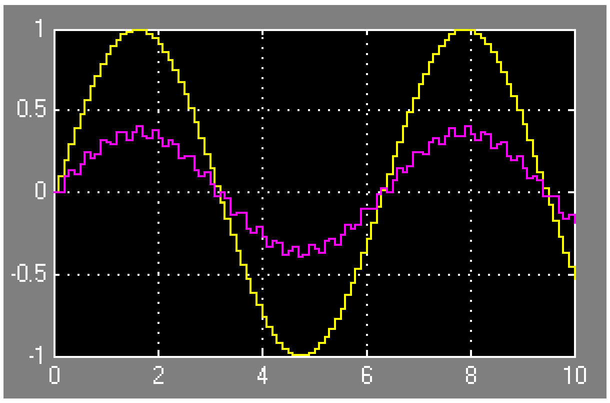
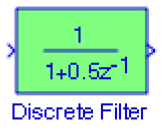


Figure 5.6. Input and Output waveforms for the model in Figure 5.5

5.1.6 The Discrete Filter Block



The **Discrete Filter** block implements Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) filters. We must specify the filter as a ratio of polynomials in z^{-1}. We can specify that the block will have a single output or multiple outputs where the outputs correspond to a set of filters that have the same denominator polynomial but different numerator polynomials.

Digital filters are classified in terms of the duration of the impulse response, and in forms of realization.

1. Impulse Response Duration

a. An *Infinite Impulse Response* (IIR) digital filter has infinite number of samples in its impulse response $h[n]$

b. A *Finite Impulse Response* (FIR) digital filter has a finite number of samples in its impulse response $h[n]$

2. Realization

a. In a *Recursive Realization* digital filter the output is dependent on the input and the *previous* values of the output. In a recursive digital filter, both the coefficients a_i and b_i are present.

b. In a *Non–Recursive Realization* digital filter the output depends on present and past values of the input only. In a non–recursive digital filter, only the coefficients a_i are present, that is, $b_i = 0$.

For block diagrams of third–order (3–delay element) recursive and non–recursive realizations please refer to Figure 2.30, Chapter 2, Page 2–25. Generally, IIR filters are implemented by recursive realization, whereas FIR filters are implemented by non–recursive realization.

Example 5.4

The step response indicates how a system will respond when the input is the unit step function. For this example, it is known that the transfer function of a system is

$$G(s) = \frac{5(s+3)}{s^2 + 3s + 15}$$

We will use the bilinear transformation to convert the transfer function to the $\mathcal{Z}$–transform equivalent and create a model showing the waveforms of both the step response in the s–domain and in the z–domain. The bilinear transformation is

$$G(z) = G(s)\big|_{s = 2 \times Fs \times (z-1)/(z+1)}$$

and the MATLAB function for this conversion is **[numd,dend]=bilinear(num,den,fs)** where **num** and **den** are row vectors containing numerator and denominator transfer function coefficients in descending powers of s, **fs** is the sample frequency in Hz, and **numd** and **dend** are the z–transform coefficients for the discrete transfer function. Thus, for this example at the MATLAB command prompt we type the following:

```
num=[1 3]; den=[1 3 15]; fs=0.25; [numd,dend] = bilinear(num,den,fs)
```

and MATLAB displays

```
numd =
    0.2090    0.3582    0.1493

dend =
    1.0000    1.7612    0.8209
```

Therefore,

$$G(z) = \frac{0.2090 + 0.3582z^{-1} + 0.1493z^{-2}}{1 + 1.7612z^{-1} + 0.8209z^{-2}}$$

and with this information we create the model shown in Figure 5.7.

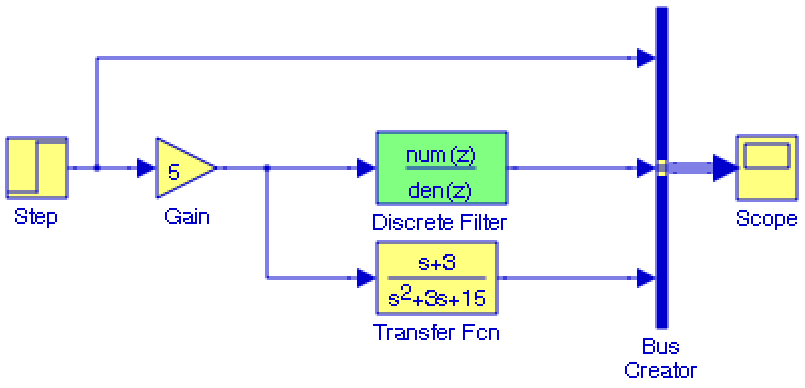


Figure 5.7. Model for Example 5.4

The output waveforms for the continuous and discrete transfer functions are shown in Figure 5.8.

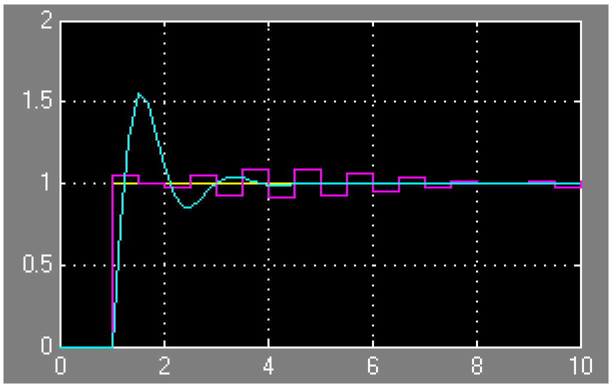
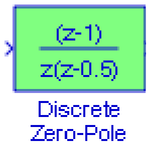


Figure 5.8. Waveforms for the model in Figure 5.7

5.1.7 The Discrete Zero–Pole Block



The **Discrete Zero–Pole** block implements a discrete system with the specified zeros, poles, and gain in terms of the delay operator $\mathcal{Z}$. A transfer function can be expressed in factored or zero–pole–gain form, which, for a single–input, single–output system in MATLAB, is

$$H(z) = K\frac{N(z)}{D(z)} = K\frac{(z-z_1)(z-z_2)\ldots(z-z_n)}{(z-p_1)(z-p_2)\ldots(z-p_n)} \tag{5.2}$$

where z_i represents the zeros, p_i the poles, and K is the gain. The number of poles must be greater than or equal to the number of zeros. If the poles and zeros are complex, they must be complex conjugate pairs.

Example 5.5

It is known that the discrete transfer function of a system is

$$H(z) = \frac{(z-0.5)}{(z-0.25)(z-0.75)}$$

We will create a model to display the input and output waveforms when the input is the discrete sine wave with amplitude 1, frequency 1 r/s, and sample time 0.1 s. The model is shown in Figure 5.9 and the input and output waveforms are shown in Figure 5.10 where in the **Function Block Parameters** dialog box for the **Discrete Pole–Zero** block we have entered:

Zeros: $[0.5]$

Poles: $[0.25 \ \ 0.75]$

Sample time: 0.1

We also specified sample time 0.1 for the discrete sine wave block.

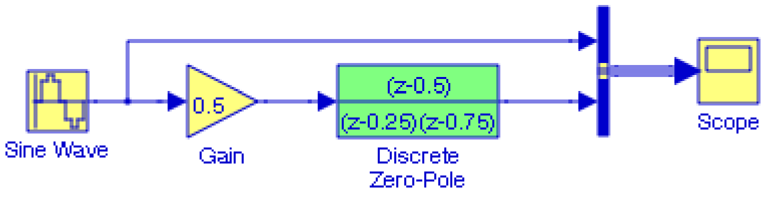


Figure 5.9. Model for Example 5.5

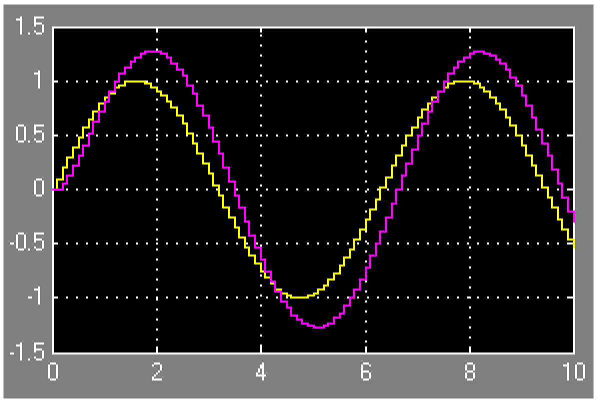
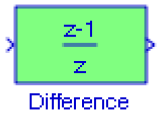


Figure 5.10. Input and output waveforms for the model in Figure 5.9

5.1.8 The Difference Block



The **Difference** block outputs the current input value minus the previous input value.

Example 5.6

Using the **Difference** block, we will create a model that will output the current input value minus the previous input value.

The model is shown in Figure 5.11 and the input and output waveforms in Figure 5.12. The **Display** blocks show the input and output values at the end of the simulation time, for this example, at the end of 10 s .

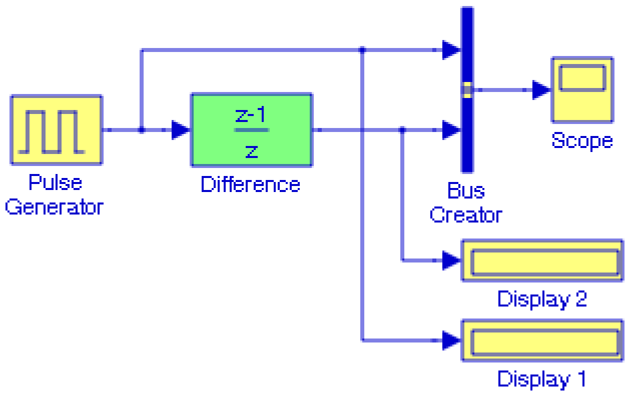


Figure 5.11. Model for Example 5.6

For this example, the amplitude for the **Pulse Generator** block is specified as 1, the period as 4, and the pulse width as 50%. The initial condition for the previous input in the **Difference** block was set to 0.

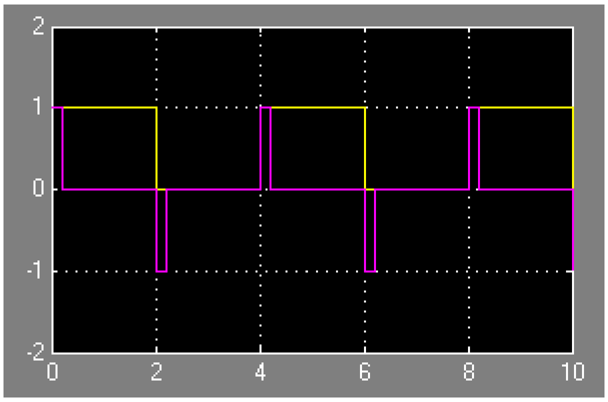


Figure 5.12. Input and output waveforms for the model in Figure 5.11

5.1.9 The Discrete Derivative Block

K (z-1)
Ts z
Discrete Derivative

The **Discrete Derivative** block computes a discrete time derivative by subtracting the input value at the previous time step from the current value, and dividing by the sample time. We observe that this block is the same as the **Difference** block except that the numerator in this case is multiplied by the Gain K, and it is divided by the sample time Ts.

Example 5.7

We will create a model using the **Discrete Derivative** block with gain $K = 1$ whose input is a Sine Wave in the Discrete mode with amplitude 1 and frequency 1 Hz.

The model is shown in Figure 5.13 and the input and output waveforms in Figure 5.14. The **Discrete Sine Wave** is obtained from the **Continuous Sine Wave** block where in the **Block Parameters** dialog box for this block the Sample time is specified as 1.

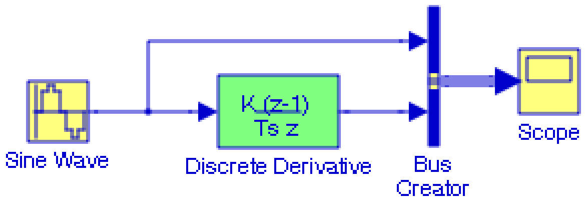


Figure 5.13. Model for Example 5.7

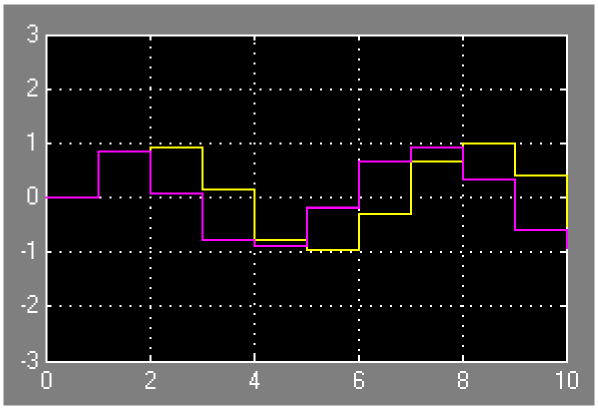
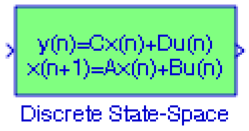


Figure 5.14. Input and output waveforms for the model in Figure 5.13

5.1.10 The Discrete State–Space Block



The **Discrete State–Space** block implements the system described by the equations

$$\begin{aligned} x[n+1] &= Ax[n]+Bu[n] \\ y[n] &= Cx[n]+Du[n] \end{aligned} \tag{5.3}$$

where n represents the current sample, $n+1$ represents the next sample, u is the input, x is the state, and y is the output. Matrix A must be an $n \times n$ square matrix where n represents the number of the states, matrix B must have dimension $n \times m$ where m represents the number of inputs, matrix C must have dimension $r \times n$ where r represents the number of outputs, and matrix D must have dimension $r \times m$.

Example 5.8

In Example 1.1, Chapter 1, Page 1–6, we derived the continuous–time state–space equations

$$\dot{x} = Ax + bu \tag{5.4}$$

or

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -4 & -4 \\ 3/4 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 4 \\ 0 \end{bmatrix} u_0(t) \tag{5.5}$$

and

$$y = Cx + du \tag{5.6}$$

or

$$y = [0 \quad 1] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + [0]u \tag{5.7}$$

Using the MATLAB **c2d** function we will convert (5.5) and (5.7) to their equivalent discrete−time state space equations shown in relation (5.3), with a sampling period of 0.1. Then, using the **Discrete State−Space** block, we will create a model to display the output waveform and the value of the output at the end of the simulation time.

To convert the given matrices to their discrete−time state−space, we use the MATLAB statement

```
[Ad,Bd]=c2d(A,B,Ts)
```

where `Ad` and `Bd` are the discrete−time state−space matrices which are equivalent to the continuous−time state−space matrices `A` and `B`, and `Ts` is the sampling period specified as *0.1 s*. Thus, for this example, we use the MATLAB script

```
Ac=[−4  −4;  3/4  0]; Bc=[4  0]'; Ts=0.1; [Ad,Bd]=c2d(Ac,Bc,Ts)
```

and MATLAB displays

```
Ad =
    0.6588   -0.3280
    0.0615    0.9868
Bd =
    0.3280
    0.0132
```

Thus, the relation

$$x[n+1] = Ax[n] + Bu[n]$$

becomes

$$\begin{bmatrix} x_1[n+1] \\ x_2[n+1] \end{bmatrix} = \begin{bmatrix} 0.6588 & -0.3280 \\ 0.0615 & 0.9868 \end{bmatrix} \begin{bmatrix} x_1[n] \\ x_2[n] \end{bmatrix} + \begin{bmatrix} 0.3280 \\ 0.0132 \end{bmatrix} u[n] \tag{5.8}$$

The discrete−time state−space equation for the output is

$$y[n] = Cx[n] + Du[n]$$

or

$$y[n] = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} x_1[n] \\ x_2[n] \end{bmatrix} + Du[n] \tag{5.9}$$

The model is shown in Figure 5.15 where we have included the continuous state–space block for comparison. We can make the **simout To Workspace** block active by assigning a name to it.

In the **Function Block Parameters** dialog box for the continuous–time state–space we have entered the values shown in (5.5), and in the **Function Block Parameters** dialog box for the discrete–time state–space we have entered the values shown in (5.8) and (5.9) with $D = 0$ and $\text{Sample time} = 0.1$.

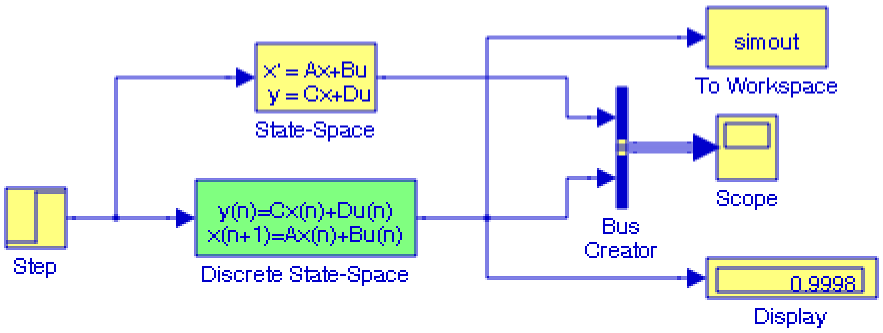


Figure 5.15. Model for Example 5.8

Figure 5.16 shows the output waveforms for both the continuous state–space block and the discrete state–space block.

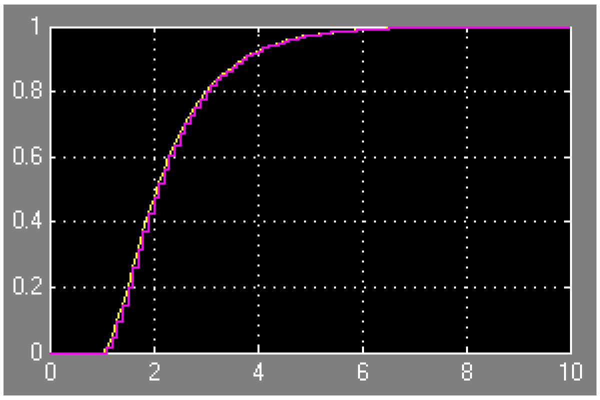


Figure 5.16. Waveforms for the model in Figure 5.15

5.1.11 The Transfer Fcn First Order Block

0.05z
z-0.95
Transfer Fcn
First Order

The **Transfer Fcn First Order** block implements a discrete−time first order transfer function of the input. The transfer function has a unity DC gain.

Example 5.9

It is known that the discrete transfer function of a first order system is

$$G(z) = \frac{0.3z}{z-0.7}$$

We will create a model to display the input and output waveforms when the input is the discrete sine wave with amplitude 1, frequency 1 r/s, and sample time 0.1 s.

The model is shown in Figure 5.17 and the input and output waveforms are shown in Figure 5.18. The sample rate for the discrete **Sine Wave** block is specified as 0.1 s.

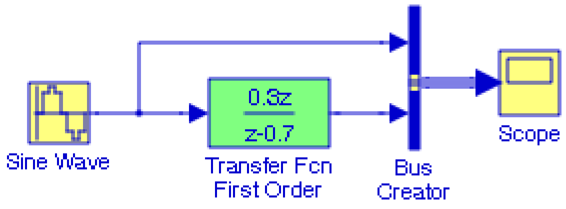


Figure 5.17. Model for Example 5.9

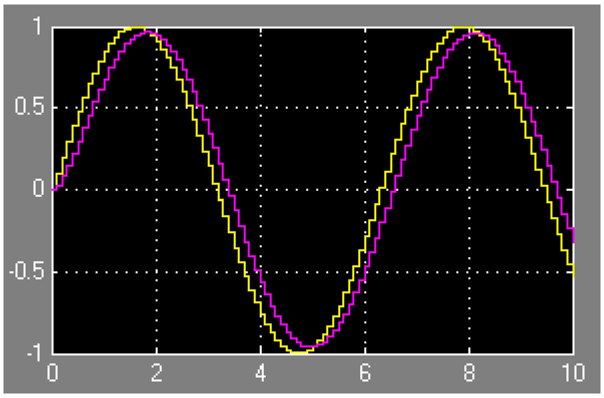
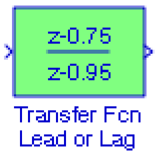


Figure 5.18. Input and output waveforms for the model in Figure 5.17

5.1.12 The Transfer Fcn Lead or Lag Block



The **Transfer Fcn Lead or Lag** block implements a discrete–time lead or lag compensator of the input. The instantaneous gain of the compensator is one, and the DC gain is equal to $(1-z)/(1-p)$, where z is the zero and p is the pole of the compensator. The block implements a lead compensator when $0<z<p<1$, and implements a lag compensator when $0<p<z<1$.

Lead and lag compensators are used quite extensively in control systems. A lead compensator can increase the stability or speed of response of a system; a lag compensator can reduce (but not eliminate) the steady state error. Depending on the effect desired, one or more lead and lag compensators may be used in various combinations. Lead, lag, and lead/lag compensators are usually designed for a system in transfer function form.

In general, the transfer function of a **lead compensator** is defined as

$$G(s)_{lead} = \frac{s+a}{s+b} \tag{5.10}$$

where $b>a$, both a and b are real, and the lead compensator has a positive phase angle.

The transfer function of a **lag compensator** is defined as

$$G(s)_{lag} = \frac{a(s+b)}{b(s+a)} \tag{5.11}$$

where $b>a$. We observe that in (5.11) the zero is at $s=-b$ and the pole is at $s=-a$. Both a and b are real, and the lag compensator has a negative phase angle. The ratio a/b is the gain factor.

The transfer function of a **lead–lag compensator** is defined as

$$G(s)_{lead-lag} = \frac{(s+a_1)(s+b_2)}{(s+b_1)(s+a_2)} \tag{5.12}$$

Example 5.10

An R–C network implementation of a lead compensator is shown in Figure 5.19 where $C = 1\ F$, $R_1 = R_2 = 1\ \Omega$, and $v_C(0) = 0$.

a. We will derive its transfer function

b. Using the bilinear transformation we will convert the continuous–time transfer function to its equivalent discrete–time transfer function. We will use the sample rate of 0.25 s.

c. We will create a model that includes the Transfer Fcn Lead of Lag block.

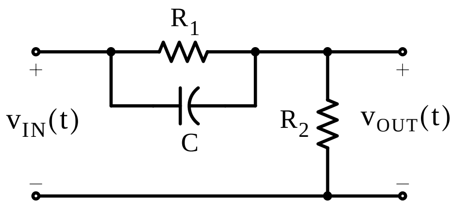


Figure 5.19. R–C lead compensator for Example 5.10

a. The s–domain equivalent circuit is shown in Figure 5.20.

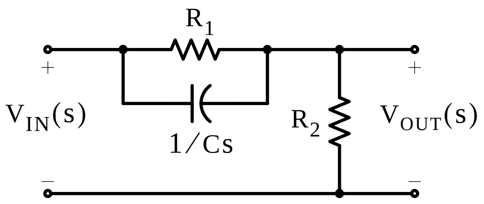


Figure 5.20. The s–domain equivalent circuit of Figure 5.19

By KCL,

$$\frac{V_{OUT}(s) - V_{IN}(s)}{R_1} + \frac{V_{OUT}(s) - V_{IN}(s)}{1/Cs} + \frac{V_{OUT}(s)}{R_2} = 0$$

$$\frac{V_{OUT}(s)}{R_1} + \frac{V_{OUT}(s)}{R_2} + CsV_{OUT}(s) = \frac{V_{IN}(s)}{R_1} + CsV_{IN}(s)$$

$$\left(\frac{1}{R_1} + \frac{1}{R_2} + Cs\right)V_{OUT}(s) = \left(\frac{1}{R_1} + Cs\right)V_{IN}(s)$$

Thus,

$$G(s) = \frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{1/R_1 + Cs}{1/R_1 + 1/R_2 + Cs} \qquad (5.13)$$

and by substitution of the given values,

$$G(s) = \frac{s+1}{s+2} \qquad (5.14)$$

a. Using MATLAB's bilinear transformation function, we obtain

```
num=[1  1]; den=[1  2]; fs=0.25; [numd,dend] = bilinear(num,den,fs)
numd  =
    0.6000    0.2000
dend =
    1.0000    0.6000
```

Therefore, the discrete transfer function is

$$G(z) = \frac{0.6 + 0.2z^{-1}}{1 + 0.6z^{-1}}$$

or

$$G(z) = \frac{z + 1/3}{z + 0.6}$$

c. The model is shown in Figure 5.21. The input and output waveforms are shown in Figure 5.22.

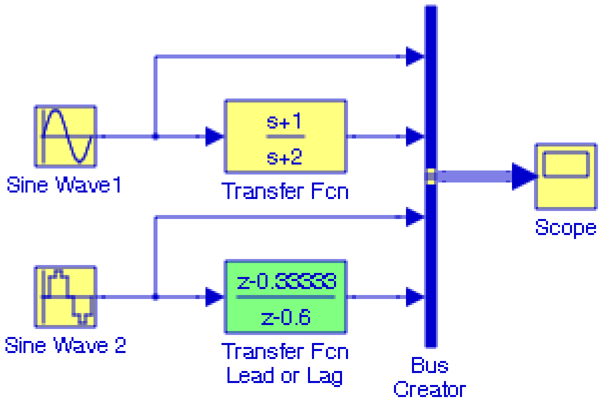


Figure 5.21. Model for Example 5.10

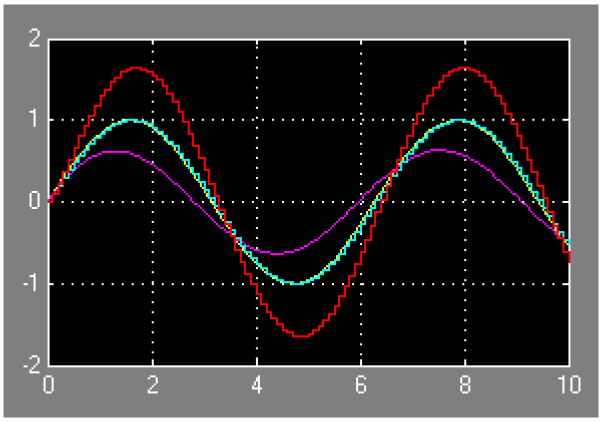


Figure 5.22. Input and output waveforms for the model in Figure 5.21

5.1.13 The Transfer Fcn Real Zero Block

z-0.75
z
Transfer Fcn
Real Zero

The **Transfer Fcn Real Zero** block implements a discrete–time transfer function that has a real zero and no pole.

Example 5.11

We will create a model with a **Transfer Fcn Real Zero** block that has a real zero with value 0.5.

The model is shown in Figure 5.23 and the input and output waveforms are shown in Figure 5.24.

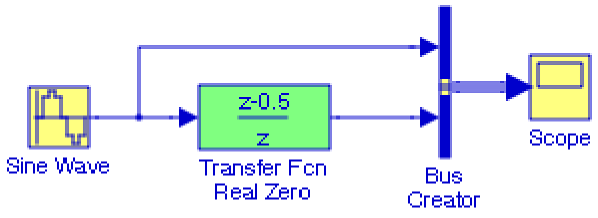


Figure 5.23. Model for Example 5.11

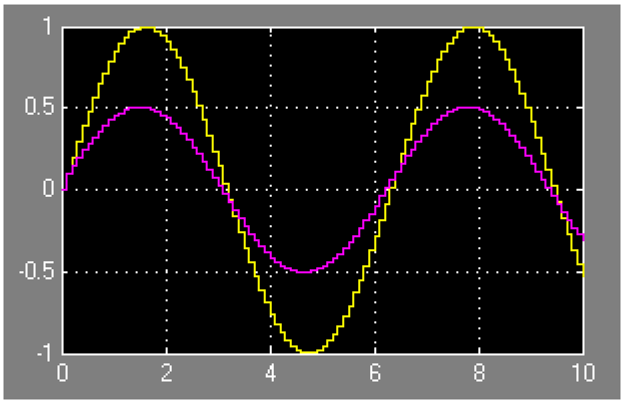


Figure 5.24. Input and output waveforms for the model in Figure 5.23

5.1.14 The Discrete FIR Filter Block

The **Discrete FIR Filter** block is essentially a moving average[*] filter.

Let us consider the sequence of values $x_1, x_2, \ldots, x_n$, and let k be a non-zero positive number, i.e., $k > 0$. Then the $k-\text{th}$ moving average of the n sequence is defined as follows:

$$\begin{aligned} y_1 &= \frac{1}{k}(x_1 + x_2 + \ldots + x_k) \\ y_2 &= \frac{1}{k}(x_2 + x_3 + \ldots + x_{k+1}) \\ y_3 &= \frac{1}{k}(x_3 + x_4 + \ldots + x_{k+2}) \\ &\ldots \\ y_{n-k+1} &= \frac{1}{k}(x_{n-k+1} + x_4 + \ldots + x_{k+2}) \end{aligned} \tag{5.15}$$

That is, the number of moving average sequence is equal to $n-k+1$ values. Thus, with $k = 4$ of a ten-value ($n = 10$) sequence, the moving average sequence has $n-k+1 = 10-4+1 = 7$ values.

Example 5.12

The price of a particular security (stock) over a 10−day trading period is as follows:

$$77 \quad 80 \quad 82 \quad 85 \quad 90 \quad 84 \quad 81 \quad 82 \quad 86 \quad 79$$

where the last value is the most recent. We will create a model of moving averages with $k = 5$ over this 10−day trading period. For this example, the moving average sequence has $n-k+1 = 10-5+1 = 6$ values.

The model is shown in Figure 5.25, and the settings for the **Function Block Parameters** dialog box for the **Discrete FIR Filter 1** block is shown in Figure 5.26. The settings for the remaining **Discrete FIR Filter** blocks are shown in the model.

* *The earlier versions of Simulink included the Weighted Moving Average block. An introduction to moving averages provided in Appendix D of this text. The latest version of Simulink has replaced the Weighted Moving Average block with the Discrete FIR filter block and an example is presented in this section.*

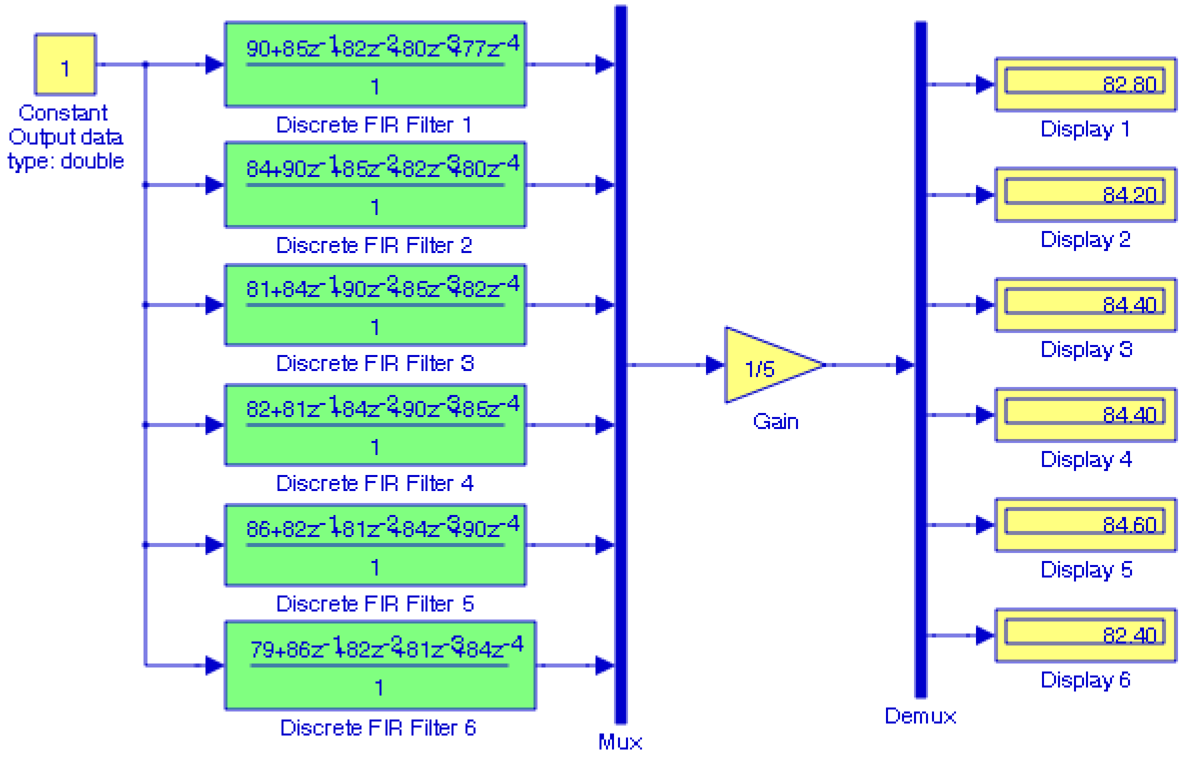
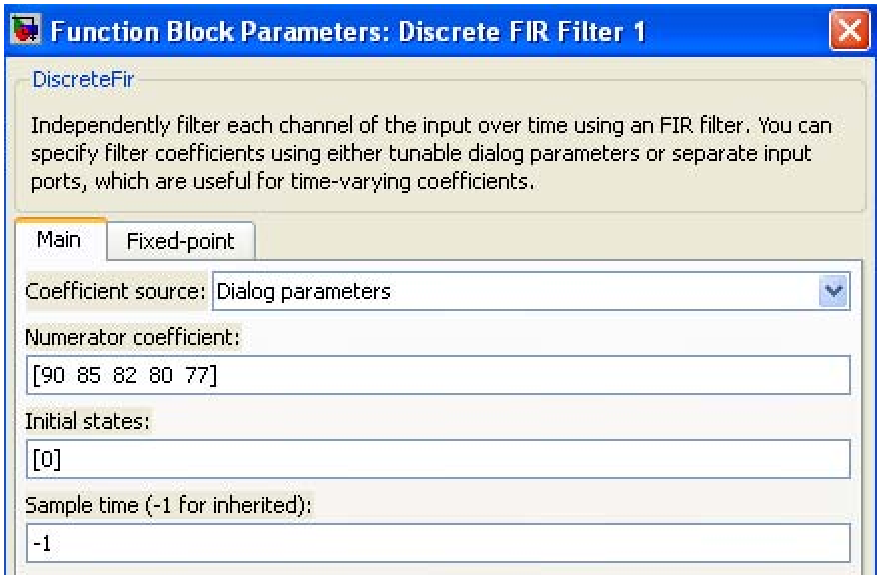


Figure 5.25. Model for Example 5.12



Independently filter each channel of the input over time using an FIR filter. You can specify filter coefficients using either tunable dialog parameters or separate input ports, which are useful for time-varying coefficients.

Coefficient source: Dialog parameters

Numerator coefficient:

[90 85 82 80 77]

Initial states:

[0]

Sample time (-1 for inherited):

-1

Figure 5.26. The Function Block Parameters dialog box settings for the Discrete FIR Filter 1 block

The plots in Figure 5.27 show how the moving average smooths out the 10-day data series, and this makes it easier to spot future trends in financial markets.

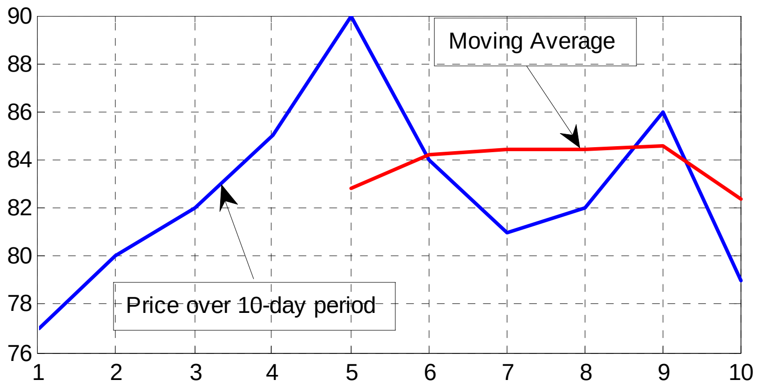
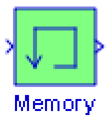


Figure 5.27. Plot with stock prices over 10-day period and moving average for Example 5.12

5.2 The Sample & Hold Delays Sub–Library

The **Sample & Hold Delays Sub–Library** contains the blocks described in Subsections 5.2.1 through 5.2.3 below.

5.2.1 The Memory Block



The **Memory** block outputs its input from the previous time step, applying a one integration step sample–and–hold to its input signal.

Example 5.13

We will create a model using a **Memory** block whose output is subtracted from its input where the input is a **Pulse Generator** block with amplitude 1, period 5 s, pulse width 50%, and Phase delay 1 sec. For the **Memory** block, the Initial condition is specified as 0 and the Inherit sample time is checked.

The model is shown in Figure 5.28 and the input and output waveforms are shown in Figure 5.29.

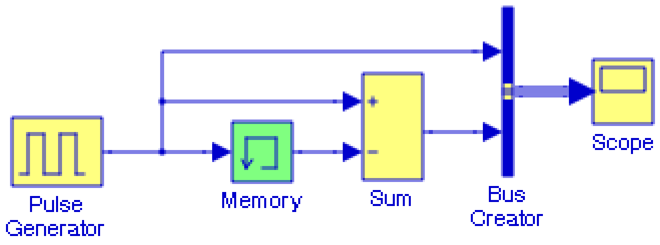


Figure 5.28. Model for Example 5.13

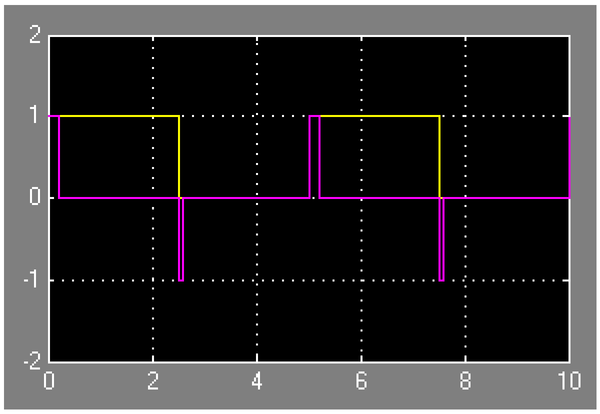


Figure 5.29. Input and output waveforms for the model in Figure 5.28

5.2.2 The First–Order Hold Block

The **First–Order Hold** block implements a first–order sample–and–hold that operates at the specified sampling interval. In some signal processing applications it is necessary to retain (hold) the value that a signal has at a specified instant of time. A circuit used to perform this function is referred to as **sample–and–hold circuit**. For example, a sample–and–hold circuit can be used to provide a steady voltage into a device that cannot process a continuously varying signal. An analog–to–digital converter is such a device.

Example 5.14

We will create a model using a **First–Order Hold** block with sample time $0.5\ s$ where the input is a sine wave with amplitude 1, and frequency $1\ Hz$.

The model is shown in Figure 5.30 and the input and output waveforms are shown in Figure 5.31.

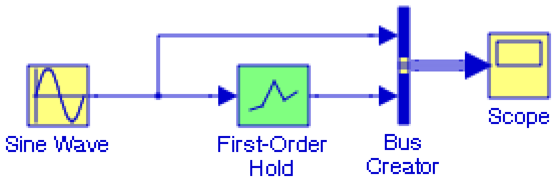


Figure 5.30. Model for Example 5.14

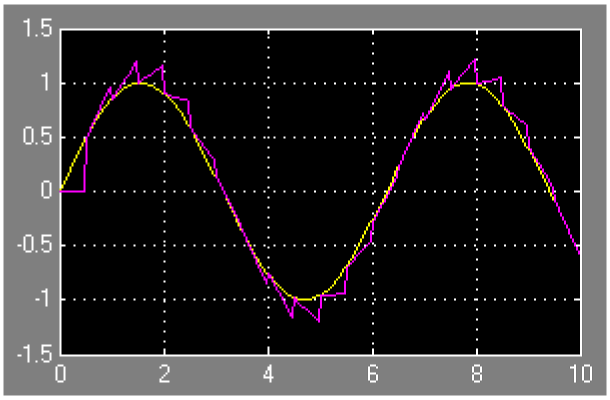


Figure 5.31. Input and output waveforms for the model in Figure 5.30

5.2.3 The Zero–Order Hold Block

The **Zero–Order Hold** block samples and holds its input for the specified sample period. The block accepts one input and generates one output, both of which can be scalar or vector. If the input is a vector, all elements of the vector are held for the same sample period. If the model contains multirate transitions, we must add Zero–Order Hold blocks between the fast–to–slow transitions. The sample rate of the Zero–Order Hold must be set to that of the slower block. For slow–to–fast transitions, we use the **Unit Delay** block which is described in Section 2.15, Chapter 2, Page 2–27.

For multirate transitions it is preferable to use the **Rate Transition** block since it is easier to use and offers a wider range of options. The **Rate Transition** block and multirate transitions are described in Subsection 12.1.8, Chapter 12, Page 12–8.

Example 5.15

We will create a model using a **Zero–Order Hold** block with sample time 1 and input a random waveform with amplitude 1 and frequency $1\ \mathrm{Hz}$.

The model is shown in Figure 5.32 and the input and output waveforms are shown in Figure 5.33.

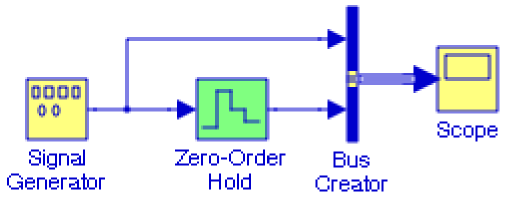


Figure 5.32. Model for Example 5.15

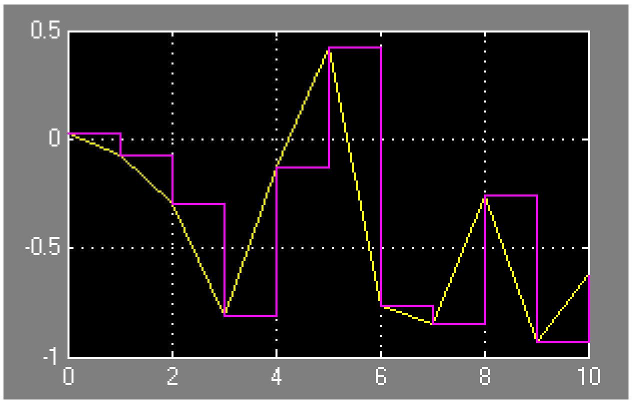


Figure 5.33. Input and output waveforms for the model in Figure 5.32

5.3 Summary

- The **Unit Delay** block delays its input by the specified sample period. That is, the output equals the input delayed by one sample. This block is equivalent to the z^{-1} discrete–time operator. This block allows for discretization of one or more signals in time, or for resampling the signal at a different rate. If our model contains multirate transitions, then we must add **Unit Delay** blocks between the slow–to–fast transitions. The sample rate of the **Unit Delay** block must be set to that of the slower block.
- The **Integer Delay** block delays its input by N sample periods. This block accepts one input and generates one output, both of which can be scalar or vector.
- The **Tapped Delay** block delays its input by the specified number of sample periods, and outputs all the delayed versions. Each delay is equivalent to the z^{-1} discrete–time operator, which is represented by the Unit Delay block.
- The **Discrete–Time Integrator block** performs discrete–time integration or accumulation of a signal. This block appears also in the **Discrete Library** Browser. We use this block in discrete–time systems instead of the Continuous Integrator block in continuous–time systems. The block can integrate or accumulate using the Forward Euler, Backward Euler, and Trapezoidal methods.
- The **Discrete Transfer Fcn** block implements the z–transform transfer function described by the following equation:

$$G(z) = \frac{N(z)}{D(z)} = \frac{a_0 z^n + a_1 z^{n-1} + \ldots + a_m z^{n-m}}{b_0 z^n + b_1 z^{n-1} + \ldots + b_m z^{n-m}}$$

  The order of the denominator must be greater than or equal to the order of the numerator.
- The **Discrete Filter** block implements Infinite Impulse Response (IIR) and Finite Impulse Response (FIR) filters. We must specify the filter as a ratio of polynomials in z^{-1}. We can specify that the block have a single output or multiple outputs where the outputs correspond to a set of filters that have the same denominator polynomial but different numerator polynomials.
- The **Discrete Zero–Pole** block implements a discrete system with the specified zeros, poles, and gain in terms of the delay operator $\mathcal{Z}$. A transfer function can be expressed in factored or zero–pole–gain form, which, for a single–input, single–output system in MATLAB, is

$$G(z) = K\frac{N(z)}{D(z)} = K\frac{(z-z_1)(z-z_2)\ldots(z-z_n)}{(z-p_1)(z-p_2)\ldots(z-p_n)}$$

  where z_i represents the zeros, p_i the poles, and K the gain. The number of poles must be greater than or equal to the number of zeros.

- The **Difference** block outputs the current input value minus the previous input value.
- The **Discrete Derivative** block computes a discrete time derivative by subtracting the input value at the previous time step from the current value, and dividing by the sample time. This block is the same as the Difference block except that the numerator is multiplied by the Gain K and it is divided by the sample time Ts.
- The **Discrete State–Space** block implements the system described by the equations

$$\begin{aligned} x[n+1] &= Ax[n]+Bu[n] \\ y[n] &= Cx[n]+Du[n] \end{aligned}$$

  where n represents the current sample, $n+1$ represents the next sample, u is the input, x is the state, and y is the output. Matrix A must be an $n \times n$ square matrix where n represents the number of the states, matrix B must have dimension $n \times m$ where m represents the number of inputs, matrix C must have dimension $r \times n$ where r represents the number of outputs, and matrix D must have dimension $r \times m$.
- The **Transfer Fcn First Order** block implements a discrete–time first order transfer function of the input. The transfer function has a unity DC gain.
- The **Transfer Fcn Lead or Lag** block implements a discrete–time lead or lag compensator of the input. The instantaneous gain of the compensator is one, and the DC gain is equal to $(1-z)/(1-p)$, where z is the zero and p is the pole of the compensator. The block implements a lead compensator when $0<z<p<1$, and implements a lag compensator when $0<p<z<1$.
- The **Transfer Fcn Real Zero** block implements a discrete–time transfer function that has a real zero and no pole.
- The **Discrete FIR Filter** block is essentially a moving average filter. An introduction to moving averages is presented in Appendix D.
- The **Memory** block outputs its input from the previous time step, applying a one integration step sample–and–hold to its input signal.
- The **First–Order Hold** block implements a first–order sample–and–hold that operates at the specified sampling interval. In some signal processing applications it is necessary to retain (hold) the value that a signal has at a specified instant of time.
- The **Zero–Order Hold** block samples and holds its input for the specified sample period. The block accepts one input and generates one output, both of which can be scalar or vector. If the input is a vector, all elements of the vector are held for the same sample period.

5.4 Exercises

1. It is known that the transfer function of a system is

$$G(s) = \frac{0.5279}{s^2 + 1.0275s + 0.5279}$$

Use the bilinear transformation to convert this transfer function to the $\mathcal{Z}$–transform equivalent, and create a model showing the waveforms of both the step response in the s–domain and in the z–domain.

2. It is known that the discrete transfer function of a system is

$$G(z) = \frac{0.8394z^2 - 1.5511z + 0.8394}{z^2 - 1.5511z + 0.6791}$$

Create a model to display the input and output waveforms when the input is the unit step function and the sample time is specified as $0.1\ s$.

3. It is known that the discrete transfer function of a system is

$$G(z) = \frac{0.2(z^2 - 1.1z + 0.3)}{z^3 - 2.4z^2 + 1.91z - 0.504}$$

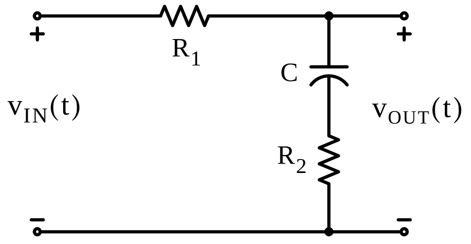
Create a model to display the input and output waveforms when the input is the discrete sine function and the sample time is specified as $0.1\ s$.

4. An *R*–C network implementation of a lag compensator is shown below where $C = 1\ F$, $R_1 = R_2 = 1\ \Omega$, and $v_C(0) = 0$.

a. Derive its transfer function

b. Use the bilinear transformation, convert the continuous–time transfer function to its equivalent discrete–time transfer function. Use the sample rate of $0.25\ s$.

c. Create a model that includes the Transfer Fcn Lead or Lag block to implement the discrete–time transfer function.



5. The price of a particular security (stock) over a 10–day period is as follows:

12 18 16 15 17 18 20 18 19 14

where the last value is the most recent. Create a model with **Discrete FIR Filter** blocks for the moving average sequence $n-k+1$ with $k = 4$.

6. The price of a particular security (stock) over a 5–day period is as follows:

39 38 40 41 42

where the last value is the most recent.

a. Create a model with a **Discrete FIR Filter** block for the moving average sequence $n-k+1$ with $k = 4$.

b. Repeat (a) for a weighted moving average. Refer to Appendix D for the description of the weighted moving average.

5.5 Solutions to End–of–Chapter Exercises

1.

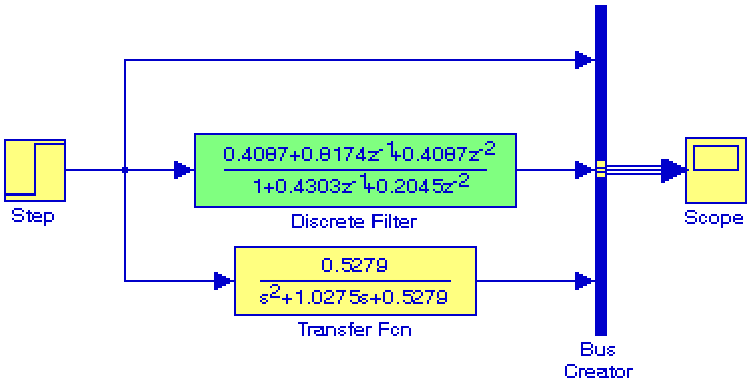
Using the bilinear transformation we enter the following in MATLAB's Command window:

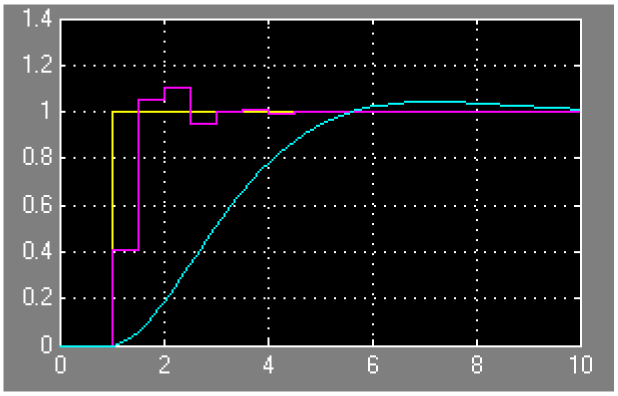
```
num=[0.5279]; den=[1 1.0275  0.5279]; fs=0.25; [numd,dend] = bilinear(num,den,fs)
```

MATLAB outputs the following *z*–domain coefficients:

```
numd =
    0.4087    0.8174    0.4087
dend =
    1.0000    0.4303    0.2045
```

The model and the waveforms are shown below.





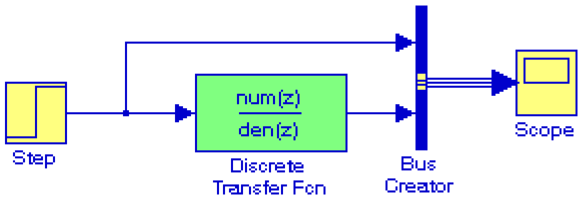
2.

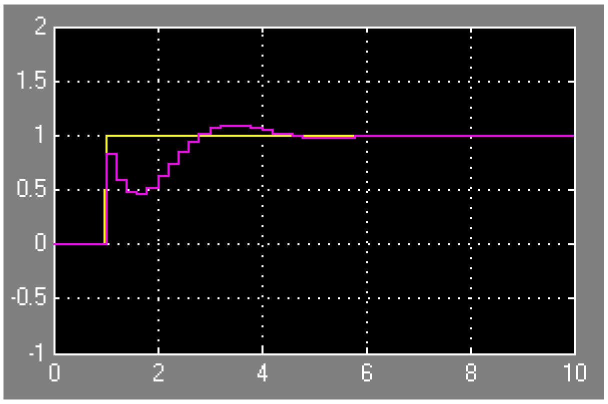
The model and the input and output waveforms are shown below where in the Function Block Parameters for the Discrete Transfer Fcn block we have entered:

Numerator coefficient: [0.8394 -1.5511 0.8394]

Denominator coefficient: [1 -1.5511 0.6791]

Sample time: 0.1





3.

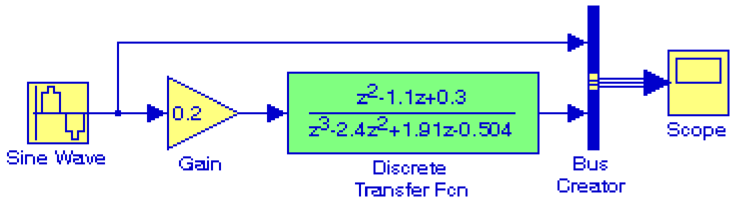
The model and the input and output waveforms are shown below where in the Function Block Parameters for the Discrete Transfer Fcn block we have entered:

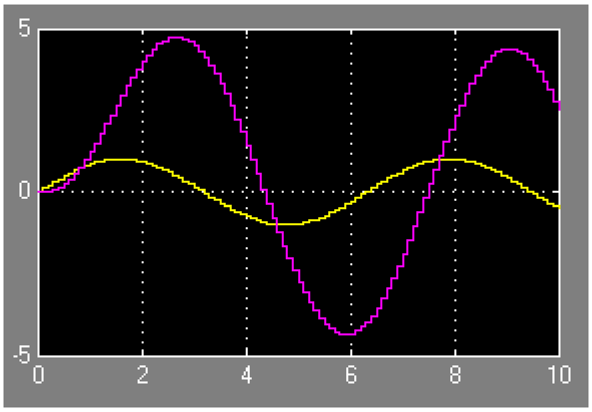
Numerator coefficient: [1 –1.1 0.3]

Denominator coefficient: [1 -2.4 1.91 -0.504]

Sample time: 0.1

We also specify sample time 0.1 for the discrete sine wave block.

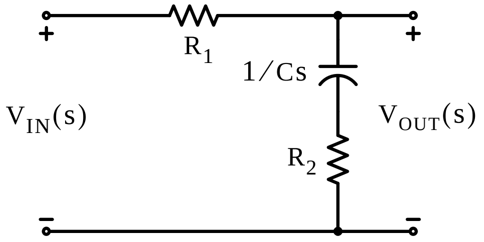




4.

a.

The s–domain equivalent circuit is shown below.



Application of the voltage division expression yields,

$$V_{OUT}(s) = \frac{1/Cs + R_2}{R_1 + 1/Cs + R_2} \cdot V_{IN}(s)$$

$$G(s) = \frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{1/Cs + R_2}{R_1 + 1/Cs + R_2} = \frac{R_2Cs + 1}{(R_1 + R_2)Cs + 1}$$

and by substitution of the given values,

$$G(s) = \frac{s+1}{2s+1} = \frac{0.5(s+1)}{(s+0.5)} \tag{5.16}$$

b.

Using MATLAB's bilinear transformation function, we obtain

```
num=[1  1]; den=[1  0.5]; fs=0.25; [numd,dend] = bilinear(num,den,fs)
```

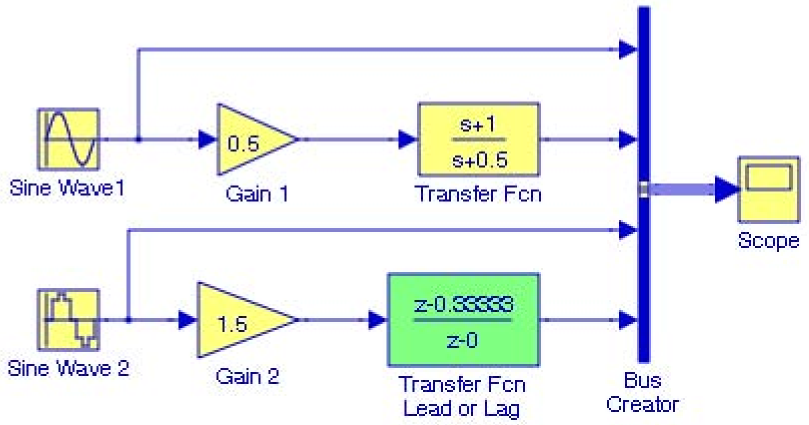
```
numd =
    1.500    0.500
dend =
    1    0
```

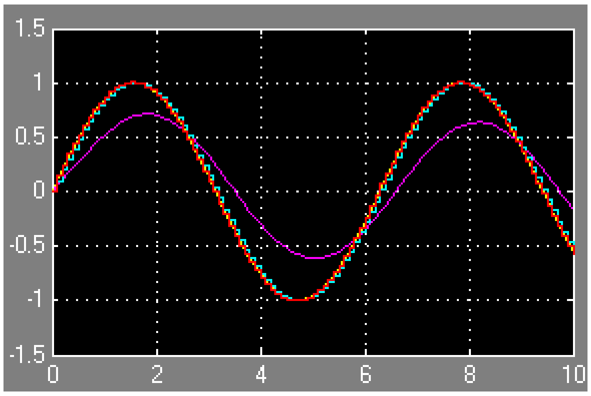
Therefore, the discrete transfer function is

$$G(z) = \frac{1.5z + 0.5}{z + 0} = \frac{1.5(z + 1/3)}{z + 0}$$

c.

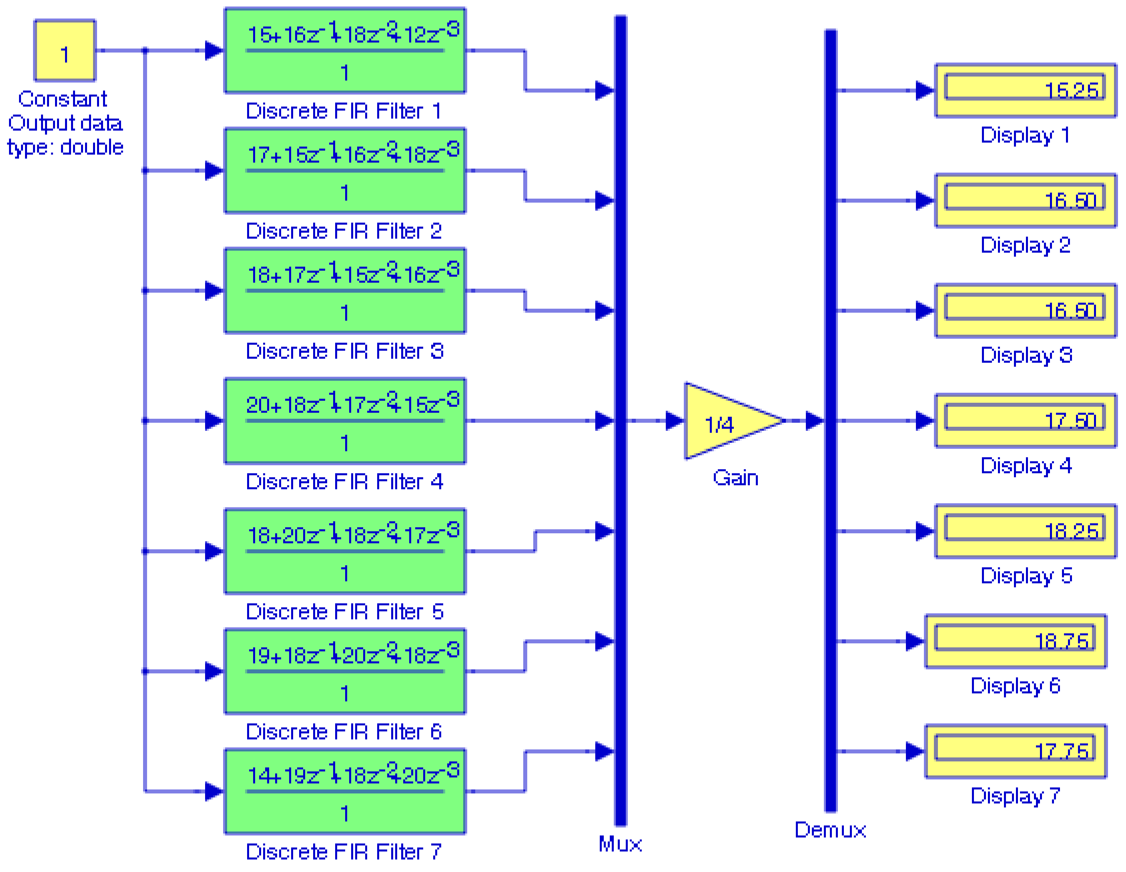
The model and the input and output waveforms are shown below. The sample rate for the discrete **Sine Wave** block is specified as $0.1\ s$.



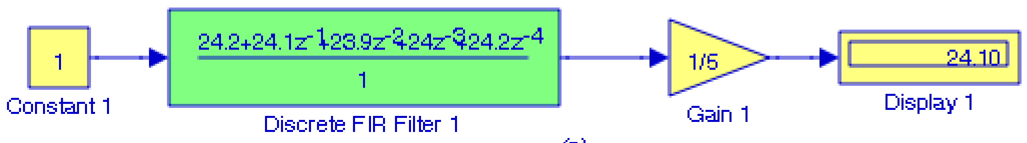


5.

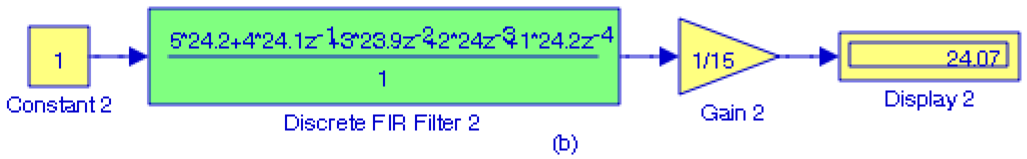
For this model the moving average sequence has $n - k + 1 = 10 - 4 + 1 = 7$ values and the model is shown below.



6.


1
Constant 1
24.2+24.1z-1+23.9z-2+24z-3+24.2z-4
1
Discrete FIR Filter 1
1/5
Gain 1
24.10
Display 1

(a)

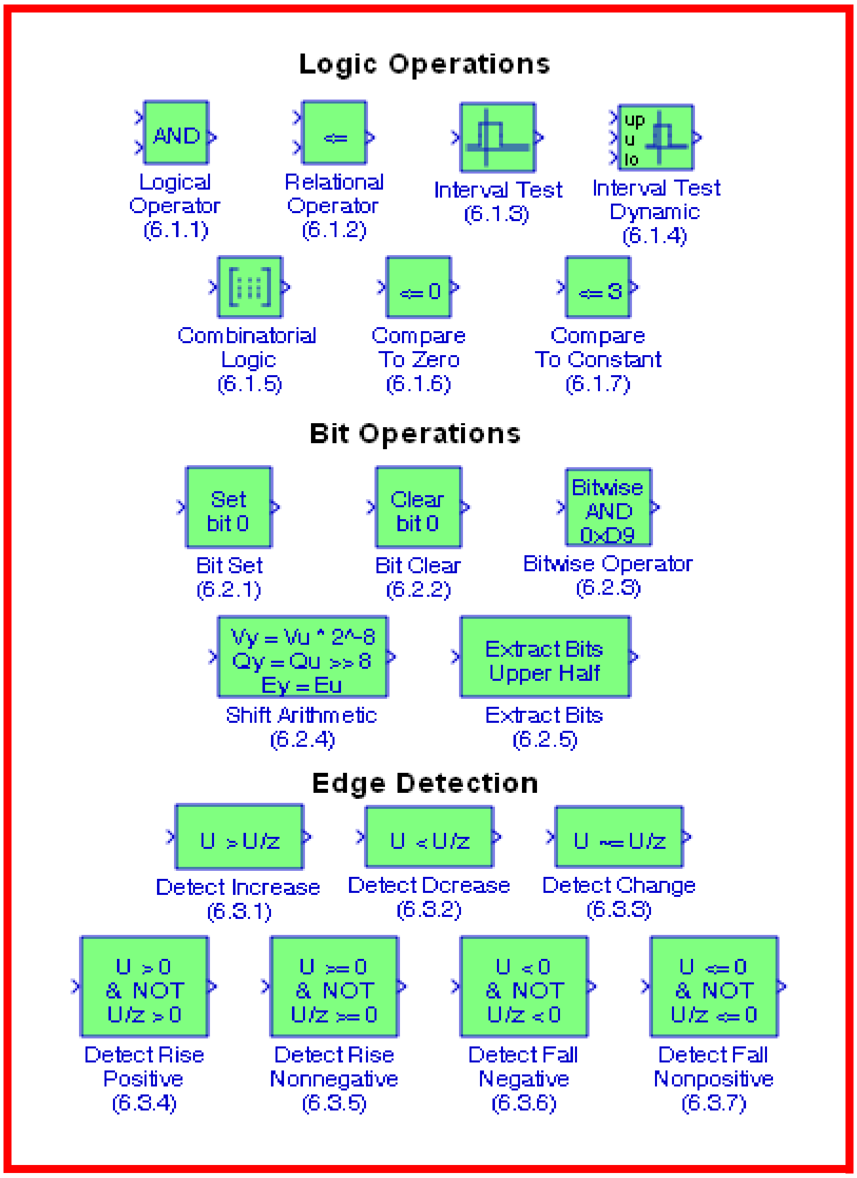

1
Constant 2
5*24.2+4*24.1z-1+3*23.9z-2+2*24z-3+1*24.2z-4
1
Discrete FIR Filter 2
1/15
Gain 2
24.07
Display 2

(b)

Chapter 6

The Logic and Bit Operations Library

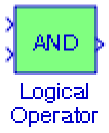
This chapter is an introduction to the **Logic and Bit Operations** Library. This is the fifth library in the Simulink group of libraries and contains the **Logic Operations Group Sub–Library**, the **Bit Operations Group Sub–Library**, and the **Edge Detection Group Sub–Library** blocks shown below. Their functions are illustrated with examples.



6.1 The Logic Operations Group Sub–Library

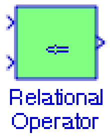
The **Logic Operations Group Sub–Library** contains the blocks described in Subsections 6.1.1 through 6.1.7 below.

6.1.1 The Logical Operator Block



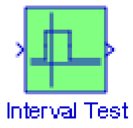
The **Logical Operator** block is described in Section 2.12, Chapter 2, Page 2–20.

6.1.2 The Relational Operator Block



The **Relational Operator** block is described in Section 2.11, Chapter 2, Page 2–19.

6.1.3 The Interval Test Block



The **Interval Test** block performs a test to determine if a signal is in a specified interval. The block outputs TRUE if the input is between the values specified by the Lower limit and Upper limit parameters. The block outputs FALSE if the input is outside those values. The output of the block when the input is equal to the Lower limit or the Upper limit is determined by whether the boxes next to Interval closed on left and Interval closed on right are selected in the dialog box.

Example 6.1

We will create a model with an **Interval Test** block where the Upper limit parameter is set to the binary value [01111111], the Lower limit is set to the binary value [10000000], and the boxes next to Interval closed on left and Interval closed on right are selected in the dialog box. Select the largest positive value and the smallest negative value so that the Interval Test block will be TRUE.

The model is shown in Figure 6.1. We recall that in an 8–bit binary string the largest positive number is 127 (binary [01111111]) and the smallest negative number in an 8–bit binary string is –128 (binary [10000000]). In the model of Figure 6.1, the **Constant** 1 and **Constant** 2 blocks have been specified as Output data type sfix(8), the **Display 1** and **Display 3** blocks have been specified as binary (Stored Integer), and the **Display 2** block has been specified as Format short.

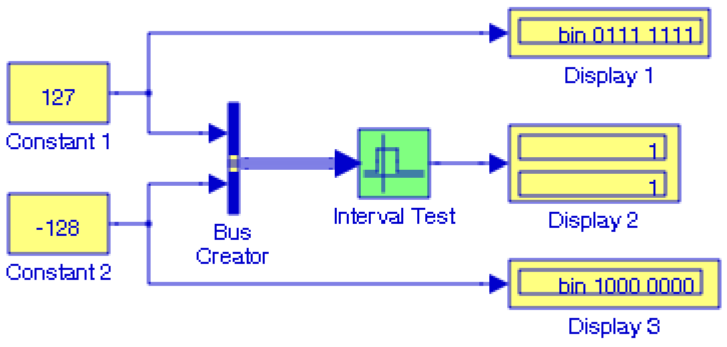
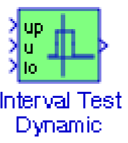


Figure 6.1. Model for Example 6.1

6.1.4 The Interval Test Dynamic Block



Like the Interval Test block, the **Interval Test Dynamic** block performs a test to determine if a signal is in a specified interval. This block outputs TRUE (1) if the input is between the values of the external signals up and lo. The block outputs FALSE (0) if the input is outside those values. The output of the block when the input is equal to the signal up or the signal lo is determined by whether the boxes next to Interval closed on left and Interval closed on right are selected in the Parameters dialog box.

Example 6.2

We will create a model with an **Interval Test Dynamic** block where the external signal up is specified as the decimal value [127], the external signal lo is specified as the decimal value [–128], and the boxes next to Interval closed on left and Interval closed on right are both checked in the Block Parameters dialog box. We will use a **Display** block to show the output when the input to the **Interval Test Dynamic** block is specified for the decimal value [129].

The model is shown in Figure 6.2. The **Constant 1**, **Constant 2**, and **Constant 3** blocks have been specified as Output data type sfix(12), the **Display 1**, **Display 3**, and **Display 4** blocks have been specified as binary (Stored Integer), and the **Display 2** block has been specified as Format short.

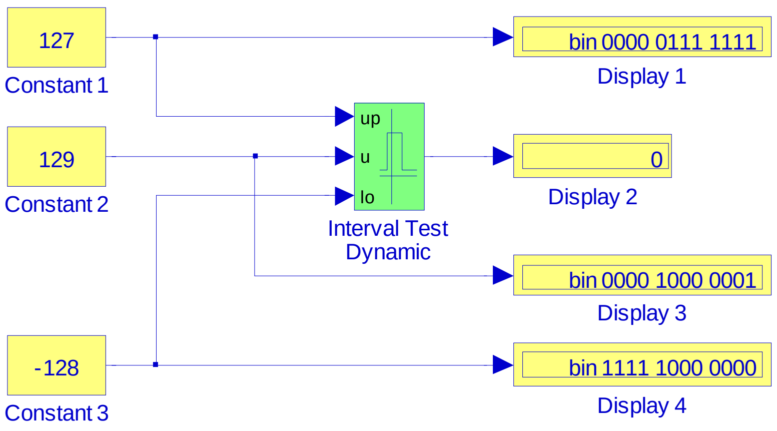
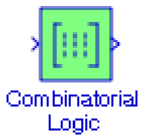


Figure 6.2. Model for Example 6.2

6.1.5 The Combinatorial Logic Block



The **Combinatorial Logic** block, often referred to as combinational block, implements a standard truth table for modeling programmable logic arrays (PLAs)[*], logic circuits, decision tables, and other Boolean expressions. In a Combinatorial Logic block we specify a matrix that defines all outputs as the Truth table parameter. Each row of the matrix contains the output for a different combination of input elements. We must specify outputs for every combination of inputs. The number of columns is the number of block outputs.

Example 6.3

We will create a model with Combinatorial Logic blocks to implement a full adder[†] logic circuit.

The Truth table for a full adder digital circuit is shown in Table 6.1 where X is the augend, Y is the addend, C_{IN} is the carry from a previous addition, S is the Sum of the present addition, and C_{OUT} is the output carry, i.e., the carry generated by the present addition.

* *For a detailed description of PLAs, please refer to Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978−1−934404−05−8.*

† *For a detailed description of full adders, full subtractors, and other logic circuits please refer to the reference cited above.*

TABLE 6.1 Truth table for a full adder

Inputs			Outputs	
X	Y	C_{IN}	S	C_{OUT}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

The model is shown in Figure 6.3 where we have specified:

Constant blocks – Constant value: [0 0 0], [0 0 1], ... [1 1 1] in **Constant** blocks 1 through 8 respectively – Signal data types: boolean – Interpret vector parameters: check mark

Combinatorial Logic blocks (all) – Truth table: [0 0; 1 0; 1 0; 0 1; 1 0; 0 1; 0 1; 11] – Sample time: –1

Display blocks – Format: short

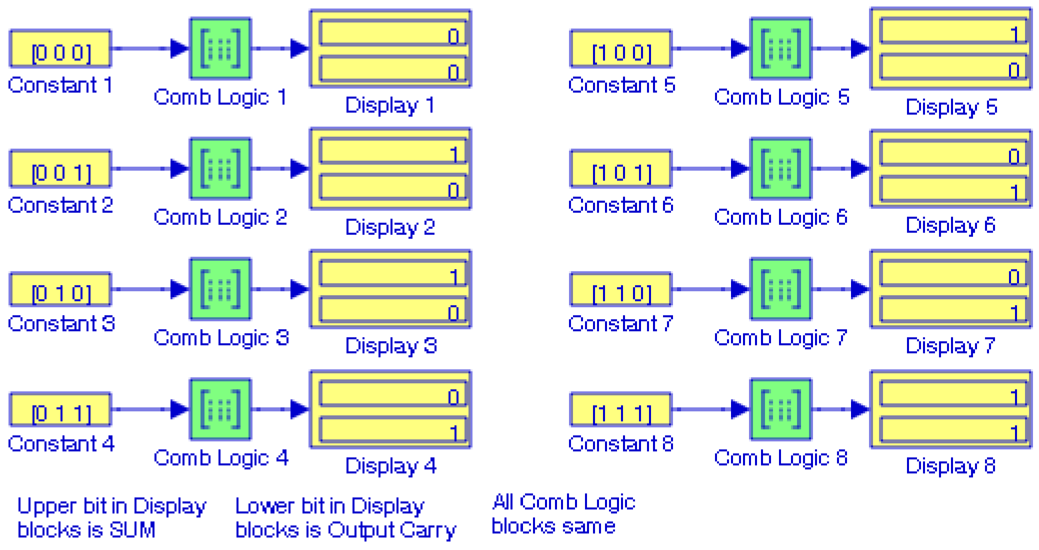


Figure 6.3. Model for Example 6.3

The model in Figure 6.3 looks more presentable in Figure 6.4 below where the individual segments were lined–up one below the other,* we selected all **Combinatorial Logic** blocks, and from the **Edit** drop menu we selected **Create Subsystem**.

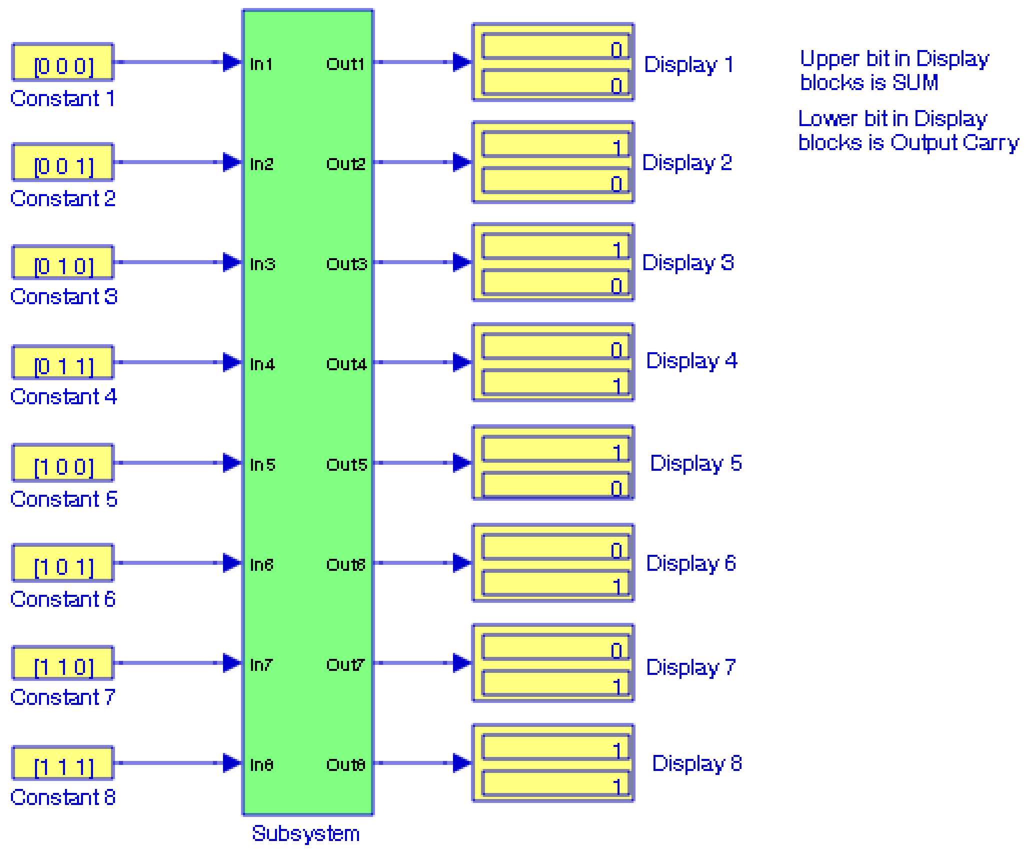


Figure 6.4. Modified model for Example 6.3

We can also implement sequential circuits (that is, circuits with states) with the Combinatorial Logic block by including an additional input for the state of the block and feeding the output of the block back into this state input.

Example 6.4

We will create a model with **Combinatorial Logic** blocks to simulate a Set–Reset (S–R) flip–flop constructed with NAND gates.

* *It was necessary to edit the view (Fit Selection to View) so that we could see all segments of the model and select all Combinatorial Logic blocks at once.*

Figure 6.5(a) shows a basic *Set–Reset (S–R) flip flop* constructed with two NAND gates, and Figure 6.5(b) shows the symbol for the S–R flip flop where S stands for Set and R stands for Reset.

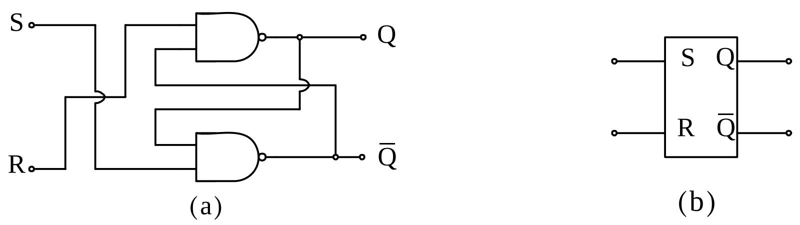


Figure 6.5. Construction and symbol for the S–R flip flop

We recall that for a 2–input NAND gate the output is logical 0 when both inputs are 1s and the output is 1 otherwise. We denote the *present state* of the flip flop as Q_n and the *next state* as Q_{n+1}, and with reference to Figure 6.5(a) we construct the *characteristic table* shown in Table 6.2.

TABLE 6.2 Characteristic table for the SR flip flop with NAND gates

Inputs		Present State	Next State		
S	R	Q_n	Q_{n+1}		
0	0	0	1	But $\overline{Q_{n+1}} = 1$ also	The condition where $S = R = 0$ must be avoided
0	0	1	1	But $\overline{Q_{n+1}} = 1$ also	
0	1	0	0	No Change	
0	1	1	0	Reset (or Clear)	
1	0	0	1	Set	
1	0	1	1	No Change	
1	1	0	0	No Change	
1	1	1	1	No Change	

The characteristic table of Table 6.2 shows that when both inputs S and R are logic 0 simultaneously, both outputs Q and $\overline{Q}$ are logic 1 which is an invalid condition since Q and $\overline{Q}$ are complements of each other. Therefore. the $S = R = 0$ condition must be avoided during flip–flop operation with NAND gates.* When $R = 1$ and $S = 0$, the next state output Q_{n+1} becomes 0 regardless of the previous state Q_n and this is known as the reset or clear condition, that is, whenever $Q = 0$, we say that the flip–flop is reset or clear. When $R= 0$ and $S = 1$, the next state output Q_{n+1} becomes 1 regardless of the previous state Q_n and this is known as the preset or simply

* *For an S–R flip–flop constructed with NOR gates, the condition S=R=1 must be avoided. For a detailed discussion please refer to Chapter 8, Section 8.2 of Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–05–8.*

set condition, that is, whenever $Q = 1$, we say that the flip–flop is set. When $R = 1$ and $S = 1$, the next state output Q_{n+1} remains the same as the present state, i.e., there is no state change.

The model is shown in Figure 6.6.

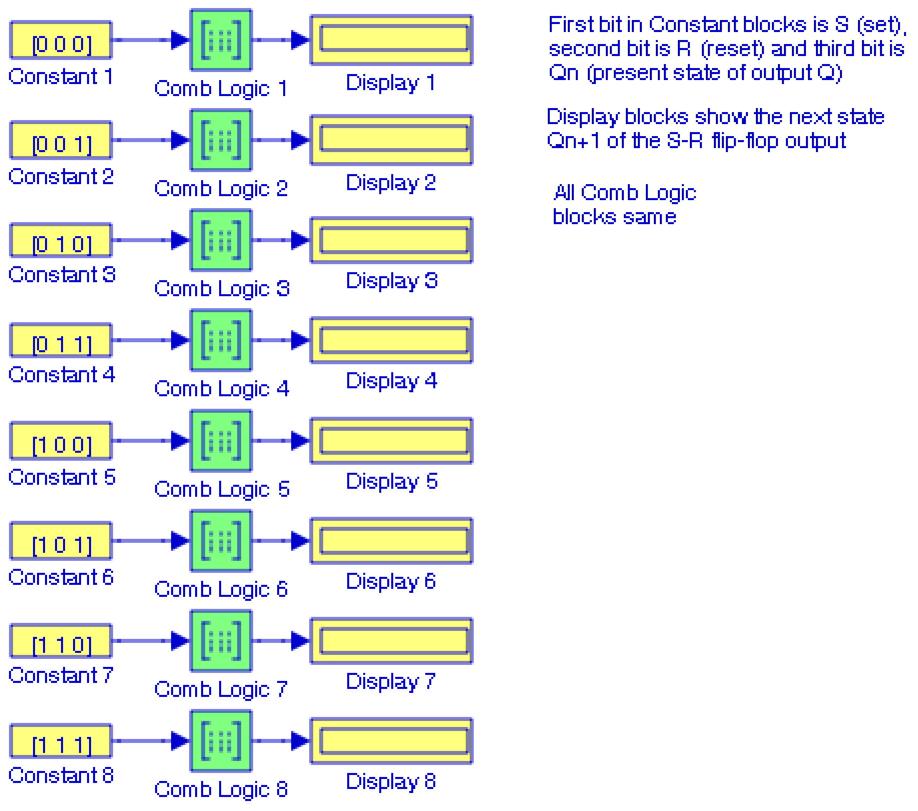


Figure 6.6. Model for Example 6.4

For the model in Figure 6.6, we have specified:

Constant blocks 1 through 8 – Constant value: [0 0 0], [0 0 1], ... [1 1 1] – Signal data types: boolean – Interpret vector parameters: check mark

Combinatorial Logic blocks (all) – Truth table: [1; 1; 0; 0; 1; 1; 0; 1] – Sample time: –1 – Display blocks – Format: short

The model looks more presentable in Figure 6.7 where we selected all Combinatorial Logic blocks, and from the Edit drop menu we selected **Create Subsystem**.

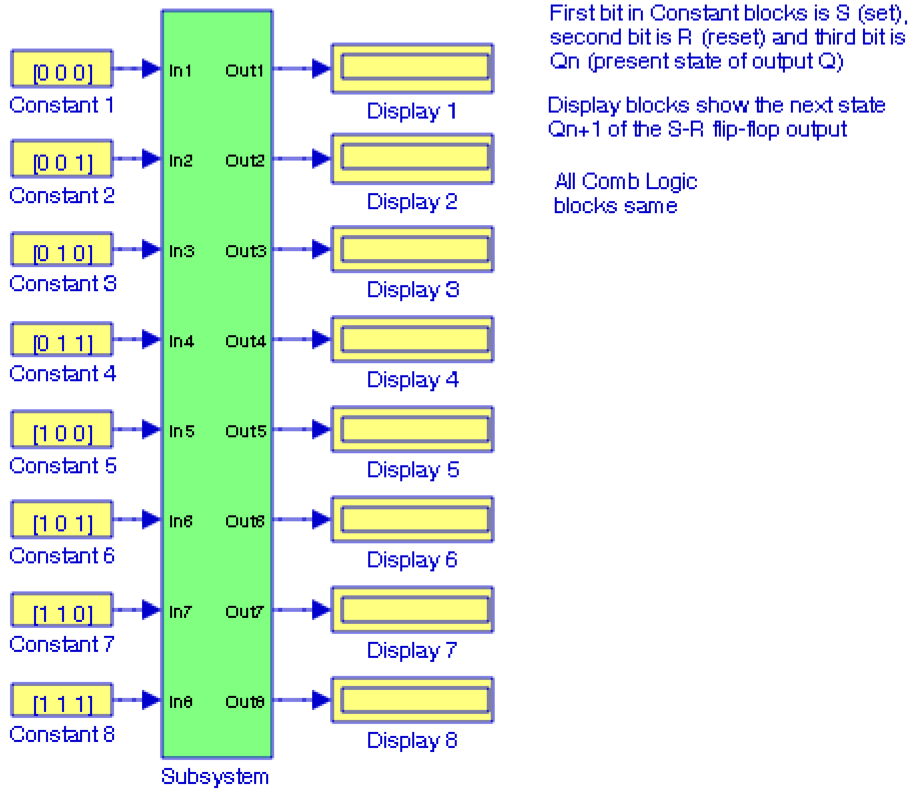
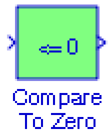


Figure 6.7. Simplified model for Example 6.4

6.1.6 The Compare to Zero Block



The **Compare To Zero** block compares an input signal to zero. We specify how the input is compared to zero with the Operator parameter. The Operator parameters are listed in Table 6.3.

TABLE 6.3 Operator parameters for the Compare to Zero block

Operator	Action
==	Determine whether the input is equal to the specified constant
~=	Determine whether the input is not equal to the specified constant
<	Determine whether the input is less than the specified constant
<=	Determine whether the input is less than or equal to the specified constant
>	Determine whether the input is greater than the specified constant
>=	Determine whether the input is greater than or equal to the specified constant

Example 6.5

We will create a model with the Compare To Zero block to test a matrix for singularity.

As we know, an n square matrix A is called *singular* if $detA = 0$; if $detA \neq 0$, it is called non–singular. To test for singularity, we will use the operator = =. For this example we will use the matrix

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 2 & 3 & 4 \\ 3 & 5 & 7 \end{bmatrix}$$

The model is shown in Figure 6.8 where the matrix A was defined at the MATLAB command prompt as

```
A=[1 2 3; 2 3 4; 3 5 7];
```

In the model of Figure 6.8, the Display 1 block value of zero indicates that the matrix is singular and the Display 2 block indicates logical 1, a true condition.

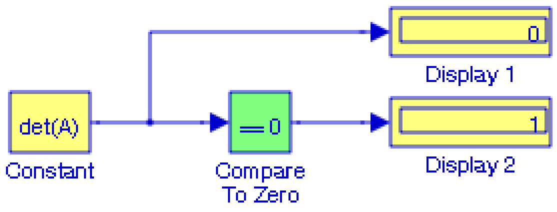
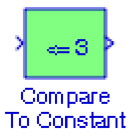


Figure 6.8. Model for Example 6.5

6.1.7 The Compare to Constant Block



The **Compare To Constant** block compares an input signal to a constant. We must specify the constant in the Constant value parameter and how the input is compared to the constant value with the specified Operator parameter. The Operator parameters are listed in Table 6.4.

TABLE 6.4 *Operator parameters for the Compare to Constant block*

Operator	Action
$==$	Determine whether the input is equal to the specified constant
$\sim=$	Determine whether the input is not equal to the specified constant
$<$	Determine whether the input is less than the specified constant
$<=$	Determine whether the input is less than or equal to the specified constant
$>$	Determine whether the input is greater than the specified constant
$>=$	Determine whether the input is greater than or equal to the specified constant

The output is 0 if the comparison is false, and 1 if it is true.

Example 6.6

We will create a model with the Compare To Zero block to determine whether the product **A*B** of matrices **A** and **B**, where $\mathbf{A} = [a_1 \ a_2 \ \dots \ a_n]$, and $\mathbf{B} = [b_1 \ b_2 \ \dots \ b_n]'$, results in a positive or negative value. The elements $[a_1 \ a_2 \ \dots \ a_n]$ and $[b_1 \ b_2 \ \dots \ b_n]'$ are assumed to be real numbers.

We observe that **A** is a row vector and **B** is a column vector and thus the product **A*B** is conformable for multiplication. The model is shown in Figure 6.9 where in MATLAB's Command Window we have entered

```
A=[1  2  3  4  5]; B=[–2  6  –3  –8  –4]';
```

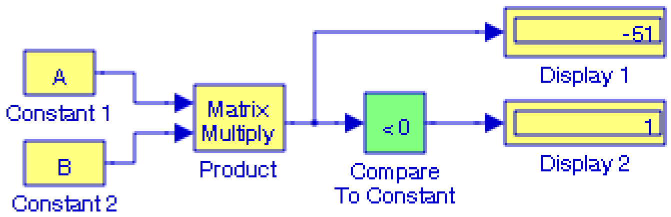


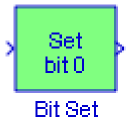
Figure 6.9. Model for Example 6.6

In the model of Figure 6.9, the **Display 1** block value of –51 indicates the product **A*B** and the **Display 2** block indicates logical 1, a true condition.

6.2 The Bit Operations Group Sub–Library

The **Bit Operations Group Sub–Library** contains the blocks described in Subsections 6.2.1 through 6.2.5 below.

6.2.1 The Bit Set Block



The **Bit Set** block sets the specified bit of the stored integer to one. Scaling is ignored. We specify the bit to be set to one with the Index of bit parameter. Bit zero is the least significant bit.

Example 6.7

We will express the row vector [12 8 5 7] in 8–bit binary form, and using the Bit Set block we will create a model that will convert this vector to [13 12 7 15]. The converted vector will be displayed in binary form.

The model is shown in Figure 6.10.

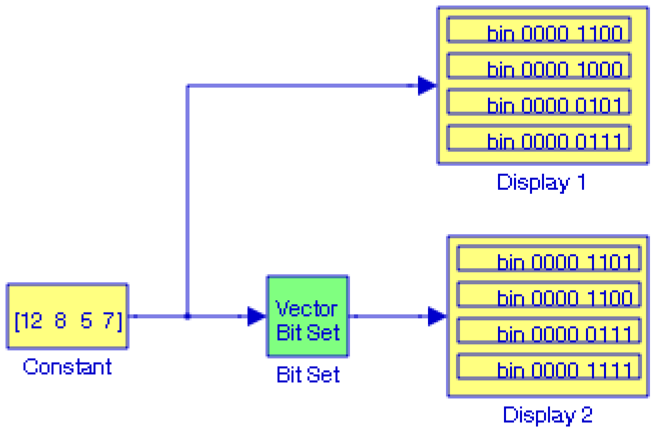


Figure 6.10. Model for Example 6.7

For this model we have configured the blocks as follows:

Constant block – Constant value: [12 8 5 7] – Signal data types: uint(8)

Bit Set block – Function block Parameters, Index of bit: [0 2 1 3]

Display 1 and **Display 2 blocks**, Format: Binary (Stored Integer)

6.2.2 The Bit Clear Block

The **Bit Clear** block sets the specified bit, given by its index, of the stored integer to zero. Scaling is ignored. We can specify the bit to be set to zero with the Index of bit parameter. Bit zero is the least significant bit.

Example 6.8

We will express the row vector [14 8 5 12] in 8–bit binary form and using the Bit Clear block we will create a model that will convert this vector to [6 0 5 4]. We will display the converted vector in binary form.

The model is shown in Figure 6.11.

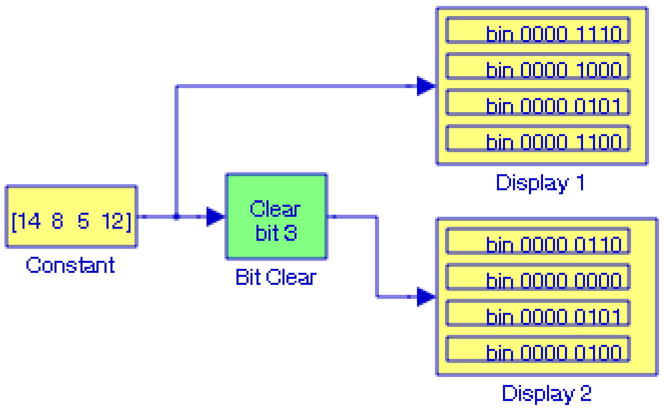


Figure 6.11. Model for Example 6.8

For this model we have configured the blocks as follows:

Constant block – Constant value: [14 8 5 12] – Signal data types: uint(8)

Bit Clear block – Function block Parameters, Index of bit: 3

Display 1 and **Display 2** blocks, Format: Binary (Stored Integer)

6.2.3 The Bitwise Operator Block

Bitwise Operator

The **Bitwise Operator** block performs the specified bitwise operation on its operands. Unlike the logic operations performed by the **Logical Operator** block described in Section 2.12, Chapter 2, Page 2–20, bitwise operations treat the operands as a vector of bits rather than a single number. The operations are listed below.

Operation Description:

AND – TRUE if the corresponding bits are all TRUE

OR – TRUE if at least one of the corresponding bits is TRUE

NAND – TRUE if at least one of the corresponding bits is FALSE

NOR – TRUE if no corresponding bits are TRUE

XOR – TRUE if an odd number of corresponding bits are TRUE

NOT – TRUE if the input is FALSE and vice–versa

The **Bitwise Operator** block cannot be used for shift operations. Shift operations are described in Subsection 6.2.4.

The size of the output of the **Bitwise Operator** block depends on the number of inputs, their vector size, and the selected operator. For a single vector input, the block applies the operation (except the NOT operator) to all elements of the vector. If a bit mask is not specified, then the output is a scalar. If a bit mask is specified, then the output is a vector. The NOT operator accepts only one input, which can be a scalar or a vector. If the input is a vector, the output is a vector of the same size containing the bitwise logical complements of the input vector elements.

For two or more inputs, the block performs the operation between all of the inputs. If the inputs are vectors, the operation is performed between corresponding elements of the vectors to produce a vector output. If we do not select the Use bit mask check box, the block will accept multiple inputs. We select the number of input ports from the Number of input ports parameter. The input data types must be identical. For more information on the **Bitwise Operator** block please refer to the Simulink Help menu for this block.

Example 6.9

We will create a model containing a 3–input Bitwise AND block, a 3–input Bitwise NOR block, and a 2–input Bitwise XOR block. The inputs to the Bitwise AND and Bitwise NOR blocks are:

$$(152)_{10} = (10011000)_2$$
$$(141)_{10} = (10001101)_2$$
$$(75)_{10} = (01001011)_2$$

The inputs to the Bitwise XOR block are:

$$(152)_{10} = (10011000)_2$$
$$(141)_{10} = (10001101)_2$$

The model is shown in Figure 6.12.

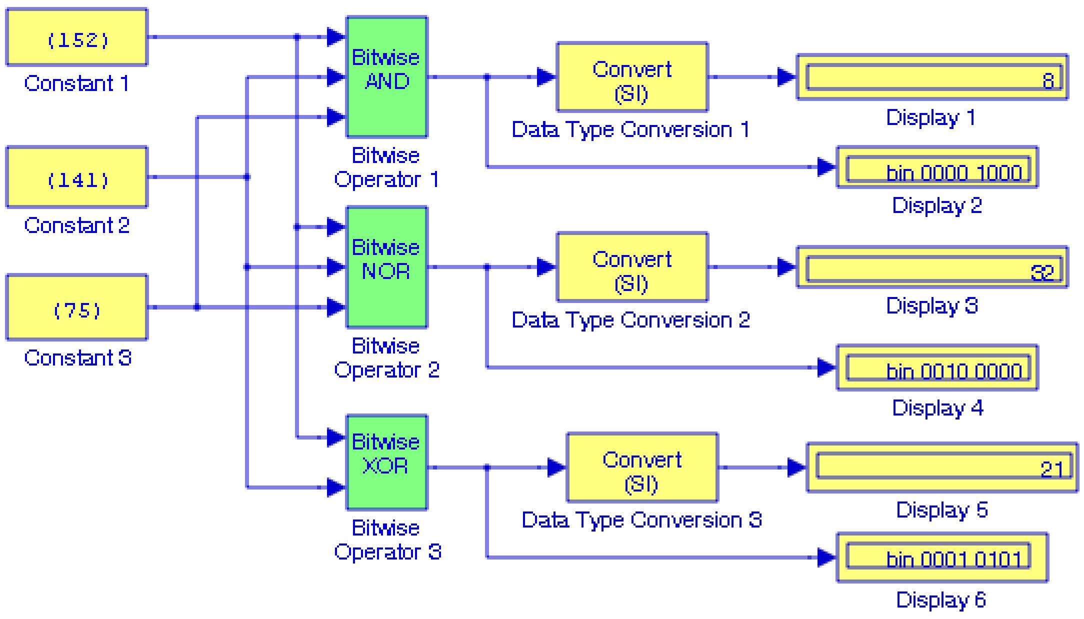


Figure 6.12. Model for Example 6.9

For the model of Figure 6.12 we have entered:

Constant blocks 1, 2, and 3 – Constant value: [152], [141], and [75] respectively – Signal data types: uint8

Bitwise AND block – Operator: AND, Number of input ports: 3

Bitwise NOR block – Operator: NOR, Number of input ports: 3

Bitwise XOR block – Operator: XOR, Number of input ports: 2

Data type Conversion 1, 2, and 3 blocks – Output data type mode: Specify via dialog – Output data type: 'double' – Input and output to have equal: Stored Integer (SI)

Display 1, 3, and 5 blocks – Format: decimal (Stored Integer)

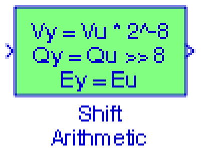
Display 2, 4, and 6 blocks – Format: binary (Stored Integer)

A binary value used to selectively screen out or let through certain bits in a data value. Masking is performed by using a logical operator (AND, OR, XOR, NOT) to combine the mask and the data value. For example, the mask $[00111111]$, when used with the AND operator, removes (masks off) the two uppermost bits in a data value but does not affect the rest of the value.

If we select the Use bit mask check box, then a single input is associated with the bit mask that we have specified with the Bit Mask parameter. We can specify the bit mask using any MATLAB expression at the Command Window. For example, we can specify the bit mask $[10100110]$ as $[2^7+2^5+2^2+2^1]$. For long strings, we can use hexadecimal bit masks, e.g., ['DA87'], and ['E2F9B']. If the bit mask is larger than the input signal data type, it is ignored.

We can use the bit mask to perform a bit set or a bit clear on the input. To perform a bit set, we set the Operator parameter list to OR and create a bit mask with a 1 for each corresponding input bit that we want to set to 1. To perform a bit clear, we set the Operator parameter list to AND and create a bit mask with a 0 for each corresponding input bit that we want to set to 0.

6.2.4 The Shift Arithmetic Block



The **Shift Arithmetic** block is be used to shift the bits or the binary point of a binary word, or both. This block performs arithmetic bit shifts on signed numbers. Therefore, the most significant bit is recycled for each bit shift. If the bits and the binary point are to be shifted to the left, we specify negative values.

Example 6.10

We will create a model with a **Shift Arithmetic** block with inputs decimal $+32.75$ and decimal -48.875 to display the outputs when both of these numbers are shifted left by 3 bits and the binary point is shifted left by 2 bits.

The model is shown in Figure 6.13 where the **Constant** blocks have been set for Output data type fixdt(1,16,2^–3,0). Since it is specified that the bits and the binary point are to be shifted to the left, in the **Shift Arithmetic** block we enter the values -3 and -2 respectively. All three display blocks have been set for binary (Stored Integer) format. We can check the **Shift Arithmetic** block outputs as follows:

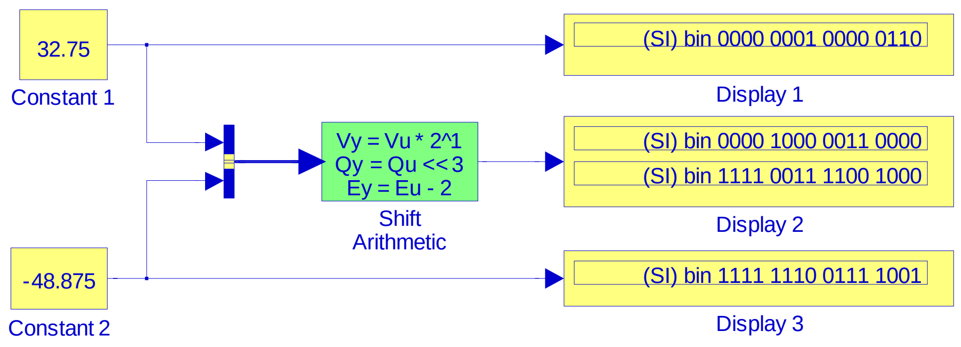

32.75
Constant 1
-48.875
Constant 2
Vy = Vu * 2^1
Qy = Qu <<3
Ey = Eu - 2
Shift Arithmetic
(SI) bin 0000 0001 0000 0110
Display 1
(SI) bin 0000 1000 0011 0000
(SI) bin 1111 0011 1100 1000
Display 2
(SI) bin 1111 1110 0111 1001
Display 3

Figure 6.13. Model for Example 6.10

$$(+32.75)_{10} = (0000\ 0001\ 0000\ 0.110)_2$$

and after shifting 3 bits to the left and the binary point 2 places to the left we obtain

$$0000\ 1000\ .0011\ 0000$$

Likewise,

$$(-48.875)_{10} = (-0000\ 0001\ 1000\ 0.111)_2 = (1111\ 1110\ 0111\ 1.001)_{2s\ complement}$$

and after shifting 3 bits to the left and the binary point 2 places to the left we obtain

$$1111\ 0011\ .1100\ 1000$$

6.2.5 The Extract Bits Block

The **Extract Bits** block allows us to output a contiguous selection of bits from the stored integer value of the input signal. The Bits to extract parameter defines the method by which we select the output bits. We select Upper half to output the half of the input bits that contain the most significant bit. If there is an odd number of bits in the input signal, the number of output bits is given by

$$Number\ of\ output\ bits = ceil(Number\ of\ input\ bits/2)^{*} \tag{6.1}$$

We select Lower half to output the half of the input bits that contain the least significant bit. If there is an odd number of bits in the input signal, the number of output bits is given by relation (6.1).

* *The notation Ceil( ) rounds "up", e.g., ceil(4.6) rounds to 5, and ceil(−4.6) rounds to −4. The notation Floor( ) rounds "down", e.g., floor(8.999) = 8.*

We select Range starting with most significant bit to output a certain number of the most significant bits of the input signal. We specify the number of most significant bits to output in the Number of bits parameter.

We select Range ending with least significant bit to output a certain number of the least significant bits of the input signal. We specify the number of least significant bits to output in the Number of bits parameter.

We select Range of bits to indicate a series of contiguous bits of the input to output in the Bit indices parameter. We indicate the range in [start end] format, and the indices of the input bits are labeled contiguously starting at 0 for the least significant bit.

Example 6.11

We will create a model with an Extract Bits block to accept the decimal number 65403 as the input and outputs the binary number [1111 1111].

The model is shown in Figure 6.14 where the Constant block is set for Signal data types – Output data type mode: uint16, the Display 1 block shows the given decimal number in binary form, and the Display 2 block shows the Upper Half of that binary number. Both display blocks have been set for binary (Stored Integer) format. Had we specified the display blocks for decimal (Stored Integer), Display 1 block would show the decimal number 65403 and Display 2 block would show the decimal value 255 which is equivalent to binary 1111 1111.

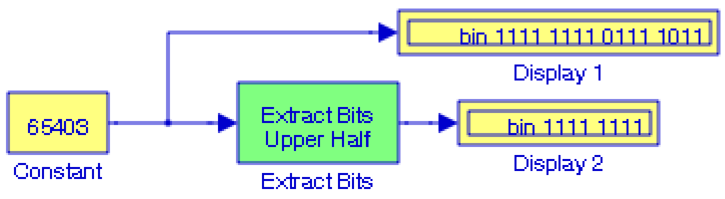
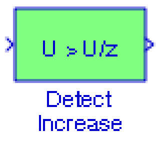


Figure 6.14. Model for Example 6.11

6.3 The Edge Detection Group Sub–Library

The **Edge Detection Group Sub–Library** contains the blocks described in Subsections 6.3.1 through 6.3.7 below.

6.3.1 The Detect Increase Block



The **Detect Increase** block determines if an input is strictly greater than its previous value. The output is true (not 0), when the input signal is greater than its previous value. The output is false (equal to 0), when the input signal is less than or equal to its previous value.

Example 6.12

We will create a model with the Detect Increase block to display changes in output for changes in the input.

The model is shown in Figure 6.15 and the input and output waveforms are shown in Figure 6.16. In Figure 6.15, the Signal Generator block is specified for a square waveform of amplitude 1 and frequency 0.5, the Unit Delay is included to delay the Step block one time unit, the Detect Increase block initial value is specified as 0, and the Convert Block is used to convert the output signal of the Detect Change block from uint(8) to double. The waveforms in Figure 6.16 indicate that the output is true (not 0), when the input signal is greater than its previous value. The output is false (equal to 0), when the input signal is less than or equal to its previous value.

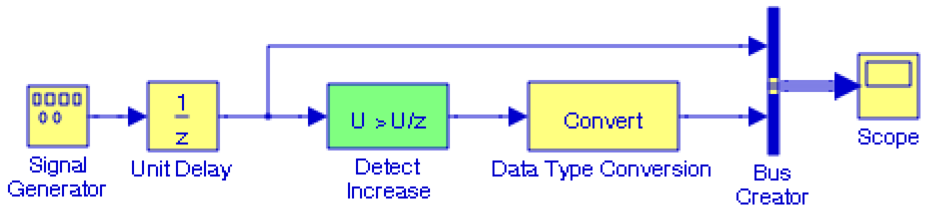


Figure 6.15. Model for Example 6.12

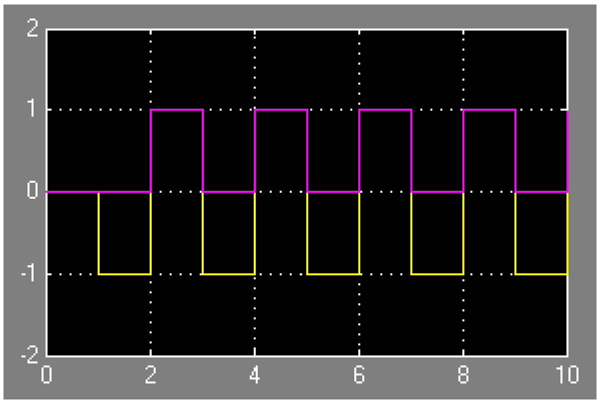
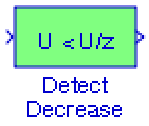


Figure 6.16. Input and output waveforms for the model in Figure 6.15

6.3.2 The Detect Decrease Block



The **Detect Decrease** block determines if an input is strictly less than its previous value where the output is true (not 0), when the input signal is less than its previous value, and the output is false (equal to 0), when the input signal is greater than or equal to its previous value.

Example 6.13

We will create a model with the **Detect Decrease** block to display changes in output for changes in the input.

The model is shown in Figure 6.17 and the input and output waveforms are shown in Figure 6.18. In Figure 6.17, the **Signal Generator** block is set for a square waveform of amplitude 1 and frequency 0.5, the **Unit Delay** block is included to delay the Signal Generator block one time unit, the **Detect Decrease** block initial value is set to 0, and the **Convert** Block is used to convert the output signal of the **Detect Change** block from uint(8) to double. The waveforms in Figure 6.18 indicate that the output waveform is true (not 0), when the input signal is less than its previous value, and the output is false (equal to 0), when the input signal is greater than or equal to its previous value.

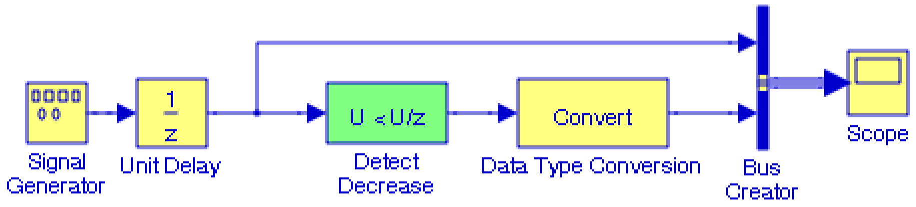


Figure 6.17. Model for Example 6.13

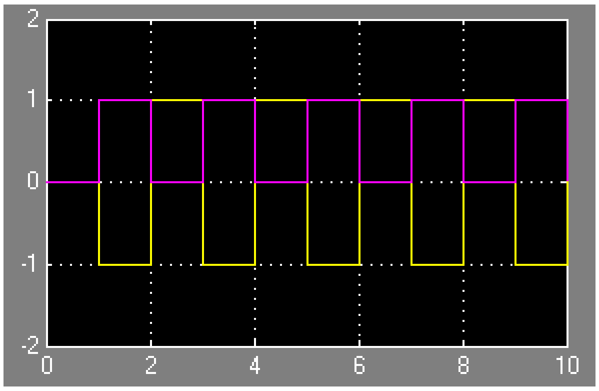
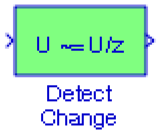


Figure 6.18. Input and output waveforms for the model in Figure 6.17

6.3.3 The Detect Change Block



The **Detect Change** block determines if an input does not equal its previous value where the output is true (not 0), when the input signal does not equal its previous value, and the output is false (equal to 0), when the input signal equals its previous value.

Example 6.14

We will create a model with the **Detect Change** block to display changes in output for changes in the input.

The model is shown in Figure 6.19 and the input and output waveforms are shown in Figure 6.20. In Figure 6.19, the **Detect Change** block value is set to 0, and the **Convert** Block is used to convert the output signal of the **Detect Change** block from uint(8) to double. The waveforms in Figure 6.20 indicate that the output waveform is 0 for the interval $0 < t < 1$ because the step function is also 0 during this interval. At $t = 1$ the step function jumps to 1 and thus the output assumes a non–zero value, in this case 1. For $t > 1$, there are no further changes in the input signal and thus the output drops to 0 indicating that the input signal equals its previous value.

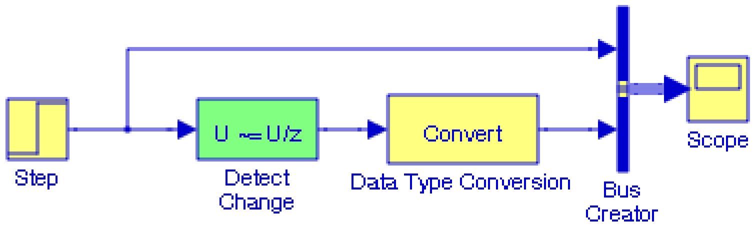


Figure 6.19. Model for Example 6.14

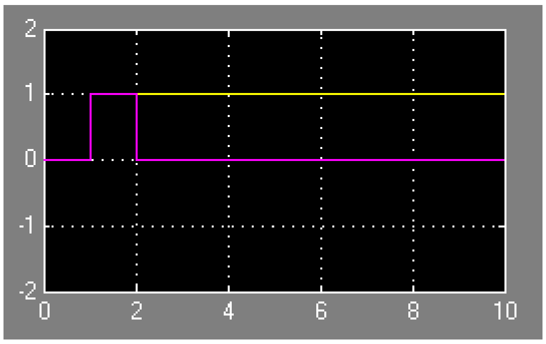
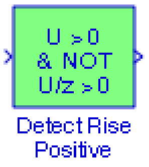


Figure 6.20. Input and output waveforms for the model in Figure 6.19

6.3.4 The Detect Rise Positive Block



The **Detect Rise Positive** block determines if the input is strictly positive, and its previous value was nonpositive. The output is true (not 0), when the input signal is greater than zero, and its previous value was less than zero. The output is false (equal to 0), when the input is negative or zero, or if the input is positive and its previous value was also positive.

Example 6.15

We will create a model with the **Detect Rise Positive** block to display changes in output for changes in the input.

The model is shown in Figure 6.21 and the input and output waveforms are shown in Figure 6.22.

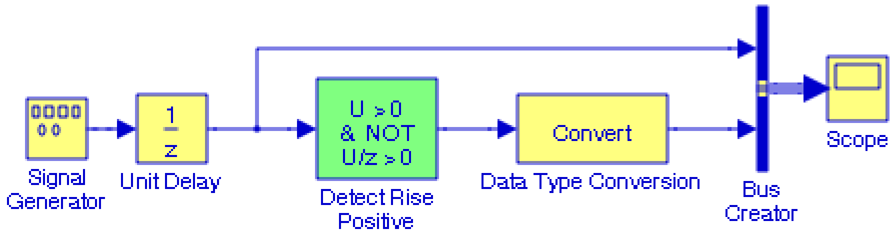


Figure 6.21. Model for Example 6.15

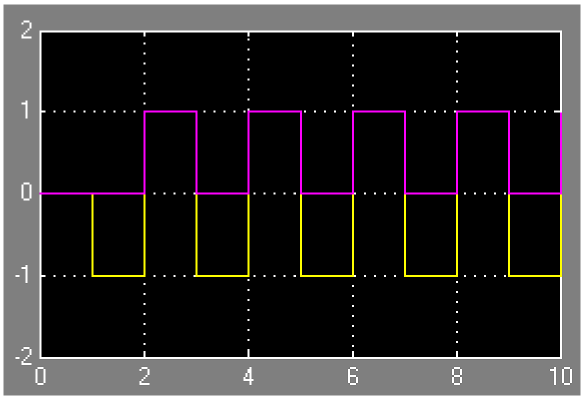
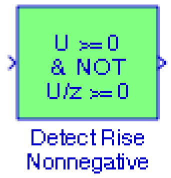


Figure 6.22. Input and output waveforms for the model in Figure 6.21

In Figure 6.21, the **Signal Generator** block is specified as a square waveform of amplitude 1 and frequency 0.5, the **Unit Delay** block is included to delay the **Signal Generator** block one time unit, the **Detect Rise Positive** block initial value is set to 0, and the **Convert** block is used to convert the output signal of the **Detect Change** block from uint(8) to double. The waveforms in Figure 6.22 indicate that the output is true (not 0), when the input signal is greater than zero, and its previous value was less than zero. The output is false (equal to 0), when the input is negative or zero, or if the input is positive and its previous value was also positive.

6.3.5 The Detect Rise Nonnegative Block



The **Detect Rise Nonnegative** block determines if the input is greater than or equal to zero, and its previous value was less than zero. The output is true (not 0), when the input signal is greater than or equal to zero, and its previous value was less than zero. The output is false (equal to 0), when the input signal is less than zero, or if nonnegative, its previous value was greater than or equal to zero.

Example 6.16

We will create a model with the **Detect Rise Nonnegative** block to display changes in output for changes in the input.

The model is shown in Figure 6.23 and the input and output waveforms are shown in Figure 6.24.

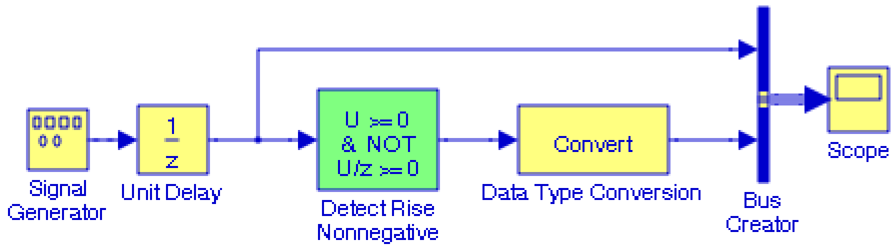


Figure 6.23. Model for Example 6.16

In Figure 6.23, the **Signal Generator** block is set for a square waveform of amplitude 1 and frequency 0.5, the **Unit Delay** block is included to delay the **Signal Generator** block one time unit, the **Detect Rise Nonnegative** block initial value is set to 0, and the **Convert** block is used to convert the output signal of the **Detect Rise Nonnegative** block from uint(8) to double. The waveforms in Figure 6.24 indicate that the output is true (not 0), when the input signal is greater than or equal to zero, and its previous value was less than zero. The output is false (equal to 0), when the input signal is less than zero, or if nonnegative and its previous value was greater than or equal to zero.

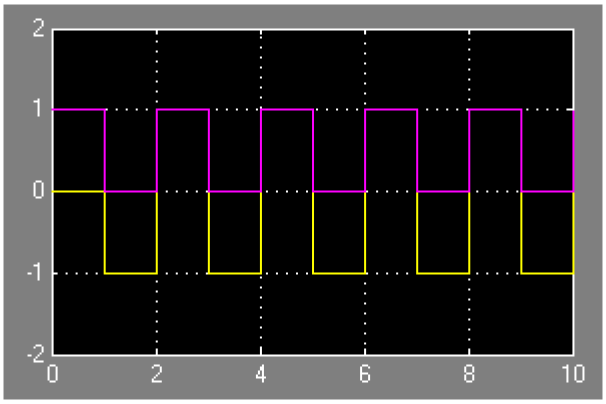
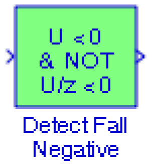


Figure 6.24. Input and output waveforms for the model in Figure 6.23

6.3.6 The Detect Fall Negative Block



The **Detect Fall Negative** block determines if the input is less than zero, and its previous value was greater than or equal to zero. The output is true (not 0), when the input signal is less than zero, and its previous value was greater than or equal to zero. The output is false (equal to 0), when the input signal is greater than or equal to zero, or if the input signal is nonnegative and its previous value was positive or zero.

Example 6.17

We will create a model with the **Detect Fall Negative** block to display changes in output for changes in the input.

The model is shown in Figure 6.25 and the input and output waveforms are shown in Figure 6.26.

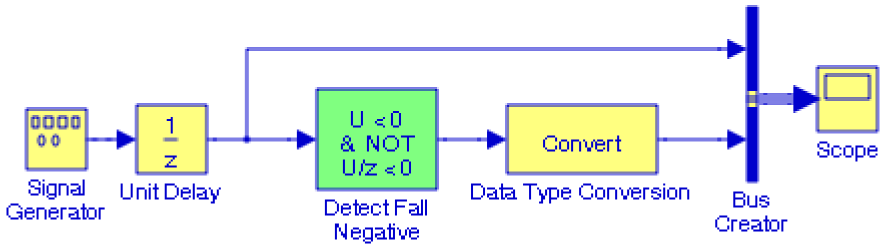


Figure 6.25. Model for Example 6.17

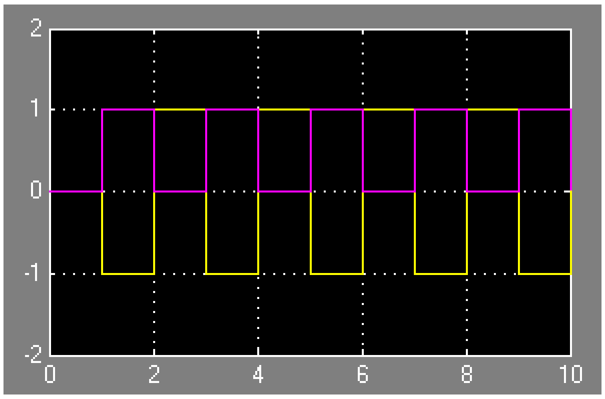
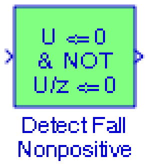


Figure 6.26. Input and output waveforms for the model in Figure 6.25

In Figure 6.25, the **Signal Generator** block is set for a square waveform of amplitude 1 and frequency 0.5, the **Unit Delay** block is included to delay the **Signal Generator** block one time unit, the **Detect Fall Negative** block initial value was set to 0, and the **Convert** block is used to convert the output signal of the **Detect Fall Negative** block from uint(8) to double. The waveforms in Figure 6.26 indicate that the output is true (not 0), when the input signal is less than zero, and its previous value was greater than or equal to zero. The output is false (equal to 0), when the input signal is greater than or equal to zero, or if the input signal is nonnegative and its previous value was positive or zero.

6.3.7 The Detect Fall Nonpositive Block



The **Detect Fall Nonpositive** block determines if the input is less than or equal to zero, and its previous value was positive. The output is true (not 0), when the input signal is less than or equal to zero, and its previous value was greater than zero. The output is false (equal to 0), when the input signal is greater than zero, or if it is nonpositive and its previous value was nonpositive.

Example 6.18

We will create a model with the **Detect Fall Nonpositive** block to display changes in output for changes in the input.

The model is shown in Figure 6.27 and the input and output waveforms are shown in Figure 6.28.

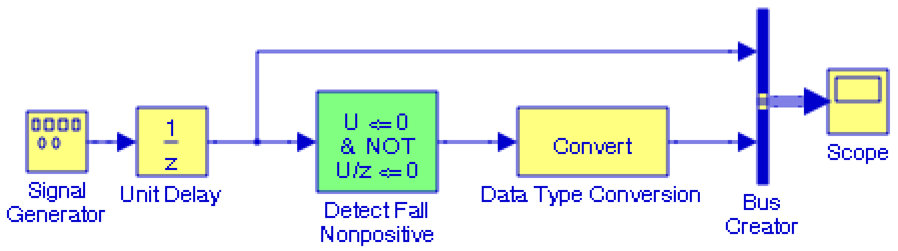


Figure 6.27. Model for Example 6.18

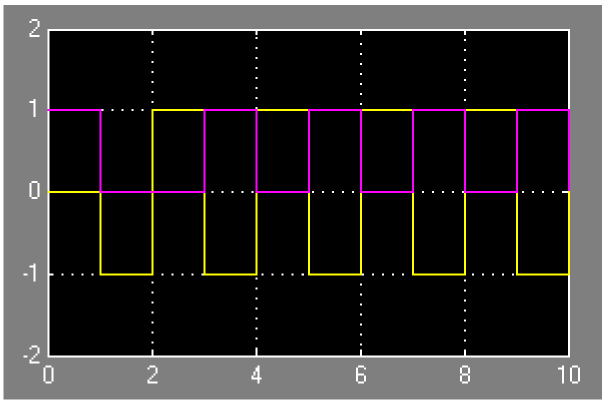


Figure 6.28. Input and output waveforms for the model in Figure 6.27

In Figure 6.27, the **Signal Generator** block is set for a square waveform of amplitude 1 and frequency 0.5, the **Unit Delay** block is included to delay the Step block one time unit, the **Detect Fall Nonpositive** block initial value is set to 0, and the **Convert** block is used to convert the output signal of the **Detect Fall Nonpositive** block from uint(8) to double. The waveforms in Figure 6.28 indicate that the output is true (not 0), when the input signal is less than or equal to zero, and its previous value was greater than zero. The output is false (equal to 0), when the input signal is greater than zero, or if it is nonpositive and its previous value was nonpositive.

6.4 Summary

- The **Logical Operator block** performs the specified logical operation on its inputs. An input value is TRUE (1) if it is nonzero and FALSE (0) if it is zero. The Boolean operation connecting the inputs is selected with the Operator parameter list in the Function Block Parameters window. The block updates to display the selected operator. The supported operations are given below.

  Operation Description:

  AND – TRUE if all inputs are TRUE

  OR – TRUE if at least one input is TRUE

  NAND – TRUE if at least one input is FALSE

  NOR – TRUE when no inputs are TRUE

  XOR – TRUE if an odd number of inputs are TRUE

  NOT – TRUE if the input is FALSE and vice–versa

  The number of input ports is specified with the Number of input ports parameter. The output type is specified with the Output data type mode and/or the Output data type parameters. An output value is 1 if TRUE and 0 if FALSE.

- The **Relational Operator block** performs the specified comparison of its two inputs. We select the relational operator connecting the two inputs with the Relational Operator parameter. The block updates to display the selected operator. The supported operations are given below.

  Operation Description:

  == TRUE if the first input is equal to the second input

  ~= TRUE if the first input is not equal to the second input

  < TRUE if the first input is less than the second input

  <= TRUE if the first input is less than or equal to the second input

  >= TRUE if the first input is greater than or equal to the second input

  > TRUE if the first input is greater than the second input

- The **Interval Test** block performs a test to determine if a signal is in a specified interval. The block outputs TRUE if the input is between the values specified by the Lower limit and Upper limit parameters. The block outputs FALSE if the input is outside those values. The output of the block when the input is equal to the Lower limit or the Upper limit is determined by whether the boxes next to Interval closed on left and Interval closed on right are selected in the dialog box.

- The **Interval Test Dynamic** block performs a test to determine if a signal is in a specified interval. This block outputs TRUE if the input is between the values of the external signals up and lo. The block outputs FALSE if the input is outside those values. The output of the block when the input is equal to the signal up or the signal lo is determined by whether the boxes next to Interval closed on left and Interval closed on right are selected in the dialog box.
- The **Combinatorial Logic** block implements a standard truth table for modeling programmable logic arrays (PLAs), logic circuits, decision tables, and other Boolean expressions. In a Combinatorial Logic block we specify a matrix that defines all outputs as the Truth table parameter. Each row of the matrix contains the output for a different combination of input elements. We must specify outputs for every combination of inputs. The number of columns is the number of block outputs. We can also implement sequential circuits (that is, circuits with states) with the Combinatorial Logic block by including an additional input for the state of the block and feeding the output of the block back into this state input. We can also implement sequential circuits (that is, circuits with states) with the Combinatorial Logic block by including an additional input for the state of the block and feeding the output of the block back into this state input.
- The **Compare To Zero** block compares an input signal to zero. We specify how the input is compared to zero with the Operator parameter. The Operator parameters are listed in the table below.

Operator	Action
==	Determine whether the input is equal to the specified constant
~=	Determine whether the input is not equal to the specified constant
<	Determine whether the input is less than the specified constant
<=	Determine whether the input is less than or equal to the specified constant
>	Determine whether the input is greater than the specified constant
>=	Determine whether the input is greater than or equal to the specified constant

  The output is 0 if the comparison is false, and 1 if it is true.
- The **Compare To Constant** block compares an input signal to a constant. We must specify the constant in the Constant value parameter and how the input is compared to the constant value with the Operator parameter. The Operator parameters are the same as those of the Compare to Zero block listed above.
- The **Bit Set** block sets the specified bit of the stored integer to one. Scaling is ignored. We specify the bit to be set to one with the Index of bit parameter, where bit zero is the least significant bit.

- The **Bit Clear** block sets the specified bit, given by its index, of the stored integer to zero. Scaling is ignored. We can specify the bit to be set to zero with the Index of bit parameter, where bit zero is the least significant bit.
- The **Bitwise Operator** block performs the specified bitwise operation on its operands. Unlike the logic operations performed by the Logical Operator block, bitwise operations treat the operands as a vector of bits rather than a single number. The supported operations are given below.

  Operation Description:

  AND – TRUE if the corresponding bits are all TRUE

  OR – TRUE if at least one of the corresponding bits is TRUE

  NAND – TRUE if at least one of the corresponding bits is FALSE

  NOR – TRUE if no corresponding bits are TRUE

  XOR – TRUE if an odd number of corresponding bits are TRUE

  NOT – TRUE if the input is FALSE and vice–versa
- Masking is performed by using a logical operator (AND, OR, XOR, NOT) to combine the mask and the data value.
- The **Shift Arithmetic** block is be used to shift the bits or the binary point of a binary word, or both. This block performs arithmetic bit shifts on signed numbers. Therefore, the most significant bit is recycled for each bit shift. If the bits and the binary point are to be shifted to the left, we specify negative values.
- The **Extract Bits** block allows us to output a contiguous selection of bits from the stored integer value of the input signal. The Bits to extract parameter defines the method by which we select the output bits. We select Upper half to output the half of the input bits that contain the most significant bit. If there is an odd number of bits in the input signal, the number of output bits is given by

  $$Number\ of\ output\ bits\ =\ ceil(Number\ of\ input\ bits/2)$$

  We select Lower half to output the half of the input bits that contain the least significant bit. If there is an odd number of bits in the input signal, the number of output bits is given by the relation above.
- The **Detect Increase** block determines if an input is strictly greater than its previous value. The output is true (not 0), when the input signal is greater than its previous value. The output is false (equal to 0), when the input signal is less than or equal to its previous value.

- The **Detect Decrease** block determines if an input is strictly less than its previous value where the output is true (not 0), when the input signal is less than its previous value, and the output is false (equal to 0), when the input signal is greater than or equal to its previous value.
- The **Detect Change** block determines if an input does not equal its previous value where the output is true (not 0), when the input signal does not equal its previous value, and the output is false (equal to 0), when the input signal equals its previous value.
- The **Detect Rise Positive** block determines if the input is strictly positive, and its previous value was nonpositive. The output is true (not 0), when the input signal is greater than zero, and its previous value was less than zero. The output is false (equal to 0), when the input is negative or zero, or if the input is positive and its previous value was also positive.
- The **Detect Rise Nonnegative** block determines if the input is greater than or equal to zero, and its previous value was less than zero. The output is true (not 0), when the input signal is greater than or equal to zero, and its previous value was less than zero. The output is false (equal to 0), when the input signal is less than zero, or if nonnegative, its previous value was greater than or equal to zero.
- The **Detect Fall Negative** block determines if the input is less than zero, and its previous value was greater than or equal to zero. The output is true (not 0), when the input signal is less than zero, and its previous value was greater than or equal to zero. The output is false (equal to 0), when the input signal is greater than or equal to zero, or if the input signal is nonnegative and its previous value was positive or zero.
- The **Detect Fall Nonpositive** block determines if the input is less than or equal to zero, and its previous value was positive. The output is true (not 0), when the input signal is less than or equal to zero, and its previous value was greater than zero. The output is false (equal to 0), when the input signal is greater than zero, or if it is nonpositive and its previous value was nonpositive.

6.5 Exercises

1. Convert the row vector [8125 5963 2473 8690] to [8117 5961 2472 8690] by creating a model using the **Bit Clear** block. Display the converted vector in decimal form. Hint: You can verify the results with the MATLAB dec2bin and bin2 dec functions

2. Create a model with the **Bitwise Operator** block to convert the binary number [01111111] to the binary number [01100010] using the bit mask check box to specify the appropriate bits.

3. Create a model with **Combinatorial Logic** blocks to implement a full subtractor[*] logic circuit.

4. Create a model with the **Detect Change** block to display changes in output when the input is a square waveform.

5. Create a model with an **Extract Bits** block that accepts the decimal number 65403 as the input and outputs the binary number [0111 1011].

6. Create a model with an **Extract Bits** block that accepts the decimal number 65403 as the input and outputs the binary number [1111].

7. Create a model with an **Extract Bits** block that accepts the decimal number 65403 as the input and outputs the binary number [111011].

8. Create a model with an **Extract Bits** block that accepts the decimal number 65403 as the input and outputs the binary number [11110111].

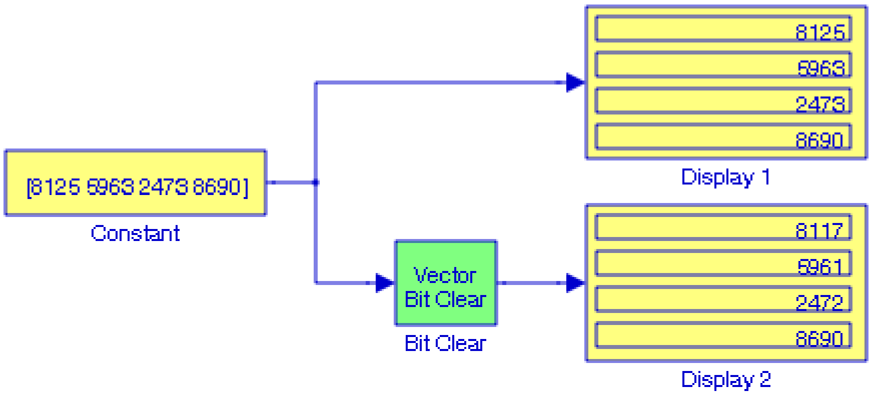
9. Create a model with a **Shift Arithmetic** block with inputs decimal +32.75 and decimal –48.875 to display the outputs when both of these numbers are shifted right by 3 bits and the binary point is shifted right by 2 bits.

* *For a detailed description of a full subtractor and other logic circuits please refer to Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–05–8*

6.6 Solutions to End–of–Chapter Exercises

1\.

The given vector is shown in the **Display 1** block and the converted vector in **Display 2** block.



For this model we have configured the blocks as follows:

Constant block – Constant value: [8125 5963 2473 8690] – Signal data types: int(32)

Clear bit block – Function block Parameters, Index bit: [3 1 0 2]

Display 1 and **Display 2** blocks, Format: decimal (Stored Integer)

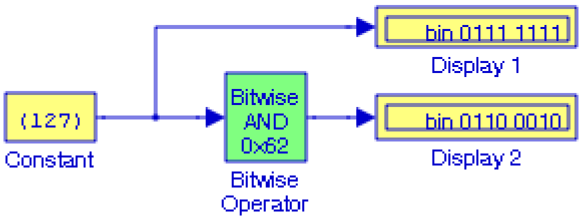
2\.

The model is shown below where the block are configured as follows:

Constant block – Constant value: [127] – Signal data types: uint(8)

Bitwise Operator block – Operator: AND – Use bit mask: Check mark – Bit Mask: $2^6 + 2^5 + 2^1$

Display 1 and **Display 2** blocks, Format: binary (Stored Integer)



3\.

The Truth table for a full subtractor digital circuit is shown below where X is the minuend, Y is the subtrahend, Z is the previous borrow, addition, D is the difference resulting from the of the present subtraction, and B is the present borrow.

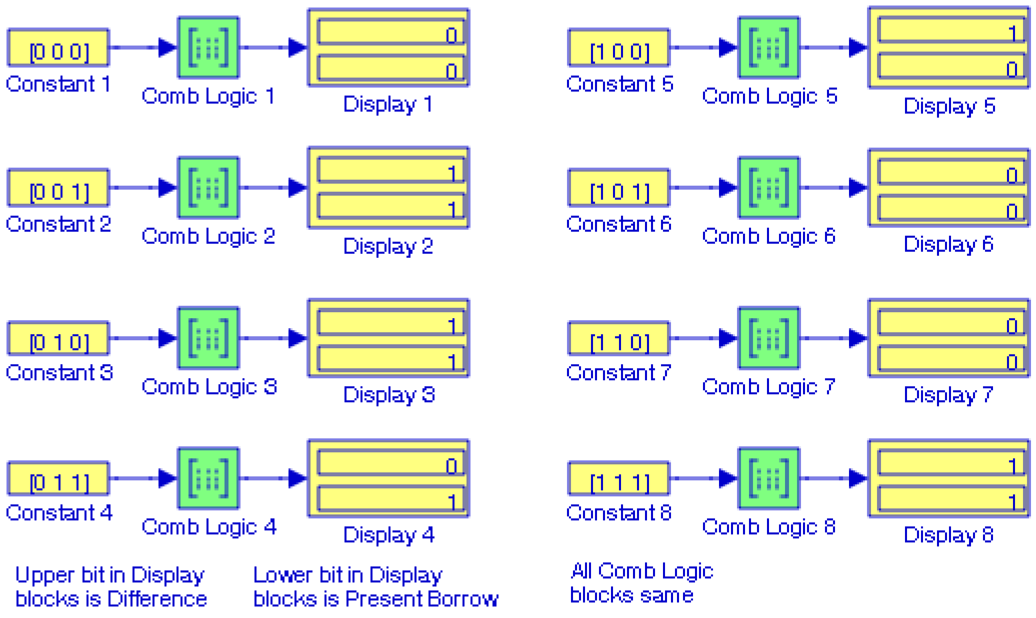
Inputs			Outputs	
X	Y	Z	D	B
0	0	0	0	0
0	0	1	1	1
0	1	0	1	1
0	1	1	0	1
1	0	0	1	0
1	0	1	0	0
1	1	0	0	0
1	1	1	1	1

The model is shown below where we have specified:

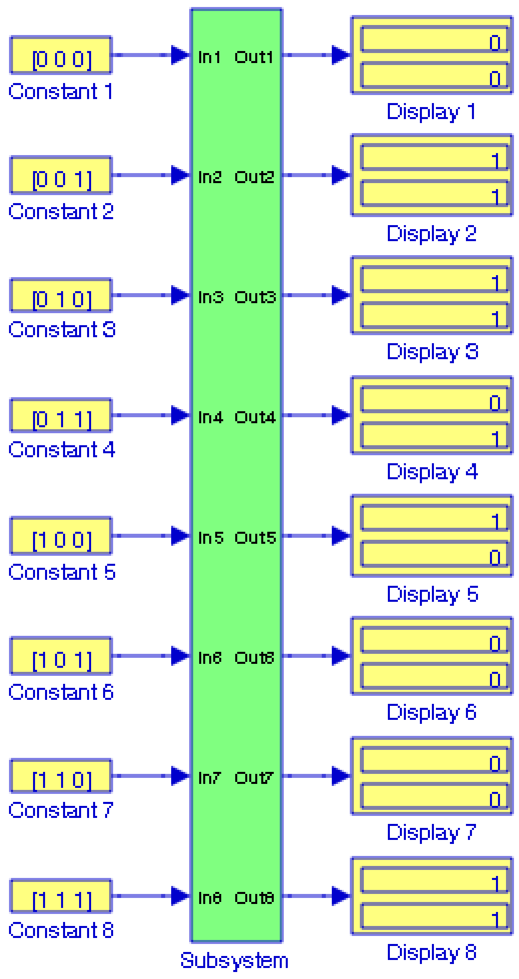
Constant blocks – Constant value: [0 0 0], [0 0 1], ... [1 1 1] in **Constant** blocks 1 through 8 respectively – Signal data types: boolean – Interpret vector parameters: check mark

Combinatorial Logic blocks (all) – Truth table: [0 0; 1 1; 1 1; 0 1; 1 0; 0 0; 0 0; 11] – Sample time: –1

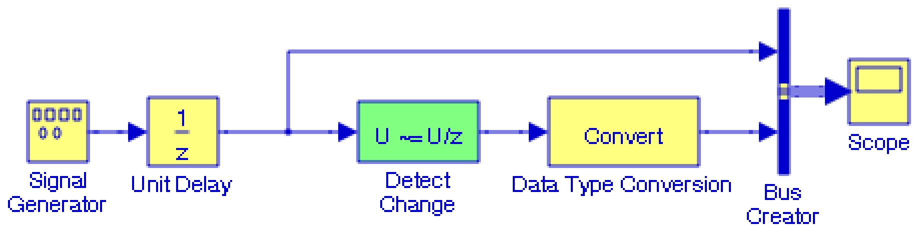
Display blocks – Format: short



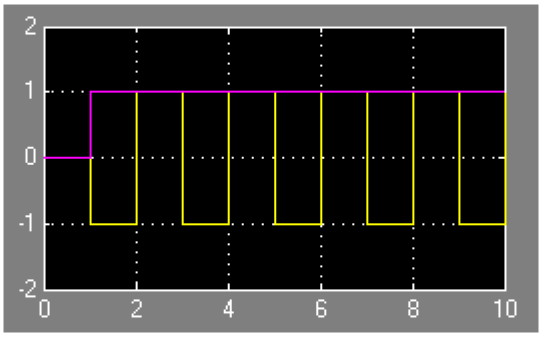
The model looks more presentable below where we lined–up the individual segments one below the other, we selected all **Combinatorial Logic** blocks, and from the **Edit** drop menu we selected **Create Subsystem**.



4.

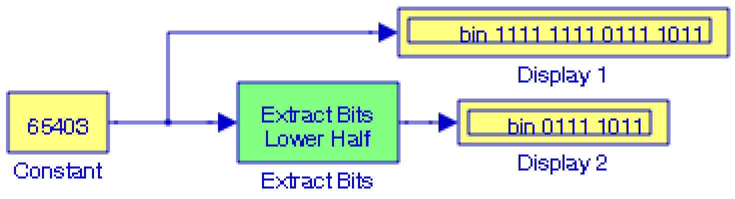


In the model above, the **Signal Generator** block is set to square waveform with amplitude 1 and frequency 0.5 Hz. The **Unit Delay** block is included to delay the **Signal Generator** block one time unit, the **Detect Change** block value was set to 0, and the **Convert** block is used to convert the output signal of the **Detect Change** block from uint(8) to double. The waveforms below indicate that the output waveform remains at a non–zero value for all $t > 1$ since the input changes repeatedly every time interval.



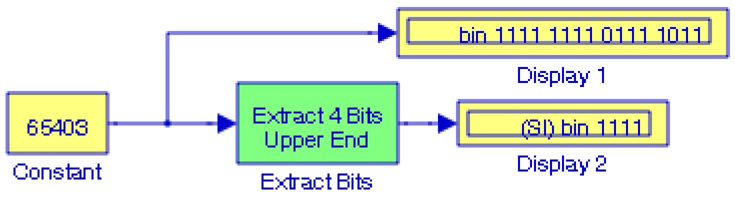
5.

The model is shown below where the **Constant** block is set for Signal data types – Output data type mode: uint16, the **Display 1** block shows the given decimal number in binary form, and the **Display 2** block shows the Lower Half of that binary number. Both **Display** blocks have been set for binary (Stored Integer) format.



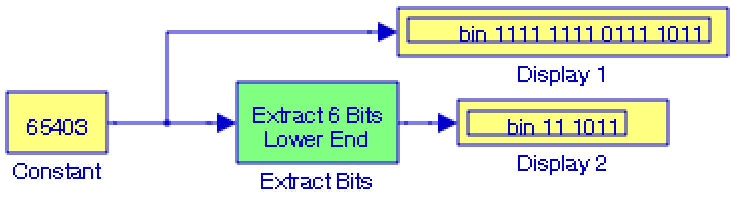
6.

The binary equivalent of the decimal number 65403 is 1111 1111 0111 1011 and since we want the output to be 1111, we select Range starting with most significant bit for the Bits to extract parameter, and specify 4 for the Number of bits parameter. The model is shown below.



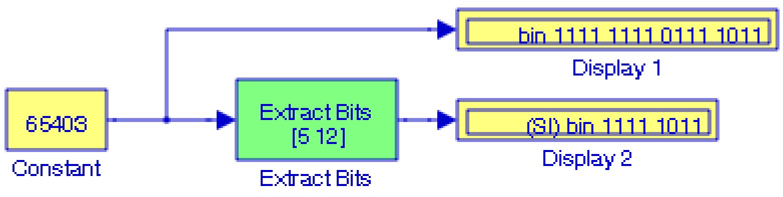
7.

The binary equivalent of the decimal number 65403 is 1111 1111 0111 1011 and since we want the output to be 111011, we select Range starting with least significant bit for the Bits to extract parameter, and specify 6 for the Number of bits parameter. The model is shown below.



8.

The binary equivalent of the decimal number 65403 is 1111 1111 0111 1011 and since we want the output to be 11110111, we select Range of bits for the Bits to extract parameter, and we specify [5 12] for the Bit indices parameter. The model is shown below.



9.

The model is shown below where the **Constant** blocks have been set for Output data type sfix(12) and the output scaling value 2^–3. Since it is specified that the bits and the binary point are to be shifted to the right, in the **Shift Arithmetic** block we enter positive values, that is, the values 3 and 2 respectively. All three display blocks are set for binary (Stored Integer) format. We can check the **Shift Arithmetic** block outputs as follows:

$$(+32.75)_{10} = (0001\ 0000\ 0.110)_2$$

and after shifting 3 bits to the right and the binary point 2 places to the right we obtain

$$0000\ 0010\ 0000$$

and the binary point is understood to be to the right of the least significant bit.

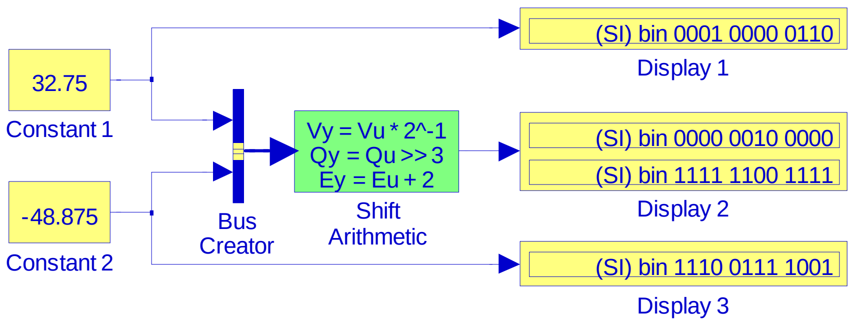
Likewise,

$$(-48.875)_{10} = (-0001\ 1000\ 0.111)_2 = (1110\ 0111\ 1.001)_{2s\ complement}$$

and after shifting 3 bits to the right and the binary point 2 places to the right we obtain

$$1111\ 1100\ 1111$$

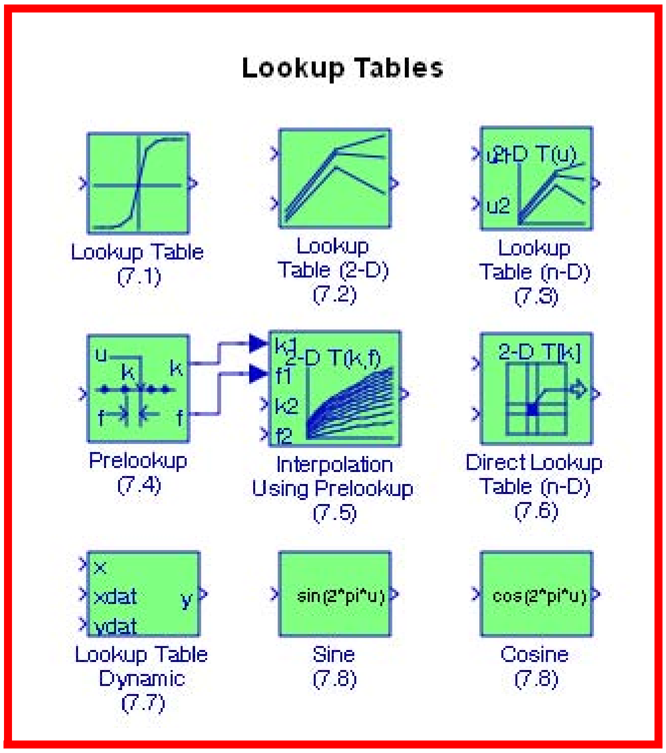
and the binary point is understood to be 2 places to the right of the least significant bit.



Chapter 7

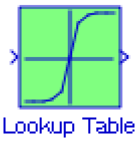
The Lookup Tables Library

This chapter is an introduction to the **Lookup Tables** library. This is the sixth library in the Simulink group of libraries and contains the blocks shown below. Their functions are illustrated with examples. The terminology *monotonically increasing* [*] is used throughout this chapter, and it is defined in the footnote below.



* *Monotonically increasing and monotonically decreasing sequences are sequences in which the successive values either consistently increase or decrease but do not oscillate in relative value. Each value of a monotonic increasing sequence is greater than, or equal to the preceding value; likewise, each value of a monotonic decreasing sequence is less than, or equal to the preceding value. Stated in other words, a monotonically increasing function is one resulting from a partially ordered domain to a partially ordered range such that* $x \le y$ *implies that* $f(x) \le f(y)$. *Likewise, a monotonically decreasing function is one resulting from a partially ordered domain to a partially ordered range such that* $x \le y$ *implies that* $f(x) \ge f(y)$.

7.1 The Lookup Table Block



The **Lookup Table** block computes an approximation to a function $y = f(x)$ where the data vectors x and y are given, and it is required that the x data vector must be monotonically increasing. Moreover, the length of the x and y data vectors must be the same. Please refer to the Help menu for this block for additional information. The **Lookup Table** icon displays a graph of the input vector versus the output vector. When a parameter is changed on the **Block Parameters** dialog box, the graph is automatically redrawn when we click on the Apply button.

To define a table, we specify the Vector of input values parameter as a $1 \times n$ vector and the Vector of output values parameter as another $1 \times n$. The block generates output based on the input values using one of these methods selected from the Look–up method parameter list:

1. *Interpolation–Extrapolation*—This is the default method; it performs linear interpolation and extrapolation of the inputs.

   If a value matches the block's input, the output is the corresponding element in the output vector. If no value matches the block's input, then the block performs linear interpolation between the two appropriate elements of the table to determine an output value. If the block input is less than the first or greater than the last input vector element, then the block extrapolates using the first two or last two points.

2. *Interpolation–Use End Values*—This method performs linear interpolation as described above but does not extrapolate outside the end points of the input vector. Instead, the end–point values are used.

The methods 3, 4, and 5 listed below neither interpolate nor extrapolate. Also, there is no difference among these methods when the input x corresponds exactly to table breakpoints.

3. *Use Input Nearest*—With this method the element in x nearest the current input is found. The corresponding element in y is then used as the output.

4. *Use Input Below*—With this method the element in x nearest and below the current input is found. The corresponding element in y is then used as the output. If there is no element in x below the current input, the nearest element is used.

5. *Use Input Above*—With this method the element in x nearest and above the current input is found. The corresponding element in y is then used as the output. If there is no element in x above the current input, the nearest element is used.

To create a table with step transitions, we repeat an input value with different output values.

Example 7.1

We will create a model with a Lookup Table block configured to use a vector of input values given by [1:5], and a vector of output values given by log([1:5]).[*]

The model is shown in Figure 7.1 where the Display 1 block shows the true values of the natural log for the range [1:5] and the Display 2 block shows the Lookup Table values for the same range of numbers. In the Constant block we have specified the range [1:5] and the Lookup Table block has been configured with Vector of input values [1:5], Vector output values log([1:5]), and Lookup method **Interpolation – Extrapolation**. The Math Function block is part of the Math Operations library, and it is described in Subsection 8.1.16, Chapter 8, Page 8.11.

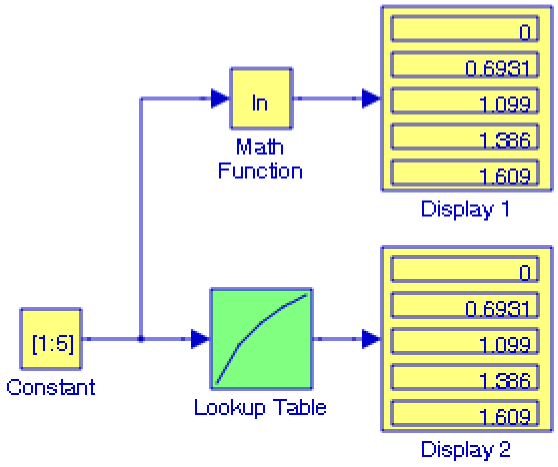
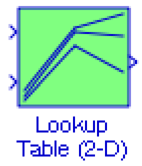


Figure 7.1. Model for Example 7.1

Another example using this block appears in the Simulink **Modeling Anti–Lock Braking System** demo. It can be accessed by typing sldemo_absbrake at the MATLAB command prompt.

7.2 The Lookup Table (2–D) Block



* *We recall that in MATLAB and Simulink log(x) implies the natural logarithm of x. The common (base 10) logarithm is denoted as log10(x).*

The **Lookup Table (2–D)** block computes an approximation for a function $z = f(x, y)$ when the data points x, y, and z are given. The Row index input values parameter is a $1 \times m$ vector of x data points, the Column index input values parameter is a $1 \times n$ vector of y data points, and the Matrix of output values parameter is an $m \times n$ matrix of z data points. Both the row and column vectors must be monotonically increasing. The block generates output based on the input values using one of these methods selected from the Look–up method parameter list:

Interpolation–Extrapolation — This is the default method; it performs linear interpolation and extrapolation of the inputs. If the inputs match row and column parameter values, the output is the value at the intersection of the row and column. If the inputs do not match row and column parameter values, then the block generates output by linearly interpolating between the appropriate row and column values. If either or both block inputs are less than the first or greater than the last row or column values, the block extrapolates using the first two or last two points.

Interpolation–Use End Values — This method performs linear interpolation as described above but does not extrapolate outside the end points of x and y. Instead, the end–point values are used.

Use Input Nearest — This method does not interpolate or extrapolate. Instead, the elements in x and y nearest the current inputs are found. The corresponding element in z is then used as the output.

Use Input Below — This method does not interpolate or extrapolate. Instead, the elements in x and y nearest and below the current inputs are found. The corresponding element in z is then used as the output. If there are no elements in x or y below the current inputs, then the nearest elements are found.

Use Input Above — This method does not interpolate or extrapolate. Instead, the elements in x and y nearest and above the current inputs are found. The corresponding element in z is then used as the output. If there are no elements in x or y above the current inputs, then the nearest elements are found.

Example 7.2

Consider the matrix

$$A = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 0 \end{bmatrix}$$

We will create a model using the **Lookup Table (2–D)** block to display the second element of the third row of the Inverse matrix of A .

The model is shown in Figure 7.2 where in the Lookup Table (2–D) block we have entered:

Row and Column index of input values: [1 2 3]

Vector of output values: inv(A)

Lookup method: Interpolation–Extrapolation

and at the MATLAB command prompt we have entered

```
A=[1 1–j 2; 1+j 3 j; 2 –j 0];
```

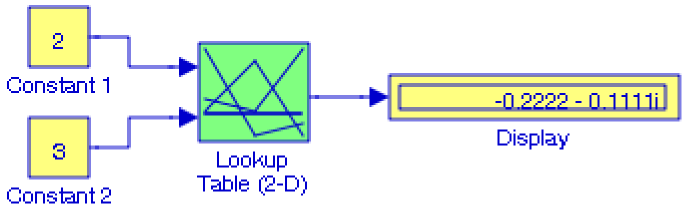


Figure 7.2. Model for Example 7.2

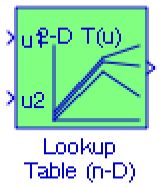
Check with MATLAB:

```
A =

   1.0000              1.0000 - 1.0000i   2.0000
   1.0000 + 1.0000i    3.0000             0 + 1.0000i
   2.0000              0 - 1.0000i        0
```

```
inv(A)

   0.1111 - 0.0000i   0.0000 + 0.2222i   0.5556 - 0.1111i
        0 - 0.2222i   0.4444 - 0.0000i  -0.2222 - 0.1111i
   0.5556 + 0.1111i  -0.2222 + 0.1111i  -0.1111
```

Another example using this block appears in the Simulink **Modeling an Automatic Transmission Controller** demo. It can be accessed by typing sldemo_absbrake at the MATLAB command prompt.

7.3 The Lookup Table (n−D) Block



The **Lookup Table (n−D)** block n−dimensional interpolated table lookup including index searches. The table is a sample representation of a function of N variables. Breakpoint sets relate the input values to the positions in the table. The first dimension corresponds to the top (or left) input port. Thus, the block generates an output value by comparing the block inputs with the breakpoint set parameters. The first input identifies the first dimension (row) breakpoints, the second breakpoint set identifies a column, the third a page, and so on.

Example 7.3

We will create a model using a **Lookup Table (n−D)** block with the following specifications:

Number of table dimensions: 2

First input (row) breakpoint set: x=[0 1 2 3 4 5];

Second input (column) breakpoint set: y=[0 1 2 3 4 5];

Index search method: Binary Search

Table data:

```
A=[0  1  2  3  4  5; 6  7  8  9  10  11; 12  13  14  15  16  17;...
18  19  20  21  22  23; 24  25  26  27  28  29; 30  31  32  33  34  35];
```

Interpolation and extrapolation method: Linear

The model is shown in Figure 7.3 where in the Lookup Table (n−D) block we have entered the following:

Number of table dimensions: 2

First input (row) breakpoint set: x

Second input (column) breakpoint set: y

Index search method: Binary Search

Table data: A

Interpolation and extrapolation method: Linear

At the In MATLAB command prompt we have entered:

```
x=[0  1  2  3  4  5]; y=[0  1  2  3  4  5];

A=[0  1  2  3  4  5; 6  7  8  9  10  11; 12  13  14  15  16  17;...
18  19  20  21  22  23; 24  25  26  27  28  29; 30  31  32  33  34  35];
```

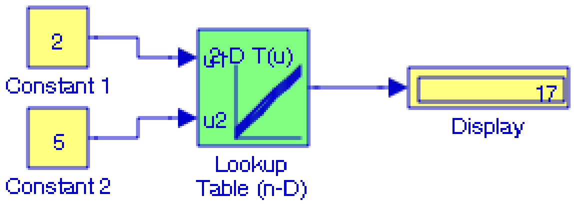


Figure 7.3. Model for Example 7.3

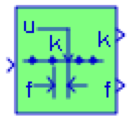
The Display block shows the value of the element located on Row 2 and Column 5. We can verify that with MATLAB by typing

```
A(3,6)

ans =
    17
```

The indices (2,5) in Simulink and (3,6) in MATLAB are same since Simulink uses zero–based indices whereas MATLAB uses one–based indices.

Another example using this block appears in the Simulink **Look Up Table Algorithm Selection** demo. It can be accessed by typing sldemo_tableplot at the MATLAB command prompt.

7.4 The PreLookup Index Search Block



Prelookup

The **PreLookup Index Search** block calculates the indices and interval fractions for the input value in the **Breakpoint data** parameter. This block is intended for use with the Interpolation (n–D) Using PreLookup block which is described in the next section.To use this block, we must define a set of breakpoint values. In normal use, this breakpoint data set corresponds to one dimension of a Table data parameter in an Interpolation (n–D) using PreLookup block. The block generates a pair of outputs for each input value by calculating the index of the breakpoint set element that is less than or equal to the input value and the resulting fractional value that is a number $0 \le f < 1$ that represents the input value's normalized position between the index and the next index value for in–range input.

Example 7.4

The breakpoint data in a **PreLookup Index Search** block are `[0 1 2 3 4 5 6 7 8 9]`. We will create a model to display the (index, fraction) pair denoted as k and f on the block when the input value u is 4.13.

The model is shown in Figure 7.4 where in the **Display** block the first value is the index, i.e., $k = 4$, and the second value is the fraction, i.e. $f = 0.13$

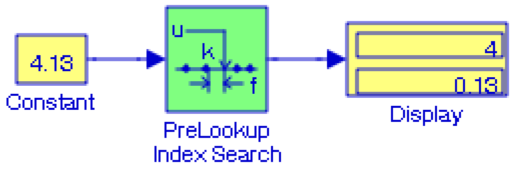
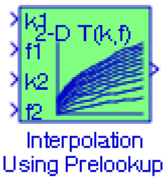


Figure 7.4. Model for Example 7.4

7.5 The Interpolation (n–D) Using PreLookup Block



The **Interpolation (n–D) Using PreLookup** block uses the precalculated indices and interval fractions from the **PreLookup Index Search** block to perform the equivalent operation that the **Lookup Table (n–D)** block performs. This block supports two interpolation methods: flat (constant) interval lookup and linear interpolation. These operations can be applied to 1–D, 2–D, 3–D, 4–D, and higher dimensioned tables. We define a set of output values as the Table data parameter. These table values must correspond to the breakpoint data sets that are in the PreLookup Index Search block. The block generates its output by interpolating the table values based on the (index, fraction) pairs fed into the block by each **PreLookup Index Search** block.

The block generates output based on the input values:

1. If the inputs match breakpoint parameter values, the output is the table value at the intersection of the row, column, and higher dimensions' breakpoints.
2. If the inputs do not match row and column parameter values, the block generates output by interpolating between the appropriate table values. If either or both block inputs are less than the first or greater than the last row or column parameter values, the block extrapolates from the first two or last two points in each corresponding dimension.

Example 7.5

We will create a model with an Interpolation (n–D) Using PreLookup block with two input indices representing the rows and columns of a square matrix and the output set to display the square root of a number in the range of integer numbers 1 through 100. For this example, we want to define the two inputs such that the output displayed will be the square root of 12.

We can form a 10×10 array with the row vector `a = [1 2 3 4 5 6 7 8 9 10]` and the column vector `b = [1 2 3 4 5 6 7 8 9 10]'` and multiplying these. The products are as shown below.

```
  1     2     3     4     5     6     7     8     9    10
  2     4     6     8    10    12    14    16    18    20
  3     6     9    12    15    18    21    24    27    30
  4     8    12    16    20    24    28    32    36    40
  5    10    15    20    25    30    35    40    45    50
  6    12    18    24    30    36    42    48    54    60
  7    14    21    28    35    42    49    56    63    70
  8    16    24    32    40    48    56    64    72    80
  9    18    27    36    45    54    63    72    81    90
 10    20    30    40    50    60    70    80    90   100
```

We can address any element of this array by indexing the rows and columns. Recalling that Simulink uses zero–based indexing, we can access the number 12 by the indices $(1, 5)$, $(2, 3)$, $(3, 2)$, or $(5, 1)$. The model is shown in Figure 7.5 where the indices for the Constant blocks are as shown, the Interpolation (n–D) Using PreLookup block has been set for

Number of table dimensions: 2

Table data: sqrt(a*b)

Interpolation and Extrapolation methods: Linear

and at the MATLAB command prompt we have entered

a=[1; 2; 3; 4; 5; 6; 7; 8; 9; 10]; b=a';

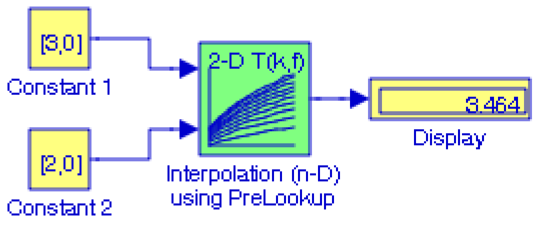
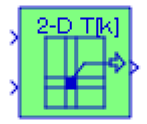


Figure 7.5. Model for Example 7.5

7.6 The Direct Lookup Table (n–D) Block



Direct Lookup Table (n-D)

The **Direct Lookup Table (n–D)** block uses its block inputs as zero–based indices into an n–D table. The number of inputs varies with the shape of the output desired. The output can be a scalar, a vector, or a 2–D matrix. The lookup table uses zero–based indexing, thus an input of 2 returns the third element in that dimension. We recall that MATLAB uses one–based indexing and thus an input of 2 returns the second element in that dimension.

We define a set of output values as the Table data parameter, and we specify whether the output shape is an element, a column, or a 2–D matrix. The first input specifies the zero–based index to the first dimension higher than the number of dimensions in the output, the second input specifies the index to the next table dimension, and so on, as illustrated in the Help menu for this block. The Help menus shows also the 15 different icons that this block displays depending on the options we choose in the block's dialog box.

To better understand the use of this block, let us review multi–dimensional arrays and illustrate with examples.

Let us consider the matrix A defined in MATLAB as

```
A=[1  2  3; 2  4 –5; 3 –5  6];
```

This is a two–dimensional array that uses two subscripts where the first references the row (1st dimension), and the second references the column (2nd dimension). Thus, A(3,3) is a two–dimensional array with 3 rows and 3 columns are displayed below.

```
A =
    1     2     3
    2     4    –5
    3    –5     6
```

A three–dimensional array adds another dimension to the two–dimensional array where the additional dimension is another page[*] behind the two–dimensional array. Thus for a 3×3 three–dimensional array with three pages the first page is displayed as

* *The term **page** used to describe the third dimension can be thought of as two or more two–dimensional arrays stacked one on top of another in the same way the pages of a closed book are stacked one on top of another. Dimensions higher than three can be created but it is not possible to visualize.*

$$\begin{bmatrix}(1,1,1) & (1,2,1) & (1,3,1)\\(2,1,1) & (2,2,1) & (2,3,1)\\(3,1,1) & (3,2,1) & (3,3,1)\end{bmatrix}$$

the second page is displayed as

$$\begin{bmatrix}(1,1,2) & (1,2,2) & (1,3,2)\\(2,1,2) & (2,2,2) & (2,3,2)\\(3,1,2) & (3,2,2) & (3,3,2)\end{bmatrix}$$

and the third page is displayed as

$$\begin{bmatrix}(1,1,3) & (1,2,3) & (1,3,3)\\(2,1,3) & (2,2,3) & (2,3,3)\\(3,1,3) & (3,2,3) & (3,3,3)\end{bmatrix}$$

It is to be noted that in a three–dimensional array the page number is indicated by the third index in each element of the array. For instance, the fourth page would contain the elements $(1,1,4)$, $(1,2,4)$, and so on.

Suppose that A is defined as

```
A=[1  2  3; –2  4  5; 3 –1  8];
```

and we want to add a third dimension to A by adding a second page with another matrix whose elements are $[4\ \ 5\ \ 6;\ \ -1\ \ 3\ \ 2;\ \ 7\ \ 8\ \ -2]$. The second page is defined as

```
A(:,:,2)=[4  5  6; –1  3  2; 7  8  –2]
```

Thus, at the MATLAB command prompt we type

```
A=[1  2  3; –2  4  5; 3  –1  8]; A(:,:,2)=[4  5  6;  –1  3  2; 7  8  –2];
```

and MATLAB outputs

```
A(:,:,1) =
     1     2     3
    -2     4     5
     3    -1     8

A(:,:,2) =
     4     5     6
    -1     3     2
     7     8    -2
```

Now suppose that we want to add a third page whose all elements have the same value, say 2. We enter

```
A(:,:,3)=2;
```

and when we type

```
A(:,:,3)=2
```

MATLAB displays

```
     2     2     2
     2     2     2
     2     2     2
```

Next let us consider the $3 \times 3 \times 3$ three–dimensional array

```
A(:,:,1)=[1 2 3; –2 4 5; 3 –1 8]; A(:,:,2)=[4 5 6; –1 3 2; 7 8 –2];...
A(:,:,3)=[2 4 –6; – 3 5 8; 7 9 –2]
```

and suppose that we want to convert it to a four–dimensional array. We enter

```
A(:,:,1)=[1 2 3; –2 4 5; 3 –1 8];
A(:,:,2)=[4 5 6; –1 3 2; 7 8 –2];
A(:,:,3)=[2 4 –6; – 3 5 8; 7 9 –2]
```

and MATLAB outputs

```
A(:,:,1,1) =
     0     0     0
     0     0     0
     0     0     0

A(:,:,2,1) =
     0     0     0
     0     0     0
     0     0     0

A(:,:,3,1) =
     0     0     0
     0     0     0
     0     0     0

A(:,:,1,2) =
     1     2     3
    -2     4     5
     3    -1     8

A(:,:,2,2) =
     4     5     6
    -1     3     2
     7     8    -2
```

```
A(:,:,3,2) =
      2      4     -6
     -3      5      8
      7      9     -2
```

We observe that `A(:,:,1,1)`, `A(:,:,2,1)`, and `A(:,:,3,1)` are padded with zeros to maintain the corresponding sizes of the dimensions.

The MATLAB User's Manual describes the procedure for generating arrays using MATLAB functions, and several examples are provided.

Let us suppose that we want to generate a four–dimensional array with 10 rows, 5 columns, 3 pages, with a fourth dimension and all elements are 2. The array that will satisfy this requirement is

```
a=ones(10,5,3,1)*2
```

and when this statement is executed, MATLAB displays

```
a(:,:,1) =
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
      2      2      2      2      2
```

Arrays a(:,:,2) and a(:,:,3) also display the same array.

The following example is similar to that in the Help menu for this block.

Example 7.6

We will create a model with a **Direct Lookup Table (n–D)** block with the four–dimensional array a=ones(10,3,4,3), to display the first column of the array a(:,:,4,3).

At the MATLAB command prompt we enter

```
a=ones(10,3,4,3); L=prod(size(a)); a(1:L)=[1:L]';
```

The model is shown in Figure 7.6 where in the **Direct Lookup Table (n–D)** block we have entered the following:

Number of table dimensions: 4

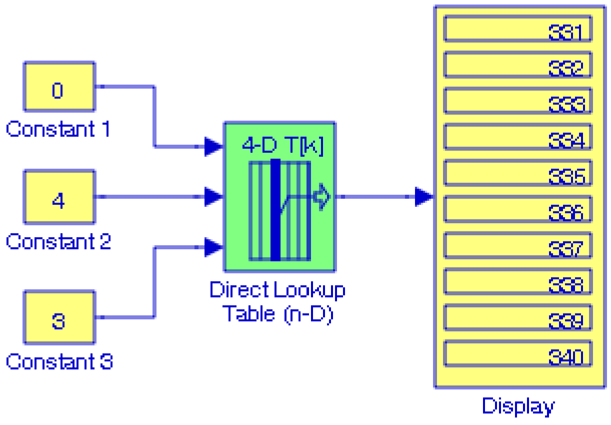


Figure 7.6. Model for Example 7.6

Input select this object from table: Column

Make table an input: unchecked

Table data: a

Constant 1 block: 0 (The Lookup table uses zero–based indexing so 0 is the index for the first column.

Constant 2 block: 4 (or uint16(3) if we wish to specify unassigned integer number)

Constant 3 block: 3 (or uint8(3) if we wish to specify unassigned integer number)

To verify the Display block in Figure 7.6, in MATLAB's Command Window we enter

```
a(:,:,4,3)
```

and MATLAB displays the array below.

```
331    341    351
332    342    352
333    343    353
334    344    354
335    345    355
336    346    356
337    347    357
338    348    358
339    349    359
340    350    360
```

To display the second or third column, in the Display 1 block we replace 0 with 1 or 2 as appropriate.

In addition to the **Lookup Table** blocks presented in this chapter, Simulink provides several interpolated thermocouple tables created from ITS–90 interpolating polynomials. These can be accessed by typing sldemo_tc_blocks at the MATLAB command prompt. For more information, we can link to:

http://www.mathworks.com/products/demos/shipping/simulink/sldemo_tc_script.html?product=SL

Example 7.7

It is given that a=ones(5,5,3,4,2); L=prod(size(a)); a(1:L)=[1:L]'; We will create a model to display the output corresponding to this array if the Input select this object from table is specified as 2–D Matrix.

The model is shown in Figure 7.7 where at the MATLAB command prompt we have entered:

```
a=ones(5,5,3,4,2); L=prod(size(a)); a(1:L)=[1:L]';
```

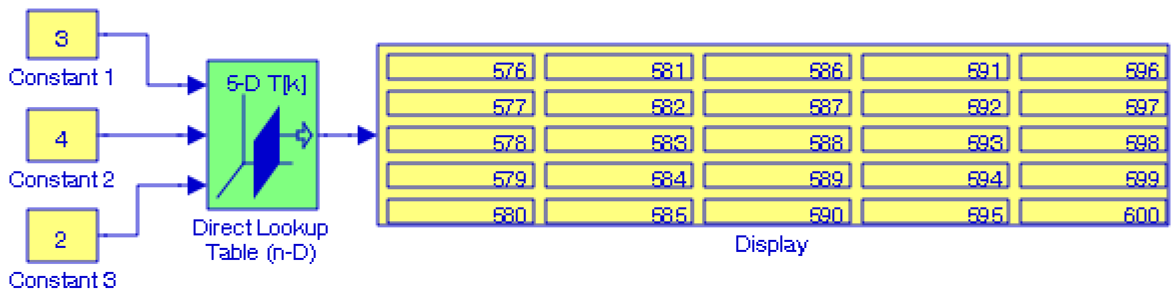


Figure 7.7. Model for Example 7.7

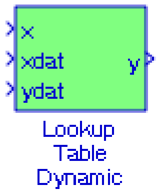
The values in the Display block of Figure 7.7 can be verified by typing

```
a(:,:,3,4,2)
```

at the MATLAB command prompt and MATLAB outputs the array below.

```
576    581    586    591    596
577    582    587    592    597
578    583    588    593    598
579    584    589    594    599
580    585    590    595    600
```

7.7 The Lookup Table Dynamic Block



The **Lookup Table Dynamic** block computes an approximation to some function $y = f(x)$ given x and y data vectors. The lookup method can use interpolation, extrapolation, or the original values of the input. Unlike the **Lookup Table** block, the **Lookup Table Dynamic** block allows us to change the table data without stopping the simulation. For example, we may want to automatically incorporate new table data if the physical system we are simulating changes.

There are certain restrictions in using this block. Please refer to the Help menu for this block.

Example 7.8

The square root of the numbers 50 through 56 is given in the table below. We will create a model with a Lookup Table Dynamic block to compute an approximation to $f(52.6)$.

x	50	51	52	53	54	55	56
$y = f(x) = \sqrt{x}$	7.071	7.141	7.211	7.280	7.348	7.416	7.483

The model is shown in Figure 7.8 where at the MATLAB command prompt we have entered:

```
xdata=[50  51  52  53  54  55  56];...
ydata=[7.07107  7.14143  7.21110  7.28011  7.34847  7.41620  7.48331];
```

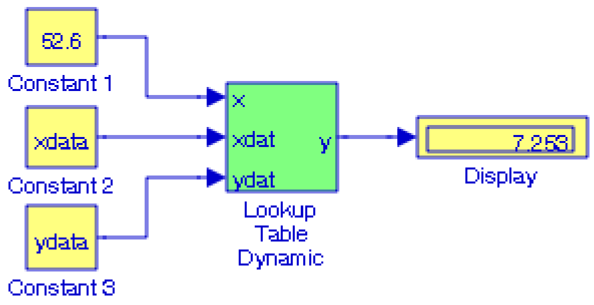
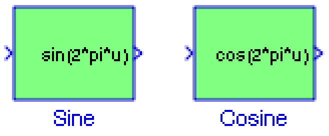


Figure 7.8. Model for Example 7.8

7.8 The Sine and Cosine Blocks



The **Sine and Cosine** blocks implement a sine and / or cosine wave in fixed point using a lookup table method that uses quarter wave symmetry. From Fourier series[*] textbooks we recall that:

1. Any waveform that repeats itself after some time, can be expressed as a series of harmonically related sinusoids, i.e., sinusoids whose frequencies are multiples of a *fundamental* frequency (or first harmonic). For example, a series of sinusoids with frequencies $1\ \text{MHz}$, $2\ \text{MHz}$, $3\ \text{MHz}$, and so on, contains the fundamental frequency of $1\ \text{MHz}$, a second harmonic of $2\ \text{MHz}$, a third harmonic of $3\ \text{MHz}$, and so on. In general, any periodic waveform $f(t)$ can be expressed as

$$\begin{aligned} f(t) = {} & \frac{1}{2}a_0 + a_1\cos\omega t + a_2\cos 2\omega t + a_3\cos 3\omega t + a_4\cos 4\omega t + \dots \\ & + b_1\sin\omega t + b_2\sin 2\omega t + b_3\sin 3\omega t + b_4\sin 4\omega t + \dots \end{aligned} \tag{7.1}$$

or

$$f(t) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty}(a_n\cos n\omega t + b_n\sin n\omega t) \tag{7.2}$$

where the first term $a_0/2$ is a constant, and represents the DC (average) component of $f(t)$. Thus, if $f(t)$ represents some voltage $v(t)$, or current $i(t)$, the term $a_0/2$ is the average value of $v(t)$ or $i(t)$.

The terms with the coefficients a_1 and b_1 together, represent the fundamental frequency component ω[†]. Likewise, the terms with the coefficients a_2 and b_2 together, represent the second harmonic component 2ω, and so on.

2. Odd functions have only sine terms.

3. Even functions have no sine terms.

4. If there is half–wave symmetry, only odd harmonics (sine and cosine) are present.

* *For a detailed discussion on Fourier series, please refer to Signals and Systems with MATLAB Computing and Simulink Modeling, ISBN 978–0–9744239–9–9.*

† *We recall that* $k_1\cos\omega t + k_2\sin\omega t = k\cos(\omega t + \theta)$ *where* θ *is a constant.*

Quarter–wave symmetry implies that a waveform contains only sine odd harmonics and these can be formed digitally with a series of zeros and ones.[*] With quarter–wave symmetry, we begin with a single quadrant, we copy it, we reverse the copy, we shift it by 90 degrees, we add it to the first quarter to obtain half of the waveform, and finally we copy the half waveform, we reverse it, we shift it by 180 degrees, and we add it to the first half too obtain the full waveform.

In Simulink, the Sine and Cosine block can output the following functions of the input signal, depending upon what we select for the Output formula parameter:

$$\sin(2\pi x)$$
$$\cos(2\pi x)$$
$$e^{i\pi x}$$
$$\sin(2\pi x) \text{ and } \cos(2\pi x)$$

We define the number of lookup table points in the Number of data points for lookup table parameter. The block implementation is most efficient when we specify the lookup table data points to be $2^n + 1$, where n is an integer. We use the Output word length parameter to specify the word length of the fixed–point output data type. The fraction length of the output is the output word length minus 2.

A function Lookup Table is a procedure by which we approximate a function by a table with a finite number of points (x,y). A tutorial on producing Lookup Tables in Simulink is presented in the Simulink Fixed Point User's Guide.

Simulink implements lookup tables that use breakpoints whose spacing is uneven, even, and power of two. For a comparison, please review the Simulink demo fxpdemo_approx_sin. To open the demo, we type at the MATLAB command prompt

```
fxpdemo_approx_sin
```

There are three fixed–point lookup tables in this model. All three lookup tables approximate the function $\sin 2\pi x$ over the first quadrant. All three achieve a worst–case error of less than 2^{-8}.

The example below illustrates the creation of a model using the **Repeating Stair Sequence** block described in the Sources Library, Section 15.2.13, Chapter 15, Page15–22, and the **Lookup Table** block described in this chapter.

[*] *Sinewaves with repeating long sequences of zeros and ones are referred to as "magic sinewaves". **They can be created with simple but extremely carefully chosen digitally switched pulses.***

Example 7.9

We will create a model using the uneven spacing fixed–point option of a **Lookup Table** block to approximate the function $\sin 2\pi x$ over the first quadrant. This function is approximated with the MATLAB script entered at the MATLAB command prompt as follows:

```
funcStr = 'sin(2*pi*x)';
xmin = 0;
xmax = 0.25;

xdt    = ufix(16);
xscale = 2^(–16);

ydt    = sfix(16);
yscale = 2^(–14);

errMax  = 2^(–8);
nPtsMax = 21;

rndMeth = 'Floor';

format long

[xuneven,yuneven] = fixpt_look1_func_approx(funcStr,...
  xmin,xmax,xdt,xscale, ydt,yscale,rndMeth,errMax,[]);
```

The model is shown in Figure 7.9 and the input and output waveforms in Figure 7.10. For the model of Figure 7.9, the **Configuration Parameters** are chosen as Type: Fixed–step, and Solver: Discrete (no continuous states). For the **Repeating Stair Sequence** block the Vector of output values was set as linspace(0, 0.25, 50). For the **Lookup Table** block the Vector of input values is specified as xuneven, the Table data is specified as yuneven, and the Lookup method is specified as Interpolation – Use End Values.

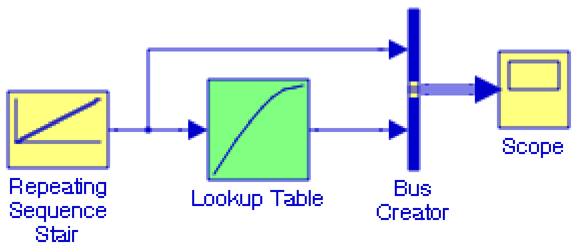


Figure 7.9. Model for Example 7.9

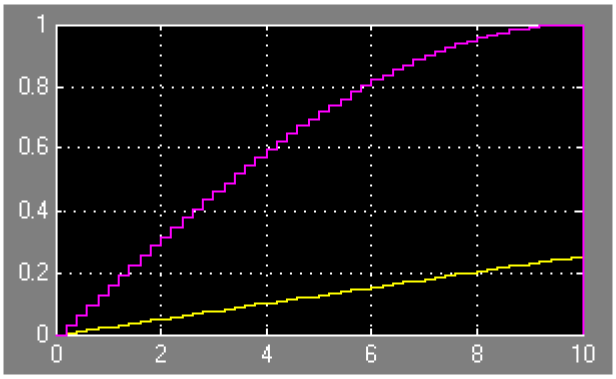


Figure 7.10. Input and output waveforms for the model in Figure 7.9

Another example using this block appears in the Simulink **Digital Waveform Generation: Approximating a Sine Wave** demo. It can be accessed by typing sldemo_tonegen at the MATLAB command prompt.

7.9 Summary

- A function Lookup Table is a procedure by which we approximate a function by a table with a finite number of points (x, y). Simulink implements lookup tables that use breakpoints whose spacing is uneven, even, and power of two. For a comparison, please review the Simulink demo fxpdemo_approx_sin. To view this demo, type at the MATLAB prompt

  ```
  fxpdemo_approx_sin
  ```

- The **Lookup Table** block computes an approximation to a function $y = f(x)$ where the data vectors x and y are given. The length of the x and y data vectors provided to this block must match. The length of the x and y data vectors provided to this block must match. It is required that the x data vector must be monotonically increasing. To create a table with step transitions, we repeat an input value with different output values.

- The **Lookup Table (2–D)** block computes an approximation for a function $z = f(x, y)$ when the data points x, y, and z are given. The Row index input values parameter is a $1 \times m$ vector of x data points, the Column index input values parameter is a $1 \times n$ vector of y data points, and the Matrix of output values parameter is an $m \times n$ matrix of z data points. Both the row and column vectors must be monotonically increasing.

- The **Lookup Table (n–D)** block evaluates a sampled representation of a function in N variables by interpolating between samples to give an approximate value for, even when the function is known only empirically. The block efficiently maps the block inputs to the output value using interpolation on a table of values defined by the block's parameters. Interpolation methods are flat (constant), linear, and cubic spline. We can apply any of these methods to 1–D, 2–D, 3–D, or higher dimensional tables.

- The **PreLookup Index Search** block calculates the indices and interval fractions for the input value in the Breakpoint data parameter. To use this block, we must define a set of breakpoint values. In normal use, this breakpoint data set corresponds to one dimension of a Table data parameter in an Interpolation (n–D) using PreLookup block. The block generates a pair of outputs for each input value by calculating the index of the breakpoint set element that is less than or equal to the input value and the resulting fractional value that is a number $0 \le f < 1$ that represents the input value's normalized position between the index and the next index value for in–range input.

- The **Interpolation (n–D) Using PreLookup** block uses the precalculated indices and interval fractions from the PreLookup Index Search block to perform the equivalent operation that the Lookup Table (n–D) performs. This block supports two interpolation methods: flat (constant) interval lookup and linear interpolation. These operations can be applied to 1–D, 2–D, 3–D, 4–D, and higher dimensioned tables.

- The **Direct Lookup Table (n–D)** block uses its block inputs as zero–based indices into an n–D table. The number of inputs varies with the shape of the output desired. The output can be a scalar, a vector, or a 2–D matrix. The lookup table uses zero–based indexing, thus an input of 2 returns the third element in that dimension. We recall that MATLAB uses one–based indexing and thus an input of 2 returns the second element in that dimension.
- The **Lookup Table Dynamic** block computes an approximation to some function $y = f(x)$ given x and y data vectors. The lookup method can use interpolation, extrapolation, or the original values of the input. Unlike the Lookup Table block, the Lookup Table Dynamic block allows us to change the table data without stopping the simulation.
- The **Sine and Cosine** blocks implement a sine and / or cosine wave in fixed point using a lookup table method that uses quarter wave symmetry. In Simulink, the Sine and Cosine block can output the following functions of the input signal, depending upon what we select for the Output formula parameter:

$$\sin(2\pi x) \qquad \sin(2\pi x) \qquad \cos(2\pi x) \qquad e^{i\pi x} \qquad \sin(2\pi x) \text{ and } \cos(2\pi x)$$

7.10 Exercises

1. Define a lookup table that will display a square waveform in the ranges $-2 < x < 2$ and $-1 < y < 1$.

2. Bessel functions* of the first kind are denoted as $J_n(x)$ where the subscript n indicates the order for $n = 0, 1, 2, 3, \ldots$. Thus, $J_0(x)$ denotes the zero order of the first kind of Bessel functions. Create a model with a Lookup Table block configured to display the values of x from 0 to 1.0 in steps of 0.1 for $J_0(x)$.

3. It is given that a=ones(5,5,3,4,2); L=prod(size(a)); a(1:L)=[1:L]'; Create a model to display the output corresponding to this array if the Input select this object from table is specified as column.

4. Create a model with an Interpolation (n–D) Using PreLookup block with two input indices representing the rows and columns of a square matrix and the output set to display the square root of a number in the range of integer numbers 1 through 100. For this example, we want to define the two inputs such that the output displayed will be the square root of 19.25.
   Hint: $19.25 = 3.5 \times 5.5$.

5. Consider the matrix

$$A = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 0 \end{bmatrix}$$

   Create a model using the Lookup Table (2–D) block to interpolate and display the value of the Inverse matrix of A at $(x, y) = (2.75, 5.25)$.

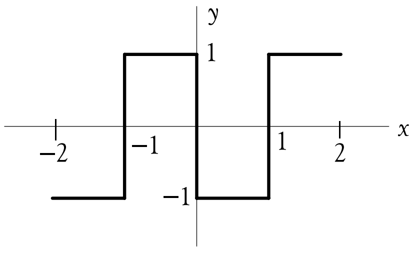
6. Using the data of the table below create a model with a Lookup Table Dynamic block to compute an approximation to $f(1.35)$.

x	1.1	1.2	1.5	1.7	1.8	2.0
y=f(x)	1.112	1.219	1.636	2.054	2.323	3.011

* *For a detailed discussion of Bessel functions, please refer to Numerical Analysis Using MATLAB and Excel, ISBN 978–1–934408–03–4.*

7.11 Solutions to End–of–Chapter Exercises

1.



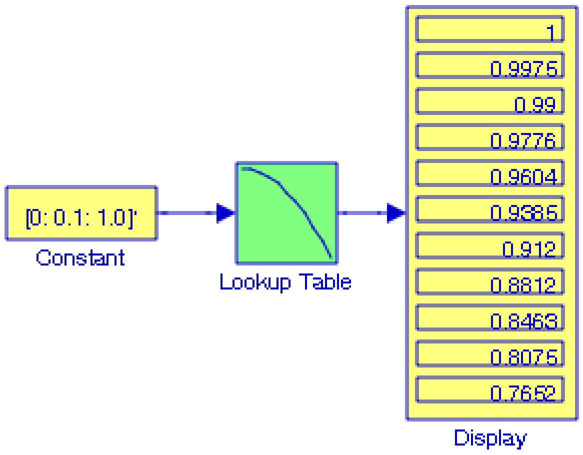
Vector x of input values: $-2 \quad -1 \quad -1 \quad 0 \quad 0 \quad 1 \quad 1 \quad 2$

Vector y of output values: $-1 \quad -1 \quad 1 \quad 1 \quad -1 \quad -1 \quad 1 \quad 1$

We observe that this waveform has three step discontinuities: at $x = -1$, $x = 0$, and $x = 1$.

2.

The model is shown below where in the **Constant** block we have entered the range [0:0.1:1.0], and in the **Lookup Table** block we have entered Vector of input values [0:0.1:1.0], Vector output values besselj(0, [0:0.0:1.0]'), and Lookup method Interpolation – Extrapolation.



3.

The model is shown below where we have entered:

Number of table dimensions: 5

Input select this object from table: Column

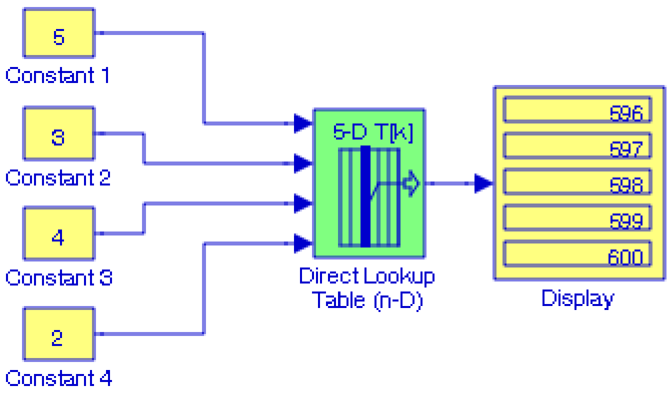
Make table an input: unchecked

Table data: a

Constant blocks: The values shown in the model

and at the MATLAB command prompt we have entered:

a=ones(5,5,3,4,2); L=prod(size(a)); a(1:L)=[1:L]';



To verify the Display block values, at the MATLAB command prompt we enter

a(:,:,3,4,2)

and MATLAB displays the array below.

```
   576    581    586    591    596
   577    582    587    592    597
   578    583    588    593    598
   579    584    589    594    599
   580    585    590    595    600
```

4.

The model is shown below where the PreLookup Index Search blocks 1 and 2 were set for:

Breakpoint data: [1 2 3 4 5 6 7 8 9 10]

Index search method: Linear Search

Process out of range input: Linear Extrapolation

We can form a 10×10 array with the row vector a = [1 2 3 4 5 6 7 8 9 10] and the column vector b = [1 2 3 4 5 6 7 8 9 10]' and multiplying these.

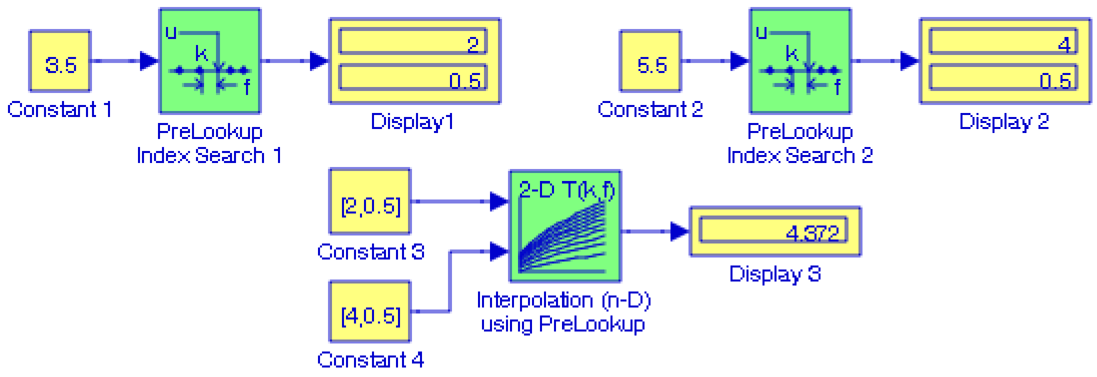
The Interpolation (n–D) Using PreLookup block has been set for

Number of table dimensions: 2

Table data: sqrt(a*b)

Interpolation and Extrapolation methods: Linear and at the MATLAB command prompt we enter

a=[1; 2; 3; 4; 5; 6; 7; 8; 9; 10]; b=a';



5.

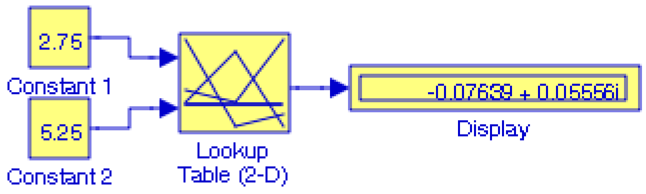
The model is shown below where Row and Column index of input values have been defined as [1 2 3] and [4 5 6] respectively.

Vector of output values: inv(A)

Lookup method: Interpolation–Extrapolation

and at the MATLAB command prompt we have entered

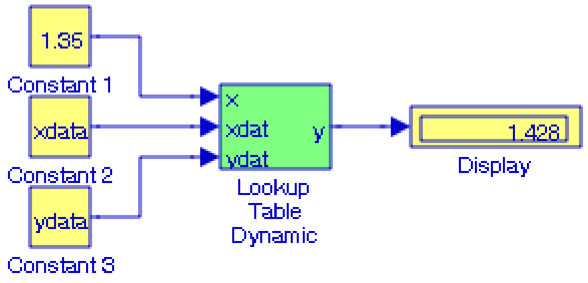
A=[1 1–j 2; 1+j 3 j; 2 –j 0];



6.

The model is shown below where at the MATLAB command prompt we have entered:

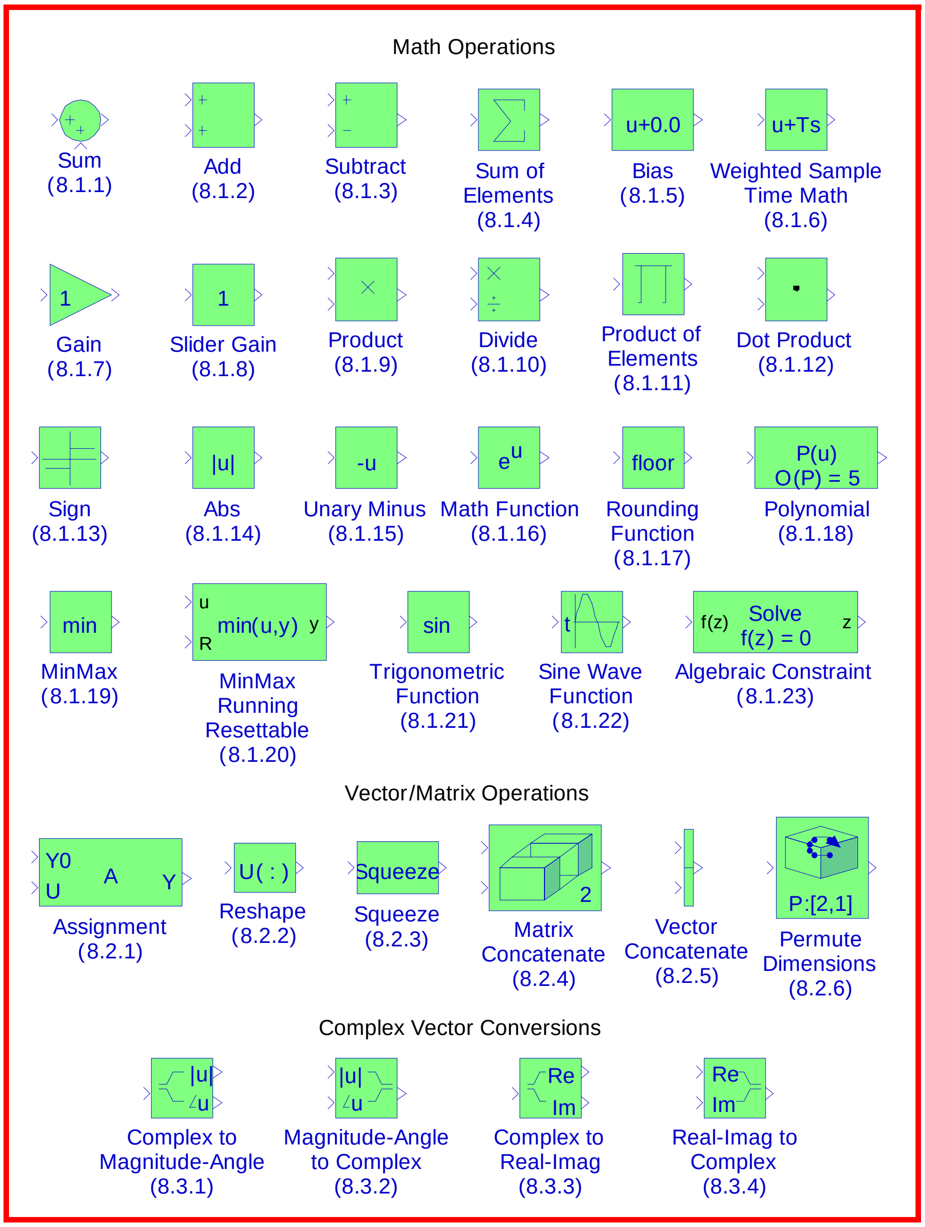
xdata=[1.1 1.2 1.5 1.7 1.8 2.0]; ydata=[1.112 1.219 1.636 2.054 2.323 3.011];



Chapter 8

The Math Operations Library

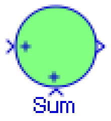
This chapter is an introduction to the **Math Operations** Library. This is the seventh library in the Simulink group of libraries and contains and contains the **Math Operations Group Sub–Library**, the **Vector / Matrix Operations Group Sub–Library**, and the **Complex Vector Conversions Group Sub–Library**. Their functions are illustrated with examples.



8.1 The Math Operations Group Sub–Library

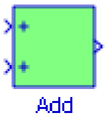
The **Math Operations Group Sub–Library** contains the blocks described in Subsections 8.1.1 through 8.1.23 below.

8.1.1 The Sum Block



The **Sum** block is an implementation of the **Add** block which is described in Section 8.1.2 below. We can choose the icon shape (round or rectangular) of the block on the **Block Parameters** dialog box.

8.1.2 The Add Block



The **Add** block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a single input vector. We specify the operations of the block with the **List of Signs parameter**. Plus (+), minus (–), and spacer (|) characters indicate the operations to be performed on the inputs. The spacer character creates extra space between ports on the block's icon.

If there are two or more inputs, then the number of characters must equal the number of inputs. For example, "+–+" requires three inputs and configures the block to subtract the second (middle) input from the first (top) input, and then add the third (bottom) input.

Example 8.1

The matrices A, B, and C are defined as shown. We will create a model using the **Add** block to display the result of $A + B - C$.

$$A = \begin{bmatrix} 1 & -1 & -4 \\ 5 & 7 & -2 \\ 3 & -5 & 6 \end{bmatrix} \quad B = \begin{bmatrix} 5 & 9 & -3 \\ -2 & 8 & 2 \\ 7 & -4 & 6 \end{bmatrix} \quad C = \begin{bmatrix} 4 & 6 & 1 \\ -3 & 8 & -2 \\ 5 & -2 & 3 \end{bmatrix}$$

The model is shown in Figure 8.1 where at the MATLAB command prompt we have entered

```
A=[1 –1 4; 5 7 –2; 3 –5 6]; B=[5 9 –3; –2 8 2; 7 –4 6]; C=[4 6 1; –3 8 –2; 5 –2 3];
```

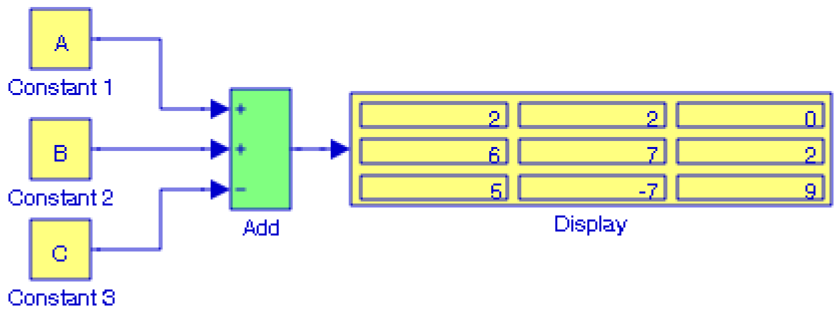
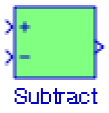


Figure 8.1. Model for Example 8.1

8.1.3 The Subtract Block



The **Subtract** block is an implementation of the **Add** block which is described in Subsection 8.1.2 above.

Example 8.2

Let $a = 1/(4+j3)$ and $b = 1/(2-j5)$. We will create a model using a Subtract block to perform the operation $a-b$.

The model is shown in Figure 8.27 where at the MATLAB command prompt we have entered

```
a=1/(4+3j); b=1/(2–5j);
```

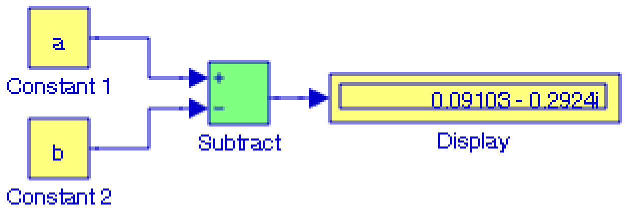
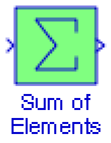


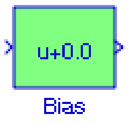
Figure 8.2. Model for Example 8.2

8.1.4 The Sum of Elements Block



The **Sum of Elements** block is an implementation of the **Add** block described in Subsection 8.1.2 above.

8.1.5 The Bias Block



The **Bias** block adds a bias (offset) to the input signal.

Example 8.3

We will create a model using a **Bias** block to display the waveform $y = \sin x + 1$.

The model is shown in Figure 8.3 and the input and output waveforms are shown in Figure 8.4 where for the **Bias block Block Parameters** dialog box we specified Bias: **1**

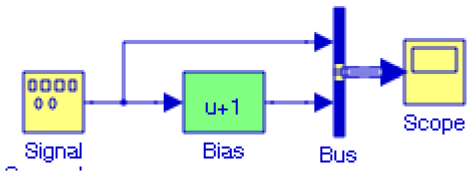


Figure 8.3. Model for Example 8.3

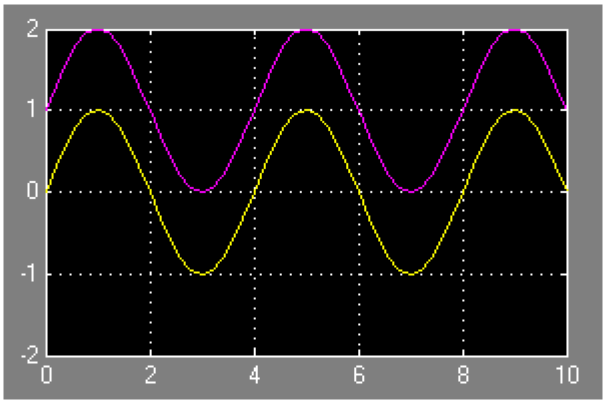
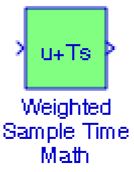


Figure 8.4. Input and output waveforms for the model in Figure 8.3

8.1.6 The Weighted Sample Time Math Block



The **Weighted Sample Time Math** block adds, subtracts, multiplies, or divides the input signal, u, by a weighted sample time Ts. We use the **Operation** parameter to specify the math operation. This block also allows us to use only the weight with either the sample time or its inverse. We enter the weighting factor in the **Weight** value parameter. If the weight is 1, w is removed from the equation.

Example 8.4

We will create a model using a **Weighted Sample Time Math** block where the input signal is a **Digital Clock** block specified at Sample time 1, and the **Weighted Sample Time Math** block **Operation** parameter is specified as **Divide** with **Weight** value 2.

The model is shown in Figure 8.5 and the input and output waveforms are shown in Figure 8.6.

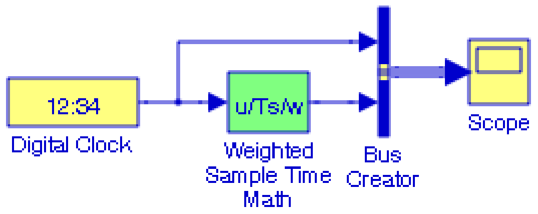


Figure 8.5. Model for Example 8.4

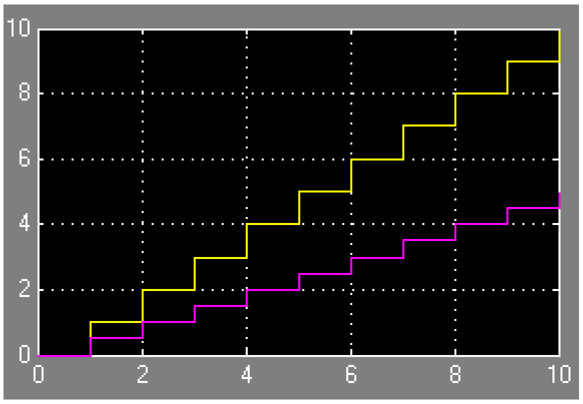
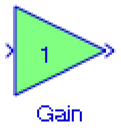


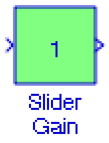
Figure 8.6. Input and output waveforms for the model in Figure 8.5

8.1.7 The Gain Block



The **Gain** block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix. This block is described in Section 2.10, Chapter 2, Page 2–18.

8.1.8 The Slider Gain Block



The **Slider Gain** block is used to vary a scalar gain during a simulation. The default for the lower limit is 0, and the default for the upper limit is 2.

Example 8.5

We will create a model using a **Slider Gain** block to display the input and output sinusoidal waveforms when the **Slider Gain** block has been specified as 0.5.

The model is shown in Figure 8.7 and the input and output waveforms are shown in Figure 8.8.

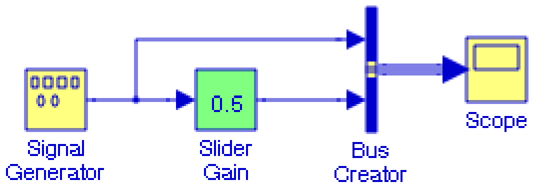


Figure 8.7. Model for Example 8.5

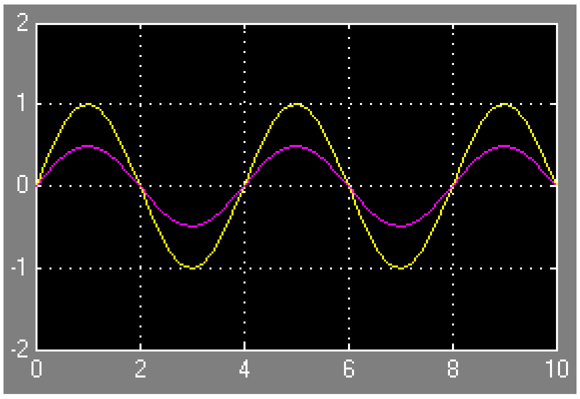
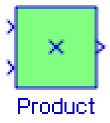


Figure 8.8. Input and output waveforms for the model in Figure 8.7

8.1.9 The Product Block



The **Product** block performs multiplication or division of its inputs. This block is described in Section 2.4, Chapter 2, Page 2–6. To perform a dot product on input vectors, we use the **Dot Product** block described in Section 8.1.12, this chapter, Page 8–8.

Example 8.6

We will create a model using a **Product** block to perform element–by–element multiplication of the row vectors `a = [1 2 3 4 5]` and `b = [–2 6 –3 8 7]`.

The model is shown in Figure 8.9 where at the MATLAB command prompt we have entered

```
a=[1 2 3 4 5]; b=[–2 6 –3 8 7];
```

and the **Product** block **Multiplication** has been specified as element–wise.

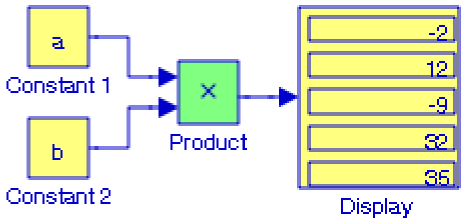
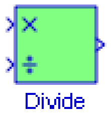


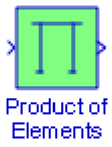
Figure 8.9. Model for Example 8.6

8.1.10 The Divide Block



The **Divide** block is an implementation of the **Product** block. The **Product** block is described in Section 2.4, Chapter 2, Page 2–6.

8.1.11 The Product of Elements Block



The **Product of Elements** block is used to multiply of divide inputs. It is essentially a **Product** block. The **Product** block is described in Section 2.4, Chapter 2, Page 2–6.

Example 8.7

We will create a model using the Product of Elements block to compute the product $a \cdot b$ where

$$a = [1 \quad 0 \quad -3 \quad 0 \quad 5 \quad 7 \quad 9]$$
$$b = [2 \quad -8 \quad 0 \quad 0 \quad 4 \quad 10 \quad 12]$$

The model is shown in Figure 8.10 where at the MATLAB command prompt we have entered

```
a=[1  0 –3  0  5  7  9]; b=[2 –8  0  0  4  10  12];
```

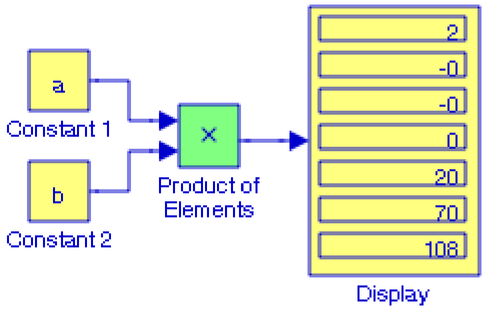
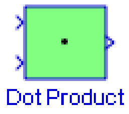


Figure 8.10. Model for Example 8.7

8.1.12 The Dot Product Block



The **Dot Product** block generates the dot product of its two input vectors. The scalar output, y, is equal to the MATLAB operation y=sum(conj(A.*B)) where vectors A and B are defined as $A = [a_1 \;\; a_2 \;\; \dots \; a_n]$, $B = [b_1 \;\; b_2 \;\; \dots \; b_n]$, and $A*B=[a_1b_1 + a_2b_2 + \;\; \dots \; + a_n \, b_n]$

Example 8.8

We will create a model using a **Dot Product** block to perform the dot (inner) product of the row vectors $A = [1 \;\; 2 \;\; 3 \;\; 4 \;\; 5]$ and $B = [-2 \quad 6 \quad -3 \;\; 8 \;\; 7]$.

The model is shown in Figure 8.11 where at the MATLAB command prompt we have entered

```
A=[1  2  3  4  5]; B=[–2  6  –3  8  7];
```

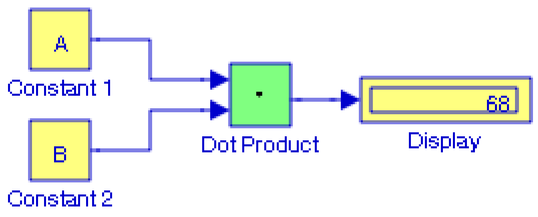
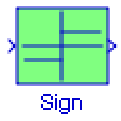


Figure 8.11. Model for Example 8.8

8.1.13 The Sign Block



The **Sign** block, also referred to as the Signum* block, indicates the sign of the input. The output is 1 when the input is greater than zero, the output is 0 when the input is equal to zero, and the output is –1 when the input is less than zero.

Example 8.9

We will create a model using the **Sign** block to determine whether the expression

$$x = \frac{1}{(-0.224)^7} + \frac{2}{(0.294)^8} - \frac{3}{(0.484)^2}$$

is positive, zero, or negative.

Solution:

The model is shown in Figure 8.12 where at the MATLAB command prompt we have entered

```
x=1/(–0.224)^7+2/(0.294)^8–3/(0.484)^2;
```

MATLAB outputs the value $x = 477.786$ and thus the Sign block outputs 1 indicating a positive value.

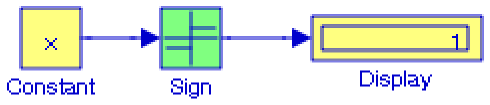
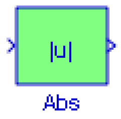


Figure 8.12. Model for Example 8.9

* *The signum function is an elementary function in Signals and Systems. The derivation of the Fourier transform of the unit step function is based on this function. For a detailed discussion, please refer to Signals and Systems with MATLAB Computing and Simulink Modeling, ISBN 978–0–9744239–9–9.*

Additional examples using the **Sign** block appear in the Simulink **Modeling Anti–Lock Braking System** demo, the **Building a Clutch Lock–Up Model** demo, and the **Friction Model with Hard Stops** demo. They can be accessed by typing sldemo_absbrake, sldemo_clutch, and sldemo_hardstop respectively at the MATLAB command prompt.

8.1.14 The Abs Block



The **Abs** block outputs the absolute value of the input. This block accepts real signals of any data type supported by Simulink, except Boolean, and supports real fixed–point data types. The block also accepts complex single and double inputs. Outputs are a real value of the same data type as the input.

When the **Saturate on integer overflow** is selected, the block maps signed integer input elements corresponding to the most negative value of that data type to the most positive value of that data type. Thus, if the input is x and the signal data type is specified as int8 for the interval $-127 \le x \le 0$, the output is the absolute value of the input, but when the input is -128, the output displayed is 127. Likewise, if the input signal data type is specified as int16, for the input -32768, the output is 32767, and if the input signal data type is specified as int32, for the input -2147483648, the output is 2147483647.

When the **Saturate on integer overflow** is not selected, the block ignores signed integer input elements and outputs the absolute value of the input.

If the input is a complex number, the signal data type must be specified either as single or double.

Example 8.10

We will create a model using the **Abs** block to display the absolute value of the product

$$(-3-j4)\times(5-j8)$$

The model is shown in Figure 8.13 where the input signal type is specified as Inherit: same as input.

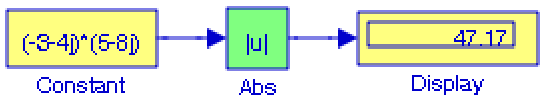
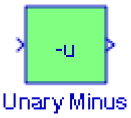


Figure 8.13. Model for Example 8.10

8.1.15 The Unary Minus Block



The **Unary Minus** block negates the input. The block accepts only signed data types. For signed data types, we cannot accurately negate the most negative value since the result is not representable by the data type. In this case, the behavior of the block is controlled by the Saturate to max or min when overflows occur check box in the Block Parameters dialog box. If selected, the most negative value of the data type wraps to the most positive value. If not selected, the operation has no effect. If an overflow occurs, then a warning is returned to the MATLAB command line.

Example 8.11

We will create a model using a **Unary Minus** block to negate the number 101101101 .

The model is shown in Figure 8.14 where the Signal data types for the **Constant** block is set to Inherit from constant value, and the **Display** block is set for Binary (Stored Integer).

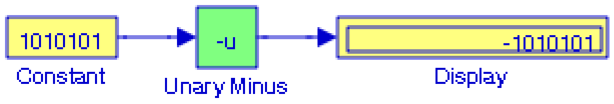
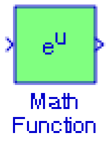


Figure 8.14. Model for Example 8.11

8.1.16 The Math Function Block



The **Math Function** block performs the following 15 mathematical functions:

exp

log

10^u

log10

magnitude^2

square

sqrt

pow (power)

conj (complex conjugate)

reciprocal

hypot (computation of the square root of the sum of squares)

rem (remainder after division)

mod (modulus after division)*

transpose (transpose of a vector or matrix)

hermitian (a square matrix such that $A^{T*} = A$)

The block output is the result of the operation of the function on the input or inputs. The name of the function appears on the block. Simulink automatically draws the appropriate number of input ports. We should use the **Math Function** block instead of the **Fcn block** when we want vector or matrix output, because the **Fcn block** produces only scalar output. For data types supported, please refer to the Help menu for this block.

Example 8.12

We will create a model with a Hermitian block to output the output the Hermitian matrix of A defined as

$$A = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 0 \end{bmatrix}$$

The model is shown in Figure 8.15 where at the MATLAB command prompt we entered

```
A=[1  1–j  2; 1+j  3  j; 2  –j  0];
```

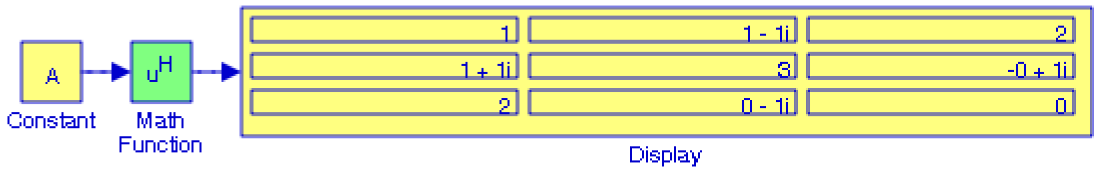


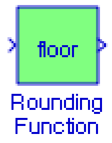
Figure 8.15. Model for Example 8.12

Check:

$$A = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 0 \end{bmatrix} \qquad A^T = \begin{bmatrix} 1 & 1+j & 2 \\ 1-j & 3 & -j \\ 2 & j & 0 \end{bmatrix} \qquad A^{T*} = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 0 \end{bmatrix} = A$$

* *For differences between **rem** and **mod** we type help rem and help mod at the MATLAB command prompt.*

8.1.17 The Rounding Function Block



The **Rounding Function** block applies a rounding function to the input signal to produce the output signal. The name of the selected function appears on the block where floor rounds each element of the input signal to the nearest integer value towards minus infinity, ceil rounds each element of the input signal to the nearest integer towards positive infinity, round rounds each element of the input signal to the nearest integer, and fix rounds each element of the input signal to the nearest integer towards zero.

Example 8.13

We will create a model using the **Rounding Function** block to round the number 3.495 towards minus infinity, towards positive infinity, to the nearest integer, and to the nearest integer towards zero.

The model is shown in Figure 8.16 where floor rounds the given number to the nearest integer value towards minus infinity, ceil rounds it to the nearest integer towards positive infinity, round rounds it to the nearest integer, and fix rounds it to the nearest integer towards zero.

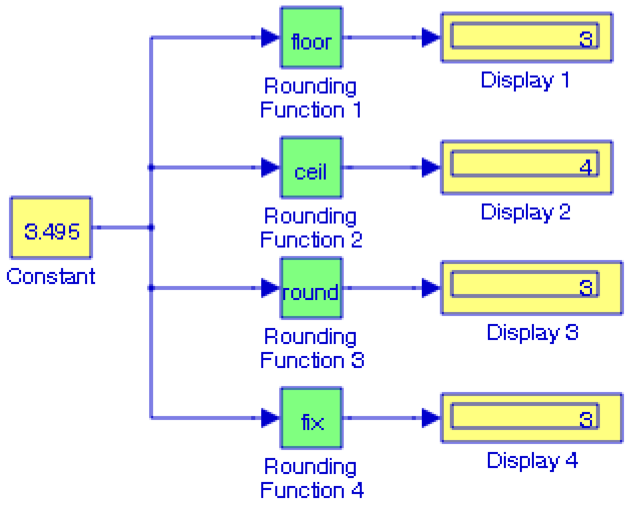
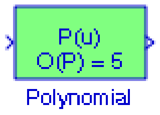


Figure 8.16. Model for Example 8.13

8.1.18 The Polynomial Block



The **Polynomial** block uses a coefficients parameter to evaluate a real polynomial for the input value. We define a set of polynomial coefficients in the form accepted by the MATLAB **polyval** command. The block then calculates P(u) for the input u. Inputs and coefficients must be real.

Example 8.14

We will create a model using the **Polynomial** block to evaluate the polynomial

$$p(x) = x^6 - 3x^5 + 5x^3 - 4x^2 + 3x + 2$$

at $x = -3.7$.

The model is shown in Figure 8.17 where at the MATLAB command prompt we have entered the coefficients of $p(x)$, i.e.,

```
px=[1 –3 0 5 –4 3 2];
```

and in the **Parameters** dialog box for the **Polynomial** block we have typed px.

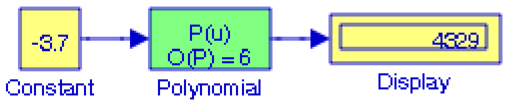
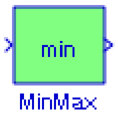


Figure 8.17. Model for Example 8.14

Another example using the **Polynomial** block appears in the Simulink **Type S Thermocouple Mode** demo. It can be accessed by typing sldemo_tc at the MATLAB command prompt.

8.1.19 The MinMax Block



The **MinMax** block outputs either the minimum or the maximum element or elements of the inputs. We choose the function to apply by selecting one of the choices from the Function parameter list. If the block has one input port, the input must be a scalar or a vector. The block outputs a scalar equal to the minimum or maximum element of the input vector. If the block has multiple input ports, the non–scalar inputs must all have the same dimensions. The block expands any scalar inputs to have the same dimensions as the non–scalar inputs. The block outputs a signal having the same dimensions as the input. Each output element equals the minimum or maximum of the corresponding input elements.

Example 8.15

We will create a model using a **MinMax** block to display smallest and the largest numbers in the row vector

```
a = [1  −1  −4  5  7  −2  3  −5  6  9  −3  8  2  4  8  5]
```

The model is shown in Figure 8.18 where at the MATLAB command prompt we have entered

```
a=[1 −1 −4 5 7 −2 3 −5 6 9 −3 8 2 4 8 5];
```

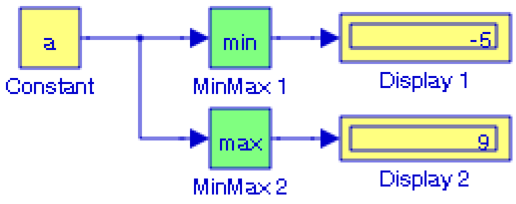
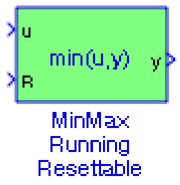


Figure 8.18. Model for Example 8.15

8.1.20 The MinMax Running Resettable Block



The **MinMax Running Resettable** block outputs the minimum or maximum of all past inputs u. We specify whether the block outputs the minimum or the maximum with the Function parameter. The block can reset its state based on an external reset signal R. When the reset signal R is TRUE, the block resets the output to the value of the Initial condition parameter.

Example 8.16

Let the input u in a MinMax Running Resettable block be

```
u = [1  −1  −4  5  7  −2  3  −5  6  9  −3  8  2  4  8  5]
```

We will create a model that will display all positive values of u and will display all negative values of u.

The model is shown in Figure 8.19 where at the MATLAB command prompt we have entered u=[1 –1 –4 5 7 –2 3 –5 6 9 –3 8 2 4 8 5];

and the initial conditions in both MinMax Running Resettable blocks is set to zero.

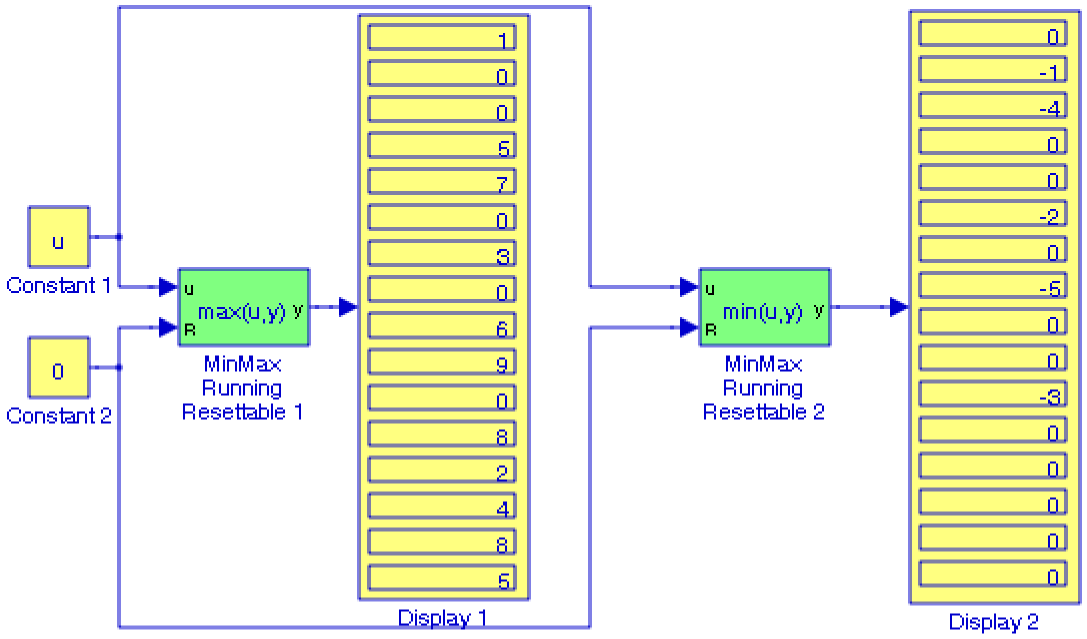
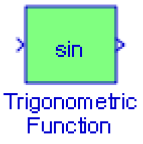


Figure 8.19. Model for Example 8.16

8.1.21 The Trigonometric Function Block



The **Trigonometric Function** block performs the principle trigonometric functions sine, cosine, and tangent, the Inverse trigonometric functions asin, acos, atan, and atan2*, the hyperbolic functions sinh, cosh, and tanh, and the Inverse hyperbolic functions asinh, acosh, and atanh. The block output is the result of the operation of the function on the input or inputs. The name of the function appears on the block. If we select the atan2 function, the block displays two inputs. The first (upper) input is the y–axis or complex part of the function argument. The second (lower) input is the x–axis or real part of the function argument.

* *The trigonometric function atan2(y,x) is referred to as the four–quadrant inverse tangent whereas atan is referred to as the two–quadrant inverse tangent. We recall that for* $-\infty < x < \infty$, $-\pi/2 < \operatorname{atan} x < \pi/2$ *and thus the two–quadrant atan(x) returns the inverse tangent in the range* $[-\pi/2, \pi/2]$. *The four–quadrant atan2(y,x) returns the inverse tangent in the range* $[-\pi, \pi]$.

We should use the **Trigonometric Function** block instead of the **Fcn** block when we want dimensionalized output, because the **Fcn** block can produce only scalar output.

Example 8.17

We will create a model to display the values of the hyperbolic functions *sinhx* and *coshx* for $x = 9.5$.

The model is shown in Figure 8.20.

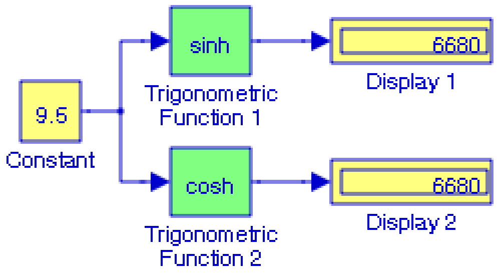


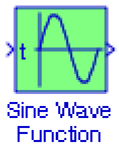
Figure 8.20. Model for Example 8.17

We recall that

$$\sinh x = \frac{e^x - e^{-x}}{2} \qquad \cosh x = \frac{e^x + e^{-x}}{2}$$

and thus for $x » 0$, $\sinh x \approx \cosh x \approx \frac{1}{2}e^x$

8.1.22 The Sine Wave Function Block



The **Sine Wave Function** block generates a sinusoid. The block can operate in either time–based or sample–based mode. The time–based mode has two submodes: continuous mode or discrete mode. The value of the Sample time parameter determines whether the block operates in continuous mode or discrete mode. Thus, zero (the default) causes the block to operate in continuous mode and a value greater than zero causes the block to operate in discrete mode.

Example 8.18

We will create a model using two **Sine Wave Function** blocks, one to display the waveform operating in the continuous mode, and the other to display the waveform operating in the discrete mode.

The model is shown in Figure 8.21 and the waveforms in Figure 8.22 where the frequency of the **Sinewave Function 1** block was specified as 2.5 Hz, the Digital Clock block was specified for sample time 2.5, the Sine type in the **Sinewave Function 2** block was selected as Sample based, and the Time as Use external signal.

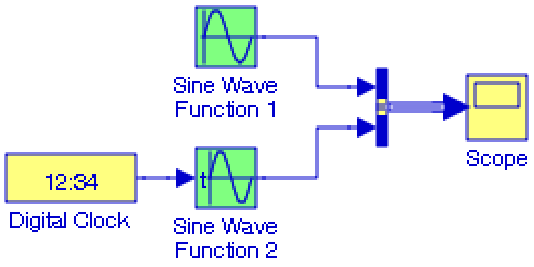


Figure 8.21. Model for Example 8.18

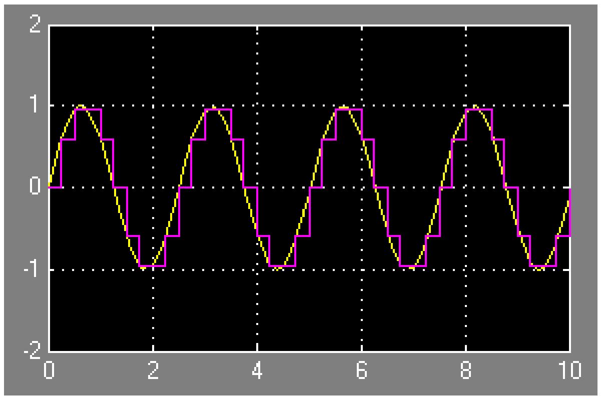
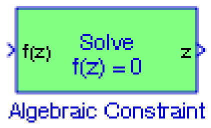


Figure 8.22. Output waveforms for the model of Figure 8.21

8.1.23 The Algebraic Constraint Block



The **Algebraic Constraint** block constrains the input signal $f(z)$ to zero and outputs an algebraic state z. The block outputs the value necessary to produce a zero at the input. The output must affect the input through a feedback path. This block accepts and outputs real values of type double.

An example using this block was presented in Chapter 1 as Example 1.3. Another example is given below.

Example 8.19

We will create a model using an **Algebraic Constraint** block to find a solution for the non–linear equation

$$F(z) = z^2 + 4z + 3 + \sin z - z\cos z$$

The model is shown in Figure 8.23 where in the **Algebraic Constraint** block the Initial guess value entered is -1. The z^2 term is represented by the u^2 block from the **Math Function** block and the sine and cosine blocks from the **Trigonometric Function** block both of which are blocks within the **Math Operations** library. We observe that all inputs are feedbacks from the output of the **Algebraic Constraint** block.

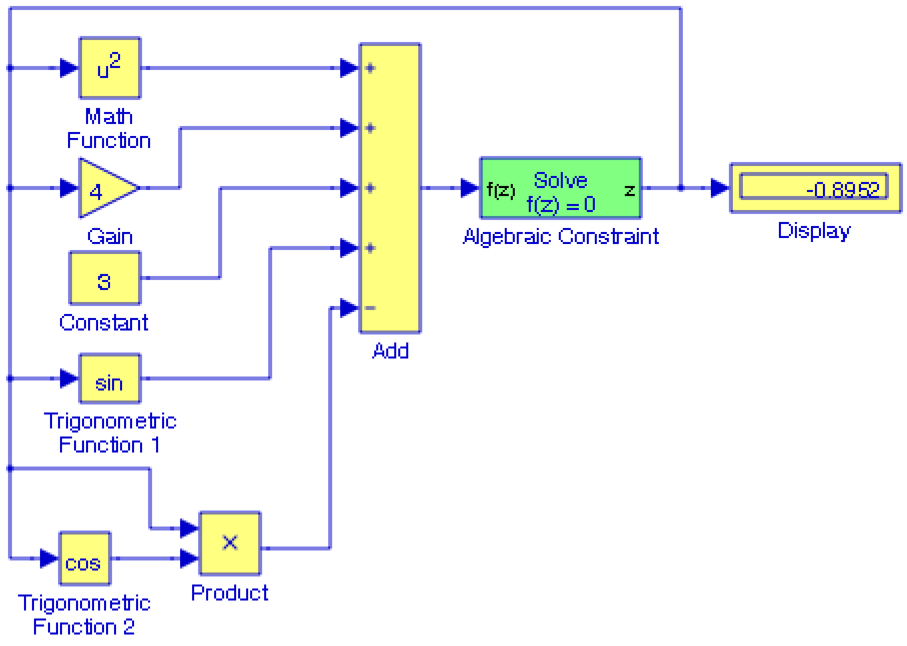
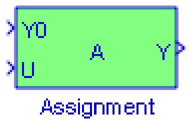


Figure 8.23. Model for Example 8.19

8.2 The Vector / Matrix Operations Group Sub–Library

The **Vector / Matrix Operations Group Sub–Library** contains the blocks described in Subsections 8.2.1 through 8.2.6 below.

8.2.1 The Assignment Block



The **Assignment** block assigns values to specified elements of the signal. We specify the indices of the elements to be assigned values either by entering the indices in the block's dialog box, or by connecting an external indices source or sources to the block. The signal at the block's data port, labeled U2 in most modes, specifies values to be assigned to Y. The block replaces the specified elements of Y with elements from the data signal, leaving unassigned elements unchanged from their initial values. If the assignment indices source is internal or is external and the Initialize using input option is selected, the **Assignment block** uses the signal at the block's initialization port, labeled U1, to initialize the elements of the output signal before assigning them values from U2.

Example 8.20

We will create a model using an **Assignment block** to assign the value 6 in the zero–based index mode A(1, 2) position of the matrix A defined as

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 0 \\ 7 & 8 & 9 \end{bmatrix}$$

The model is shown in Figure 8.24 where we have made the following entries:

Constant 1 block – Constant value: [1 2 3; 4 5 0; 7 8 9]

Constant 2 block – Constant value: [6]

Assignment block – Number of output dimensions: 2 – Index mode: Zero–based – Index Option 1 : Index vector (dialog) Index 1 – Index Option 2: Index vector (dialog) Index 2

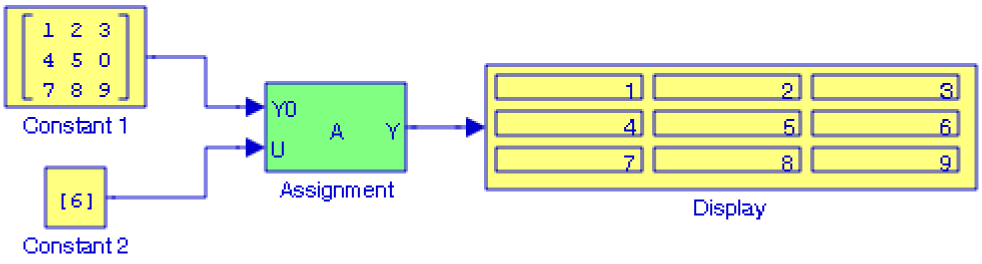
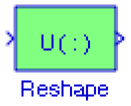


Figure 8.24. Model for Example 8.20

8.2.2 The Reshape Block



The **Reshape** block changes the dimensionality of the input signal to another dimensionality that we specify, using the block's Output dimensionality parameter. The Output dimensionality parameter allows us to select the 1–D array, Column vector, Row vector, or Customize options. These options are described in the Help menu for this block.

Example 8.21

We will create a model using the **Reshape** block to convert the row vector

$$A = [1 \quad 0 \quad -3 \quad -2 \quad 5 \quad 7 \quad 9 \quad 4 \quad 6]$$

to a column vector.

The model is shown in Figure 8.25 where at the MATLAB command prompt we have entered

```
A=[1  0  –3  –2  5  7  9  4  6];
```

and for the Reshape block we have selected the Column vector Output dimensionality option.

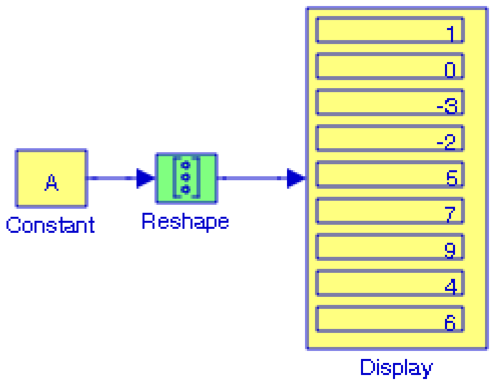
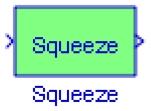


Figure 8.25. Model for Example 8.21

8.2.3 The Squeeze Block



The **Squeeze** block removes singleton dimensions[*] from its multidimensional input signal.

The **Squeeze** block operates only on signals whose number of dimensions is greater than two. Scalar, one–dimensional (vector), and two–dimensional (matrix) signals pass through the Squeeze block unchanged.

Example 8.22

For the array

```
A=rand(2,1,3)
```

MATLAB outputs:

```
A(:,:,1) =
    0.9572
    0.4854
A(:,:,2) =
    0.8003
    0.1419
A(:,:,3) =
    0.4218
    0.9157
```

That is, MATLAB outputs an array of 2 rows by three columns and ignores the singleton 1 .

Next, we create the model shown in Figure 8.26 where the array A in the **Constant** block is defined as above.

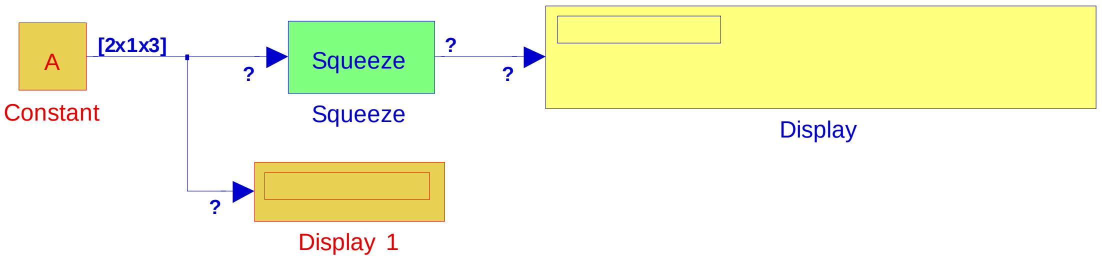


Figure 8.26. Nonexecutable model for Example 8.22

After execution of the simulation command Simulink displays the following error message:

[*] *A singleton dimension is any dimension whose size is one.*

```
Cannot propagate 3-D signal from output port 1 of block
'Section_8_2_3/Constant' to input port 1 of block 'Section_8_2_3/
Display1'. The latter block does not accept signals with greater
than 2 dimensions (either entirely or in its current configura-
tion)
```

Now, we remove the **Display 1** block and after execution of the simulation command, the **Display 2** block displays the same array as in MATLAB because the Squeeze block has removed the singleton dimension.

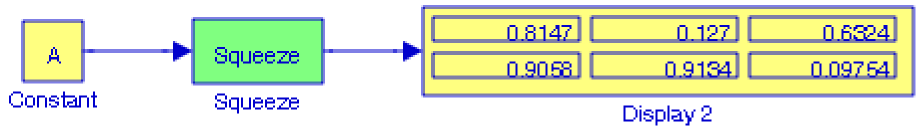
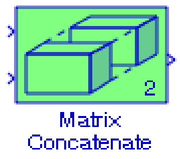


Figure 8.27. Executable model for Example 8.22

8.2.4 The Matrix Concatenate Block



The **Matrix Concatenate** block concatenates input matrices u1 u2 u3 ... un along rows or columns, where n is specified by the Number of inputs parameter. When the Concatenate method parameter is set to Horizontal, the block concatenates the input matrices along rows.

```
y = [u1 u2 u3 ... un]       % Equivalent MATLAB code
```

For horizontal concatenation, inputs must all have the same row dimension, M, but can have different column dimensions. The output matrix has dimension M–by–Ni, where Ni is the number of columns in input ui (i =1, 2, ..., n).

When the Concatenate method parameter is set to Vertical, the block concatenates the input matrices along columns.

```
y = [u1;u2;u3;...;un]       % Equivalent MATLAB code
```

For vertical concatenation, inputs must all have the same column dimension, N, but can have different row dimensions. The output matrix has dimension Mi–by–N, where Mi is the number of rows in input ui (i = 1, 2, ..., n).

Example 8.23

We will create a model using a **Matrix Concatenate** block to concatenate horizontally the matrices A, B, and C defined as

$$A = \begin{bmatrix} 1 & -1 & -4 \\ 5 & 7 & -2 \\ 3 & -5 & 6 \end{bmatrix} \quad B = \begin{bmatrix} 5 & 9 & -3 \\ -2 & 8 & 2 \\ 7 & -4 & 6 \end{bmatrix} \quad C = \begin{bmatrix} 4 & 6 \\ -3 & 8 \\ 5 & -2 \end{bmatrix}$$

The model is shown in Figure 8.28 where at the MATLAB command prompt we have entered:

```
A=[1 −1  4; 5  7 −2; 3  −5  6]; B=[5  9  −3; −2  8  2; 7  −4  6]; C=[4  6; −3  8; 5  −2];
```

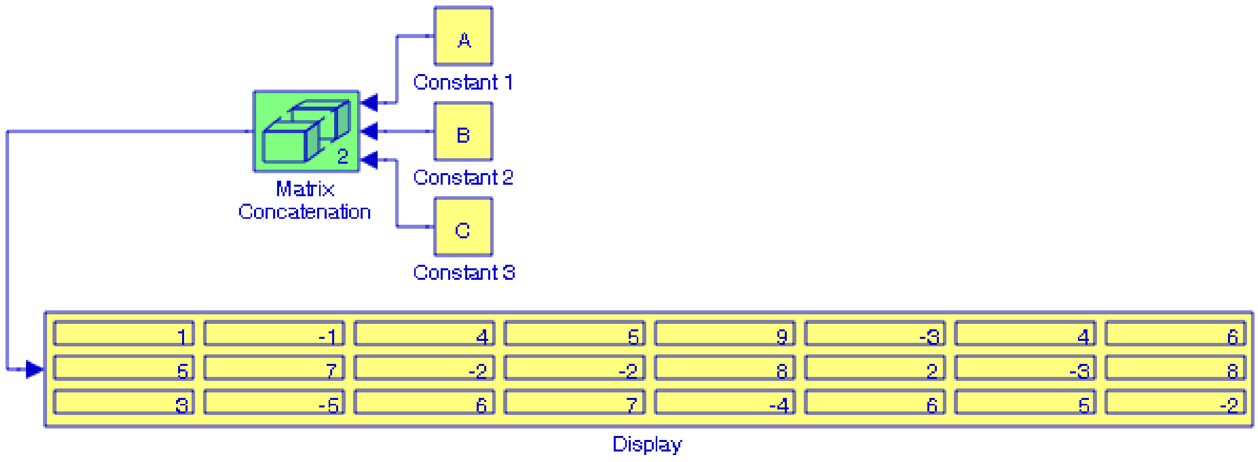
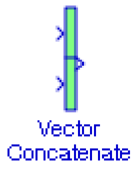


Figure 8.28. Model for Example 8.22

Another example using the **Matrix Concatenate** block appears in the Simulink **Spiral Galaxy Formation** demo. It can be accessed by typing sldemo_eml_galaxy at the MATLAB command prompt.

8.2.5 The Vector Concatenate Block



The **Vector Concatenate** block is a special case of the **Matrix Concatenate** block where the block operates in Vector Concatenation Mode, Horizontal Matrix Concatenation Mode, or Vertical Matrix Concatenation Mode. In Vector Concatenation Mode, all input signals must be either row vectors ($1 \times m$ matrices) or column vectors ($m \times 1$ matrices) or a combination of vectors and either row or column vectors. The output is a vector if all inputs are vectors.

The output is a row or column vector if any of the inputs are row or column vectors, respectively.

Example 8.24

We will create a model using a **Vector Concatenate** block to concatenate vertically the column vectors a, b, and c defined as

$$a = \begin{bmatrix} 1 \\ 5 \\ 3 \end{bmatrix} \quad b = \begin{bmatrix} 5 \\ -2 \\ 7 \end{bmatrix} \quad c = \begin{bmatrix} 4 \\ -3 \\ 5 \end{bmatrix}$$

The model is shown in Figure 8.29 where at the MATLAB command prompt we have entered the column vectors

```
a=[1  5  3 ]’; b=[5  –2  7 ]’; c=[4  –3  5 ]’;
```

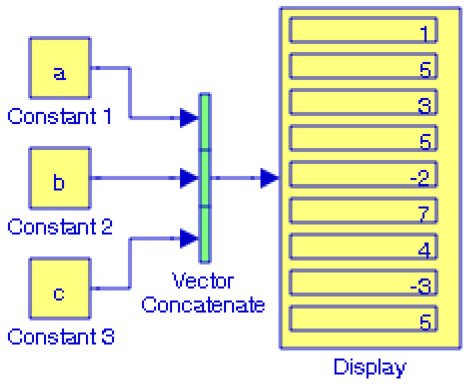


Figure 8.29. Model for Example 8.24

8.2.6 The Permute Dimensions Block

The **Permute Dimensions** block reorders the elements of the input signal so that they are in the order that we specify in the Order parameter. It can be used to find the transpose of a matrix as shown in Example 8.25 below.

Example 8.25

Let the matrix A be a 3×5 matrix defined at the MATLAB command prompt as

```
A=[1 –1 4 2 6; 5 7 –2 8 0; 3 –5 6 9 –4];
```

The model in Figure 8.30 displays the transpose of A.

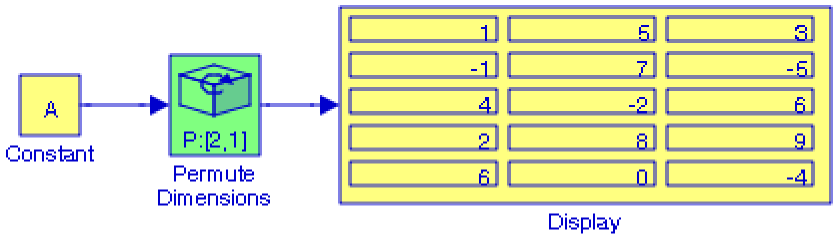


Figure 8.30. Model for Example 8.25

8.3 The Complex Vector Conversions Group Sub–Library

The **Complex Vector Conversions Group Sub–Library** contains the blocks described in Subsections 8.3.1 through 8.3.4 below.

8.3.1 The Complex to Magnitude–Angle Block

|u|
∠u
Complex to Magnitude-Angle

The **Complex to Magnitude–Angle** block accepts a complex–valued signal of type double in the form of $x + jy$. It outputs the magnitude, the phase angle in radians, or magnitude and phase depending on the setting of the Output parameter. The outputs are real values of type double. The input can be an array of complex signals, in which case the output signals are also arrays. The magnitude signal array contains the magnitudes of the corresponding complex input elements. The angle output similarly contains the angles of the input elements

Example 8.26

We will create a model using a **Complex to Magnitude–Angle** block to convert the complex number $5.43 - j4.54$ to the polar form $A\angle\theta$.

The model is shown in Figure 8.28 where the **Complex to Magnitude–Angle** block Output parameter has been specified as Magnitude and angle.

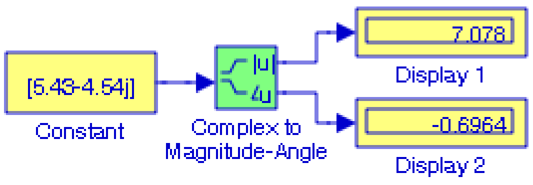
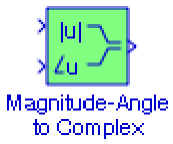


Figure 8.31. Model for Example 8.26

8.3.2 The Magnitude–Angle to Complex Block



The **Magnitude–Angle to Complex** block converts magnitude and / or phase angle inputs to a complex–valued output signal. The inputs must be real–valued signals of type double. The angle input is assumed to be in radians. The data type of the complex output signal is double.

The inputs can both be signals of equal dimensions, or one input can be an array and the other a scalar. If the block has an array input, the output is an array of complex signals. The elements of a magnitude input vector are mapped to magnitudes of the corresponding complex output elements. An angle input vector is similarly mapped to the angles of the complex output signals. If one input is a scalar, it is mapped to the corresponding component (magnitude or angle) of all the complex output signals.

Example 8.27

We will create a model using a **Magnitude–Angle to Complex** block to convert $120\angle 240°$ to its equivalent real and imaginary components.

The model is shown in Figure 8.32 where the magnitude is entered in the **Constant 1** block and phase angle in radians is entered in the **Constant 2** block.

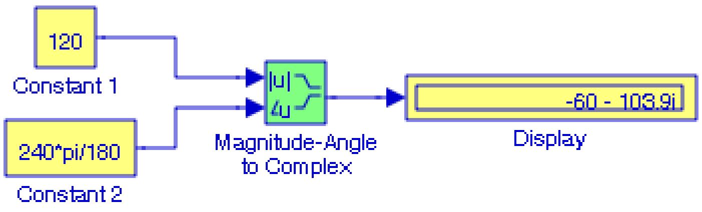
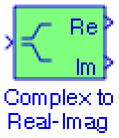


Figure 8.32. Model for Example 8.27

8.3.3 The Complex to Real–Imag Block



The **Complex to Real–Imag** block accepts a complex–valued signal of any data type supported by Simulink, including fixed–point data types. It outputs the real and / or imaginary part of the input signal, depending on the setting of the Output parameter. The real outputs are of the same data type as the complex input. The input can be an array (vector or matrix) of complex signals, in which case the output signals are arrays of the same dimensions. The real array contains the real parts of the corresponding complex input elements. The imaginary output similarly contains the imaginary parts of the input elements.

Example 8.28

Let us consider the electric network of Figure 8.33.

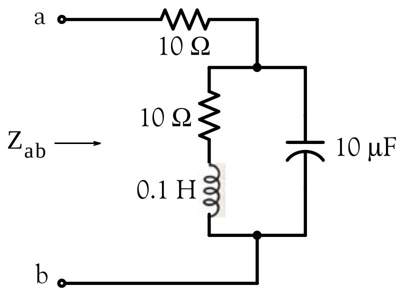


Figure 8.33. Electric network for Example 8.28

With the given values of resistance, inductance, and capacitance, the impedance Z_{ab} as a function of the radian frequency ω can be computed from the following expression.

$$Z_{ab} = Z = 10 + \frac{10^4 - j(10^6/\omega)}{10 + j(0.1\omega - 10^5/\omega)} \tag{8.1}$$

Assuming that the operating frequency is $f = 100 \text{ Hz}$, we will create a model to display the real and imaginary values of the relation (8.1).

The model is shown in Figure 8.34 where at the MATLAB command prompt we have entered

```
Z=10+(10^4 –j*10^6/(2*pi*60))/(10 + j*(0.1*(2*pi*60)–10^5/(2*pi*60)));
```

Display 1 block shows the real component and **Display 2** shows the imaginary component.

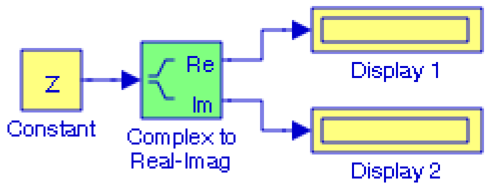
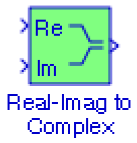


Figure 8.34. Model for Example 8.26

8.3.4 The Real–Imag to Complex Block



The **Real–Imag to Complex** block converts real and/or imaginary inputs to a complex–valued output signal. The inputs can both be arrays (vectors or matrices) of equal dimensions, or one input can be an array and the other a scalar. If the block has an array input, the output is a complex array of the same dimensions. The elements of the real input are mapped to the real parts of the corresponding complex output elements. The imaginary input is similarly mapped to the imaginary parts of the complex output signals. If one input is a scalar, it is mapped to the corresponding component (real or imaginary) of all the complex output signals.

Example 8.29

We will create a model to convert the rectangular form of the complex number $25 + j40$ to the polar form $A\angle\theta°$ where A is the magnitude and the angle θ is in degrees (not radians).

The model is shown in Figure 8.35 where $A = 47.17$, $\theta = 57.99°$, and the Gain $K = 180/\pi$.

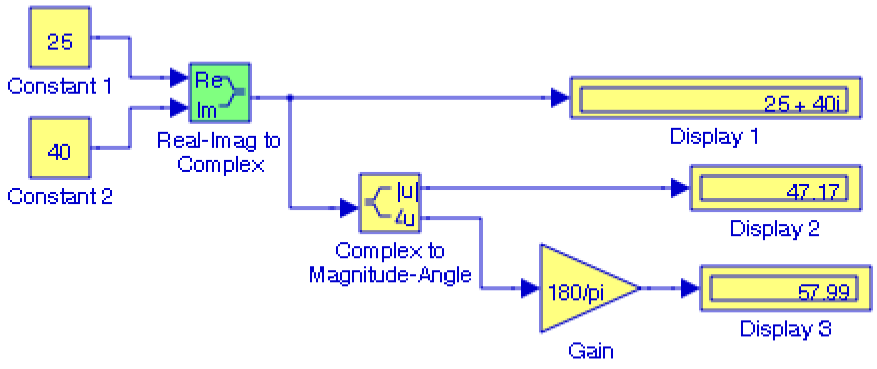


Figure 8.35. Model for Example 8.29

8.4 Summary

- The **Sum** block is an implementation of the **Add** block. We can choose the icon shape (round or rectangle) of the block.
- The **Add** block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a single input vector. We specify the operations of the block with the List of Signs parameter. Plus (+), minus (−), and spacer (|) characters indicate the operations to be performed on the inputs.
- The **Subtract** block is an implementation of the Add block.
- The **Sum of Elements** block is an implementation of the **Add** block.
- The **Bias** block adds a bias (offset) to the input signal.
- The **Weighted Sample Time Math** block adds, subtracts, multiplies, or divides the input signal, u, by a weighted sample time Ts. We use the Operation parameter to specify the math operation. This block also allows us to use only the weight with either the sample time or its inverse.
- The **Gain** block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix.
- The **Slider Gain** block allows us to vary a scalar gain during a simulation using a slider. The block accepts one input and generates one output. In the Slider Gain dialog box Low indicates the lower limit of the slider range where the default is 0, and High indicates the upper limit of the slider range where the default is 2.
- The **Product** block performs multiplication or division of its inputs.
- The **Divide** block is an implementation of the Product block.
- The **Product of Elements** block is used to multiply of divide inputs. It is essentially a Product block.
- The **Dot Product** block generates the dot product of its two input vectors. The scalar output, y, is equal to the MATLAB operation y=sum(conj(A.*B)) where vectors A and B are defined as $A = [a_1 \ a_2 \ \dots \ a_n]$, $B = [b_1 \ b_2 \ \dots \ b_n]$, and $A*B=[a_1b_1 + a_2b_2 + \ \dots \ +a_n b_n]$.
- The **Sign** block indicates the sign of the input. The output is 1 when the input is greater than zero, the output is 0 when the input is equal to zero, and the output is −1 when the input is less than zero.
- The **Abs** block outputs the absolute value of the input. This block accepts real signals of any data type supported by Simulink, except Boolean, and supports real fixed−point data types. The block also accepts complex single and double inputs.

- The **Unary Minus** block negates the input. The block accepts only signed data types. For signed data types, we cannot accurately negate the most negative value since the result is not representable by the data type.
- The **Math Function** block performs the following common mathematical functions:

  exp

  log

  10^u

  log10

  magnitude^2

  square

  sqrt

  pow (power)

  conj (complex conjugate)

  reciprocal

  hypot (computation of the square root of the sum of squares)

  rem (remainder after division)

  mod (modulus after division)

  transpose (transpose of a vector or matrix)

  hermitian (a square matrix such that $A^{T*} = A$)

  The name of the function appears on the block. Simulink automatically draws the appropriate number of input ports.
- The **Rounding Function** block applies a rounding function to the input signal to produce the output signal. The name of the selected function appears on the block where floor rounds each element of the input signal to the nearest integer value towards minus infinity, ceil rounds each element of the input signal to the nearest integer towards positive infinity, round rounds each element of the input signal to the nearest integer, and fix rounds each element of the input signal to the nearest integer towards zero.
- The **Polynomial** block uses a coefficients parameter to evaluate a real polynomial for the input value. We define a set of polynomial coefficients in the form accepted by the MATLAB **polyval** command. The block then calculates P(u) at each time step for the input u. Inputs and coefficients must be real.

- The **MinMax** block outputs either the minimum or the maximum element or elements of the inputs. We choose the function to apply by selecting one of the choices from the Function parameter list.
- The **MinMax Running Resettable** block outputs the minimum or maximum of all past inputs u. We specify whether the block outputs the minimum or the maximum with the Function parameter. The block can reset its state based on an external reset signal R. When the reset signal R is TRUE, the block resets the output to the value of the Initial condition parameter.
- The **Trigonometric Function** block performs the principle trigonometric functions sine, cosine, and tangent, the Inverse trigonometric functions asin, acos, atan, and atan2, the hyperbolic functions sinh, cosh, and tanh, and the Inverse hyperbolic functions asinh, acosh, and atanh. The block output is the result of the operation of the function on the input or inputs. The name of the function appears on the block. If we select the atan2 function, the block displays two inputs. The first (upper) input is the y–axis or complex part of the function argument. The second (lower) input is the x–axis or real part of the function argument.
- The **Sine Wave Function** block generates a sinusoid. The block can operate in either time–based or sample–based mode. The time–based mode has two submodes: continuous mode or discrete mode. The value of the Sample time parameter determines whether the block operates in continuous mode or discrete mode.
- The **Algebraic Constraint** block constrains the input signal $f(z)$ to zero and outputs an algebraic state z. The block outputs the value necessary to produce a zero at the input. The output must affect the input through a feedback path. This block accepts and outputs real values of type double.
- The **Assignment** block assigns values to specified elements of the signal. We specify the indices of the elements to be assigned values either by entering the indices in the block's dialog box or by connecting an external indices source or sources to the block. The signal at the block's data port, labeled U2 in most modes, specifies values to be assigned to Y. The block replaces the specified elements of Y with elements from the data signal, leaving unassigned elements unchanged from their initial values.
- The **Reshape** block changes the dimensionality of the input signal to another dimensionality that we specify, using the block's Output dimensionality parameter. The Output dimensionality parameter allows us to select the 1–D array, Column vector, Row vector, or Customize options. These options are described in the Help menu for this block.
- The **Squeeze** block removes singleton dimensions from its multidimensional input signal.
- The **Matrix Concatenate** block concatenates input matrices u1 u2 u3 ... un along rows or columns, where n is specified by the Number of inputs parameter. When the Concatenation method parameter is set to Horizontal, the block concatenates the input matrices along rows.

```
y = [u1 u2 u3 ... un]       % Equivalent MATLAB code
```

For horizontal concatenation, inputs must all have the same row dimension, M, but can have different column dimensions.

When the Concatenation method parameter is set to Vertical, the block concatenates the input matrices along columns.

```
y = [u1;u2;u3;...;un]      % Equivalent MATLAB code
```

For vertical concatenation, inputs must all have the same column dimension, N, but can have different row dimensions.

- The **Vector Concatenate** block is a special case of the Matrix Concatenate block where the block operates in Vector Concatenation Mode, Horizontal Matrix Concatenation Mode, or Vertical Matrix Concatenation Mode. In Vector Concatenation Mode, all input signals must be either row vectors [1xM matrices] or column vectors [Mx1 matrices] or a combination of vectors and either row or column vectors. The output is a vector if all inputs are vectors. The output is a row or column vector if any of the inputs are row or column vectors, respectively.
- The **Permute Dimensions** block reorders the elements of the input signal so that they are in the order that we specify in the Order parameter. It can be used to find the transpose of a matrix.
- The **Complex to Magnitude–Angle** block accepts a complex–valued signal of type double in the form of $x + jy$. It outputs the magnitude, the phase angle in radians, or magnitude and phase depending on the setting of the Output parameter. The outputs are real values of type double.
- The **Magnitude–Angle to Complex** block converts magnitude and/or phase angle inputs to a complex–valued output signal. The inputs must be real–valued signals of type double. The angle input is assumed to be in radians.
- The **Complex to Real–Imag** block accepts a complex–valued signal of any data type supported by Simulink, including fixed–point data types. It outputs the real and/or imaginary part of the input signal, depending on the setting of the Output parameter. The real outputs are of the same data type as the complex input.
- The **Real–Imag to Complex** block converts real and/or imaginary inputs to a complex–valued output signal. The inputs can both be arrays (vectors or matrices) of equal dimensions, or one input can be an array and the other a scalar.

8.5 Exercises

1. Create a model using an **Abs** block to display the magnitude of the expression

$$z = \frac{(-j1.49)(-0.8+j4.52)(-1.2-j7.4)}{(5+j1.84)(2.5-j4.8)(3.25+j5.2)}$$

2. Three phasors[*] are defined as $A = 3\angle 60°$, $B = -4\angle 30°$, and $C = 5\angle -45°$. Create a model using an **Abs** block to display the result of the operation $A - B + C$.

3. Create a model using an **Algebraic Constraint** block to find a solution for the non–linear equation

$$F(x) = 3x^5 - 2x^3 + 6x - 8$$

4. Create a model using an **Assignment** block to assign the value 7 in the zero–based index mode elements $[2\ \ 5]$ position of the vector A defined as $A = [0\ \ 5\ \ 10\ \ 15\ \ 20\ \ 25]$.

5. Create a model using a **Complex to Magnitude–Angle** block to convert the array of complex number $7.5 - j15.4$, $28.4 + j12.2$, and $48.3 - j72.8$ to the polar form $A_1\angle\theta_1$, $A_2\angle\theta_2$, and $A_3\angle\theta_3$ respectively.

6. Create a model using one **Magnitude–Angle to Complex** block to convert $8\angle 30°$, $20\angle 45°$, and $50\angle 60°$ to their equivalent real and imaginary components.

7. Create a model using the appropriate **Math Function** block from the Math Operations library to invert the elements of the matrix

$$A = \begin{bmatrix} 1 & 1-j & 2 \\ 1+j & 3 & j \\ 2 & -j & 5 \end{bmatrix}$$

8. Create a model using a **Matrix Concatenation** block to concatenate vertically the matrices A, B, and C defined as

$$A = \begin{bmatrix} 1 & -1 & -4 \\ 5 & 7 & -2 \\ 3 & -5 & 6 \end{bmatrix} \quad B = \begin{bmatrix} 5 & 9 & -3 \\ -2 & 8 & 2 \\ 7 & -4 & 6 \end{bmatrix} \quad C = \begin{bmatrix} 1 & -2 & 3 \\ -3 & 6 & -4 \end{bmatrix}$$

9. Create a model using a **MinMax** block to display the largest number in the row vector

$$a = [1\ \ -1\ \ -4\ \ 5\ \ 7\ \ -2\ \ 3\ \ -5\ \ 6\ \ 9\ \ -3\ \ 8\ \ 2\ \ 4\ \ 8\ \ 5]$$

* *A phasor is a rotating vector.*

10. Create a model using the **Reshape** block to convert the row vector

$$A = [1 \quad 0 \quad -3 \quad -2 \quad 5 \quad 7 \quad 9 \quad 4 \quad 6]$$

to a 3×3 matrix.

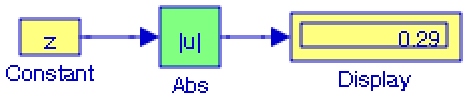
11. Create a model using the atan2 trigonometric function block to find the phase angle of the complex number $108 + j84$ in degrees.

8.6 Solutions to End-of-Chapter Exercises

1.

The model is shown below where for the **Constant** block we have Signal data types we have selected double and at the MATLAB command prompt we have entered

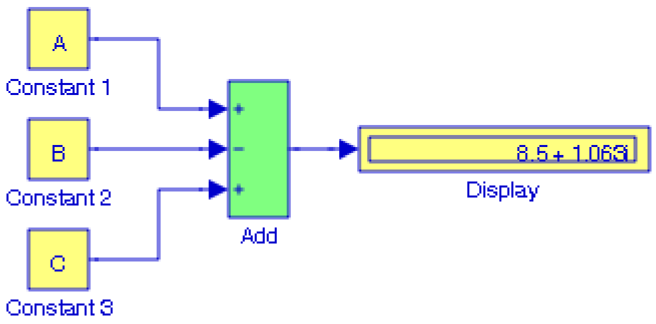
```
z=((–1.49j)*(–0.8+4.52j)*(–1.2–7.4j))/((5+1.84j)*(2.5–4.8j)*(3.25+5.2j));
```



2.

The model is shown below where at the MATLAB command prompt we have entered

```
A=3*(cos(60*pi/180)+j*sin(60*pi/180)); B=–4*(cos(30*pi/180)+j*sin(30*pi/180));...
C=5*(cos(–45*pi/180)+j*sin(–45*pi/180));
```

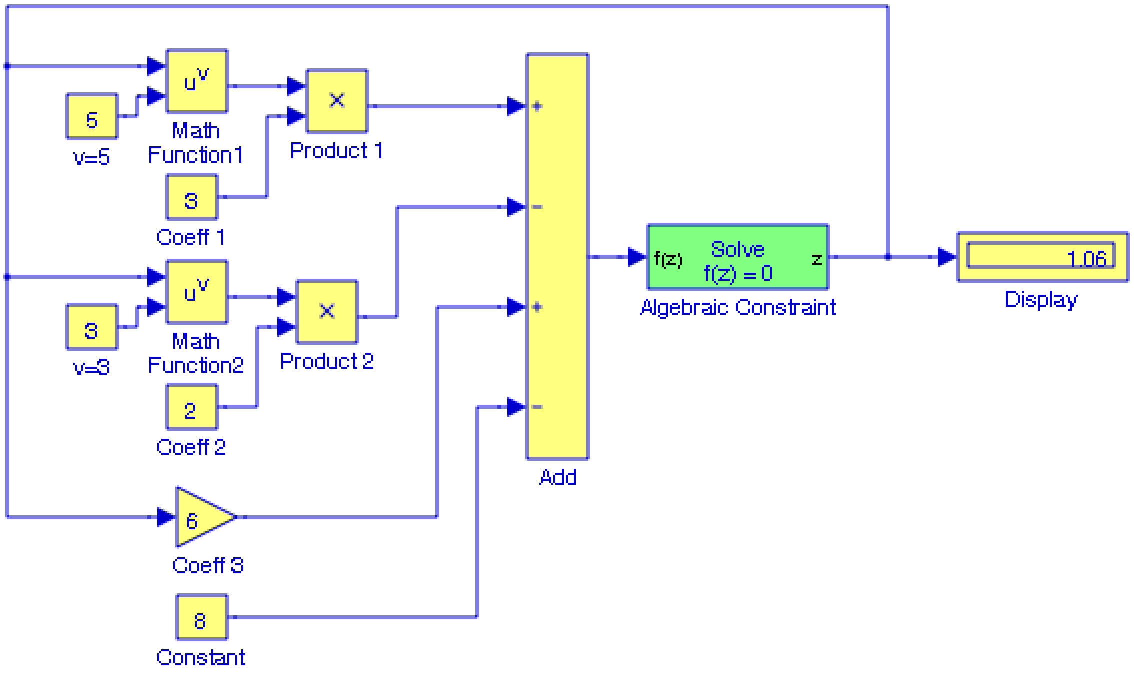


3.

We recall that the **Algebraic Constraint** block accepts and outputs real values of type double. Since the given polynomial is of fifth power and complex roots, if present occur in complex conjugate pairs, we expect at least one real root.

The model is shown below and it displays the only real root. We can use MATLAB to verify that the remaining four roots are complex and occur in conjugate pairs.

The fifth and third powers in the first and second terms of the given polynomial are represented by the pow u^v block from the Math Function block.



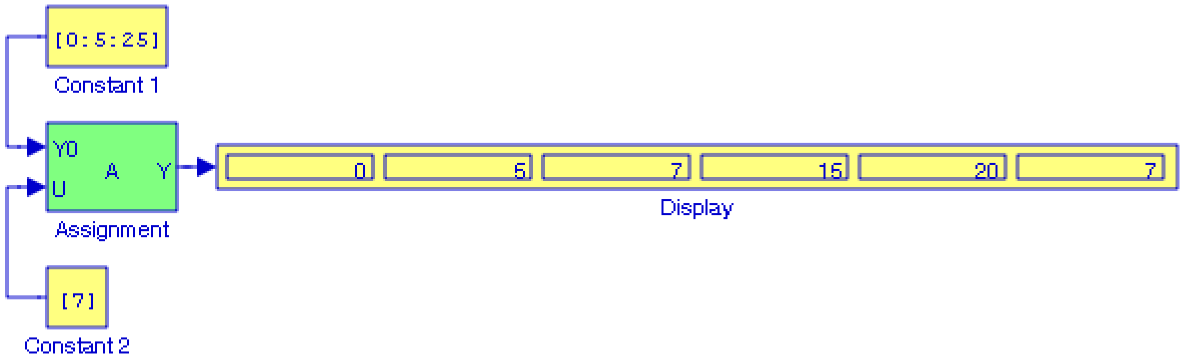
4.

The model is shown below where we have made the following entries:

Constant 1 block – Constant value: [0:5:25]

Constant 2 block – Constant value: [7]

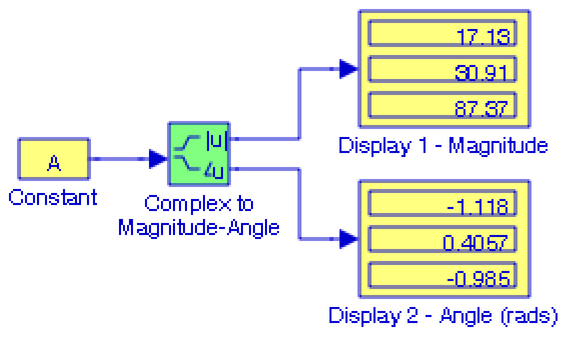
Assignment block – Input type: Vector – Index mode: Zero–based – Elements: [2 5]



5.

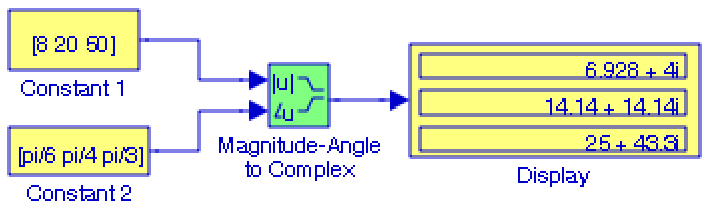
The model is shown below where at the MATLAB command prompt we have entered

A=[7.5–15.4j 28.4+12.2j 48.3–72.8j];



6.

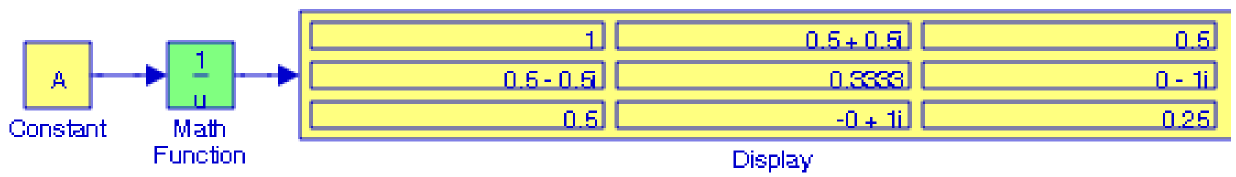
The model is shown below where in the **Constant 1** block we have enter the magnitudes and in the **Constant 2** block we have entered in phase angles in radians.



7.

The appropriate block to accomplish this task is the **Reciprocal Function** block which we select from the Math Function selection of blocks. The model is shown below where at the MATLAB command prompt we have entered

```
A=[1  1–j  2; 1+j  3  j; 2  –j  4];
```

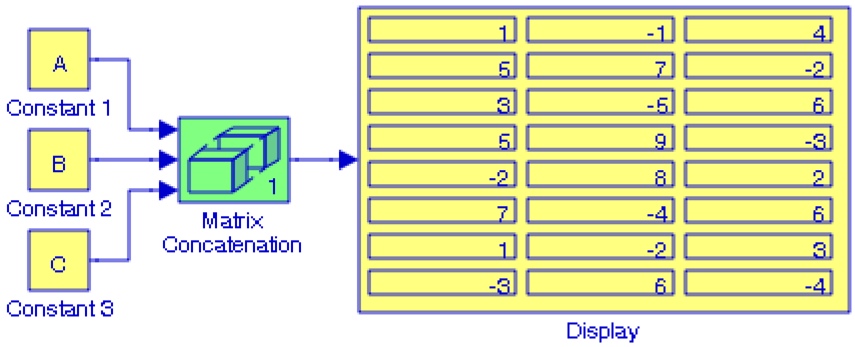


8.

The model is shown below where at the MATLAB command prompt we have entered

```
A=[1  –1  4; 5  7  –2; 3  –5  6]; B=[5  9 –3; –2  8  2; 7  –4  6]; C=[1  –2  3; –3  6 –4];
```

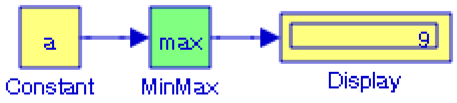
and to concatenate vertically, we specified 1 in the Concatenate dimension field in the **Function Block Parameters** dialog box



9.

The model is shown below where at the MATLAB command prompt we have entered

```
a=[1 –1 –4 5 7 –2 3 –5 6 9 –3 8 2 4 8 5];
```

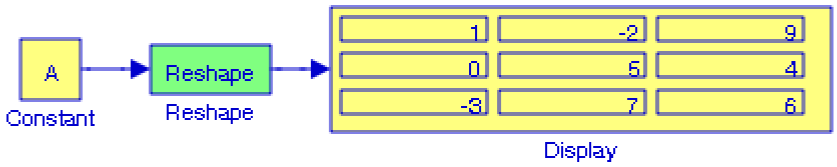


10.

The model is shown below where at the MATLAB command prompt we have entered

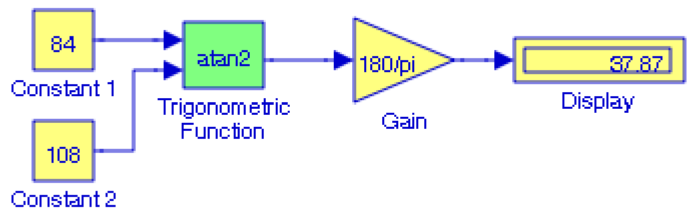
```
A=[1 0 –3 –2 5 7 9 4 6];
```

and for the **Reshape** block we have selected the Customize Output dimensionality option with Output dimensions [3, 3].



11.

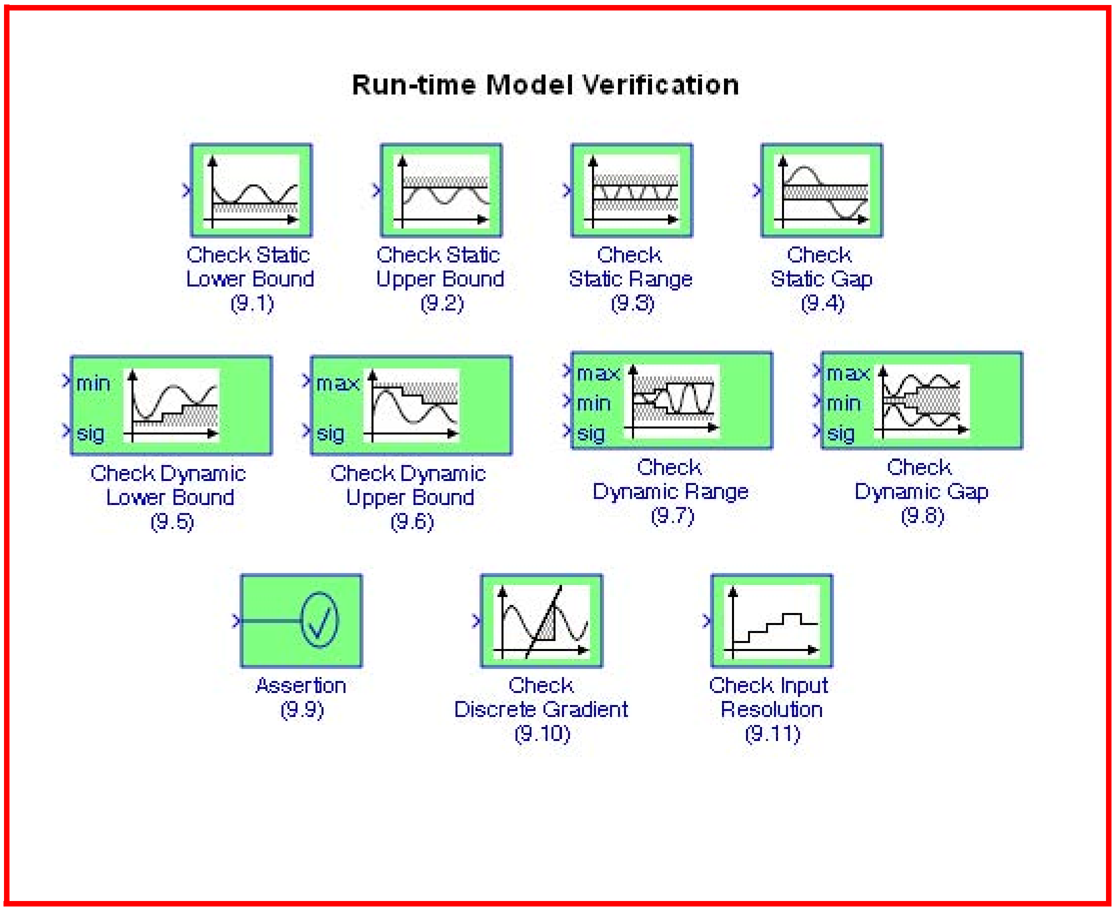
The model is shown below where the **Constant 1** block contains the imaginary part of the complex number, the **Constant 2** block contains the real part of the complex number, and the **Gain** block contains the factor $180/\pi$ to convert radians to degrees.


84
Constant 1
108
Constant 2
atan2
Trigonometric Function
180/pi
Gain
37.87
Display

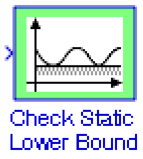
Chapter 9

The Model Verification Library

This chapter is an introduction to the **Model Verification Library**, also referred to as the **Run–Time Model Verification Library.** This is the eighth library in the Simulink group of libraries and contains the blocks shown below. The blocks in this library are intended to facilitate creation of self–validating models. We use model verification blocks to check whether the signals exceed specified limits during simulation.


Run-time Model Verification
Check Static Lower Bound (9.1)
Check Static Upper Bound (9.2)
Check Static Range (9.3)
Check Static Gap (9.4)
min
sig
Check Dynamic Lower Bound (9.5)
max
sig
Check Dynamic Upper Bound (9.6)
max
min
sig
Check Dynamic Range (9.7)
max
min
sig
Check Dynamic Gap (9.8)
Assertion (9.9)
Check Discrete Gradient (9.10)
Check Input Resolution (9.11)

9.1 The Check Static Lower Bound Block



The **Check Static Lower Bound** block performs a check to verify that each element of the input signal is greater than or equal to a specified lower bound. The block's parameter dialog box allows us to specify the value of the lower bound and whether the lower bound is inclusive. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.1

In the model of Figure 9.1, the amplitude of a sinusoidal signal may vary $\pm 10\%$ from its nominal value of $1\ \text{volt}$. We will configure this model to display error messages when the lower inclusive boundary is specified as $-1\ \text{volt}$.

The **Signal Generator** block is specified for a sine waveform with amplitude $1.1\ \text{volt}$, frequency $0.3\ \text{Hz}$, and the **Check Static Lower Bound** block is specified at -1 with the Inclusive boundary checked, Enable assertion checked, Output assertion signal checked, and icon type graphic. The **Convert** block is inserted to convert the Boolean output of the Check Dynamic Gap to double as required by the **Bus Creator**[*] block.

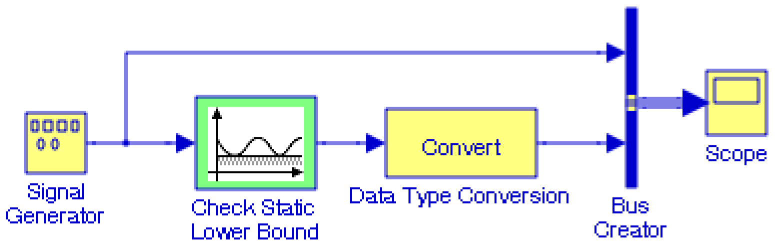


Figure 9.1. Model for Example 9.1

The input and output waveforms are shown in Figure 9.2.

* *As stated in Chapter 2, we could have used the Mux block instead of the Bus Creator block.*

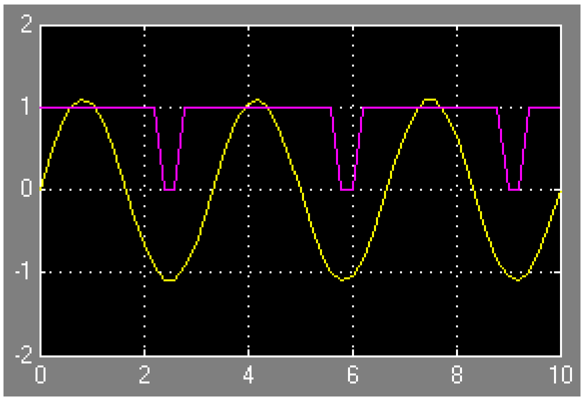
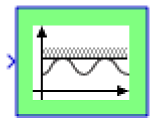


Figure 9.2. Input and output waveforms for the model in Figure 9.1

9.2 The Check Static Upper Bound Block



The **Check Static Upper Bound** block performs a check to verify that each element of the input signal is less than or equal to a specified lower bound. The block's parameter dialog box allows us to specify the value of the upper bound and whether the bound is inclusive. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.2

In the model of Figure 9.3, the amplitude of a sinusoidal signal may vary $\pm 10\%$ from its nominal value of 1 volt. We will configure this model to display error messages when the lower boundary inclusive boundary is specified as -1 volt.

The **Signal Generator** block is specified for a sine waveform with amplitude 1.1 volt, frequency 0.3 Hz, and the **Check Static Upper Bound** block is specified at $+1$ with the Inclusive boundary checked, Enable assertion checked, Output assertion signal checked, and icon type graphic. The **Convert** block was inserted to convert the Boolean output of the Check Dynamic Gap to double as required by the **Bus Creator** block.

The input and output waveforms are shown in Figure 9.4.

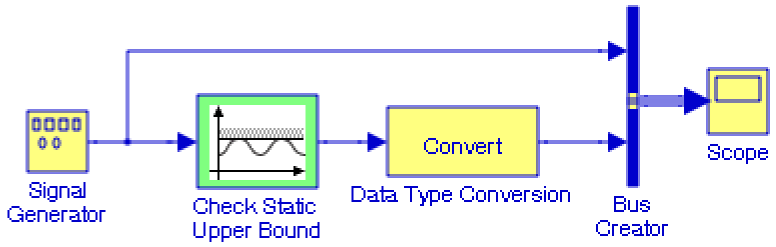


Figure 9.3. Model for Example 9.2

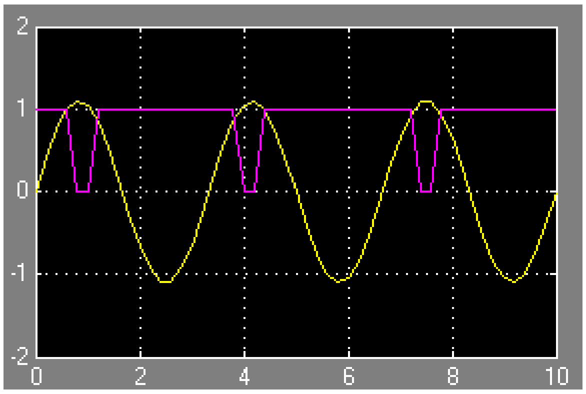
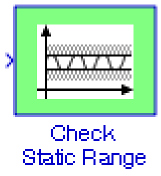


Figure 9.4. Input and output waveforms for the model in Figure 9.3

9.3 The Check Static Range Block



The **Check Static Range** block performs checks to verify that each element of the input signal falls inside the same range of amplitudes. The block's parameter dialog box allows us to specify the upper and lower bounds of the valid amplitude range and whether the range includes the bounds. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.3

In the model of Figure 9.5, the amplitude of a sinusoidal signal may vary $\pm 10\%$ from its nominal value of 1 volt. We will configure this model to convert a sine waveform of amplitude 1 to a pulse waveform of the same amplitude and frequency.

The **Signal Generator** block is specified for a sine waveform with amplitude 1 volt, frequency 0.3 Hz, and the **Check Static Range** block is specified as 1.0 with the Inclusive upper bound checked, as 0 with the Inclusive lower bound checked, Enable assertion checked, Output assertion signal checked, and icon type graphic. The **Convert** block was inserted to convert the Boolean output of the **Check Dynamic Gap** to double as required by the **Bus Creator** block.

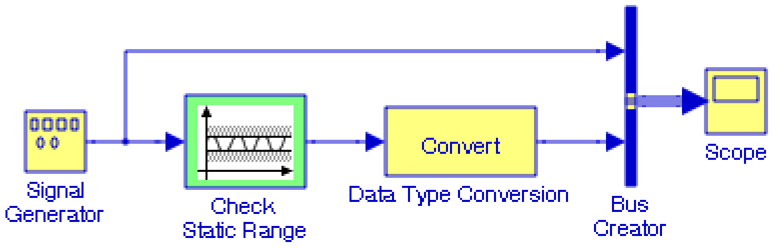


Figure 9.5. Model for Example 9.3

The input and output waveforms are shown in Figure 9.6.

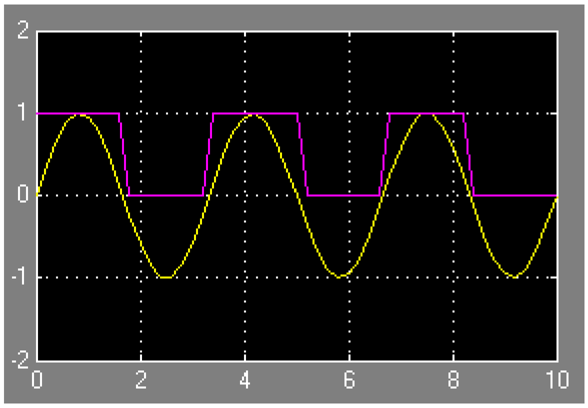
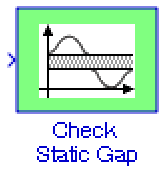


Figure 9.6. Input and output waveforms for the model in Figure 9.5

9.4 The Check Static Gap Block



The **Check Static Gap** block performs a check to verify that each element of the input signal is less than or equal to a static lower bound, or greater than or equal to a static upper bound. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.4

We will configure the model of Figure 9.7 whose input is a sawtooth waveform to display error messages when the upper bound is specified at 0.5 or greater and the lower bound is specified as -0.5 or less.

The **Signal Generator** block is specified for a sawtooth waveform with amplitude $1\ \text{volt}$, frequency $0.5\ \text{Hz}$, and the **Check Static Gap** block is specified at 0.5 with the Inclusive upper bound checked, at -0.5 with the Inclusive lower bound checked, Enable assertion checked, Output assertion signal checked, and icon type graphic. The **Convert** block was inserted to convert the Boolean output of the **Check Static Gap** to double as required by the **Bus Creator** block. The input and output waveforms are shown in Figure 9.8.

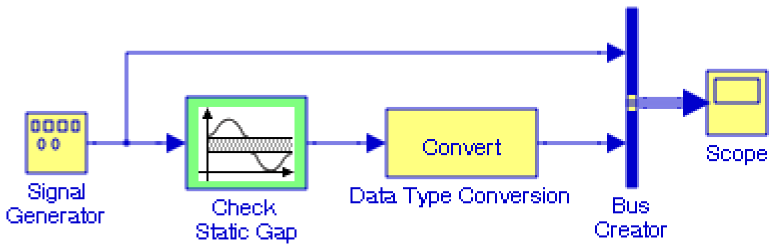


Figure 9.7. Model for Example 9.4

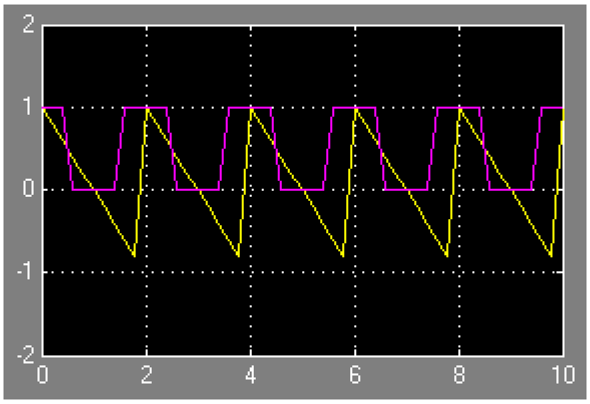
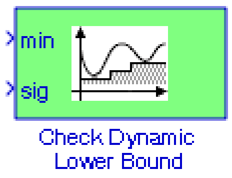


Figure 9.8. Input and output waveforms for the model in Figure 9.7

9.5 The Check Dynamic Lower Bound Block



The **Check Dynamic Lower Bound** block performs a check to verify that the amplitude of a test signal is less than the amplitude of a reference signal at the current time step. The test signal is the signal connected to the input labeled sig. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.5

For the model of Figure 9.9 the amplitude of a sinusoidal signal may vary $\pm 10\%$ from its nominal value of 1 volt. We will configure the model to display error messages when the amplitude exceeds -1 volt.

The **Signal Generator** block has been specified as a sine waveform with the amplitude set at 1.1, frequency at 0.1 Hz, **Constant** block with the values shown, in the **Check Dynamic Lower Bound** block the Enable assertion and Output assertion signal are checked, and the icon type is selected as graphic. The **Convert** block was inserted to convert the Boolean output of the Lower Bound block to double as required by the **Bus Creator** block. The input and output waveforms are shown in Figure 9.10.

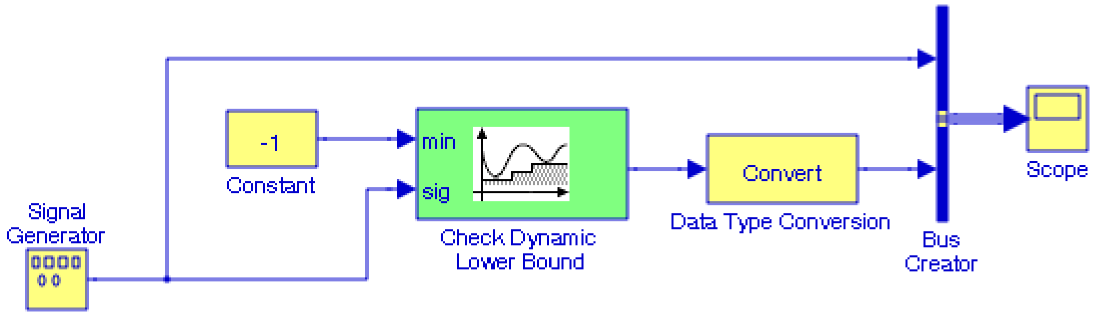


Figure 9.9. Model for Example 9.5

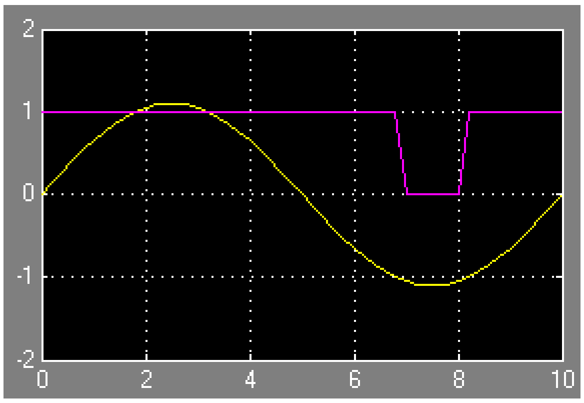
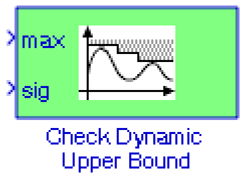


Figure 9.10. Input and output waveforms for the model in Figure 9.9

9.6 The Check Dynamic Upper Bound Block



The **Check Dynamic Upper Bound** block performs checks to verify that the amplitude of a test signal is greater than the amplitude of a reference signal. The test signal is the signal connected to the input labeled sig. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.6

For the model of Figure 9.11 the amplitude of a sinusoidal signal may vary $\pm 10\%$ from its nominal value of $1\ \text{volt}$. We will configure the model to display error messages when the amplitude exceeds $+1\ \text{volt}$.

The **Signal Generator** block has been selected as a sine waveform with the amplitude set at 1.1, frequency at 0.1 Hz, **Constant** block with the value shown, in the **Check Dynamic Upper Bound** block the Enable assertion and Output assertion signal are checked, and the icon type is selected as graphic. The **Convert** block was inserted to convert the Boolean output of the **Check Dynamic Upper Bound** block to double as required by the Bus Creator block. The input and output waveforms are shown in Figure 9.12.

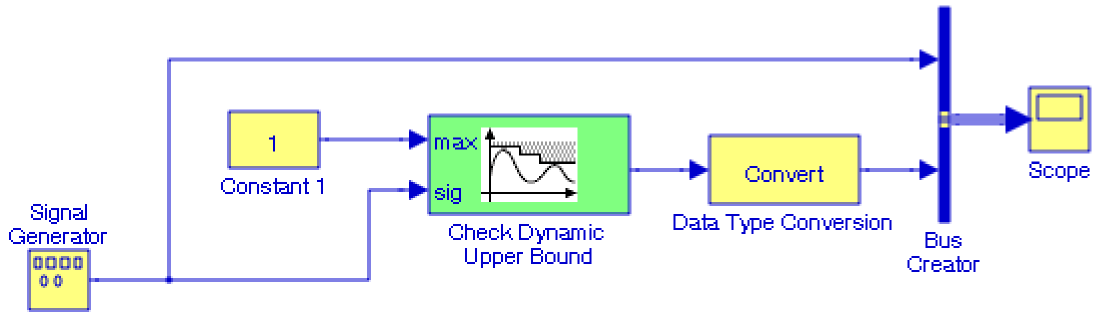


Figure 9.11. Model for Example 9.6

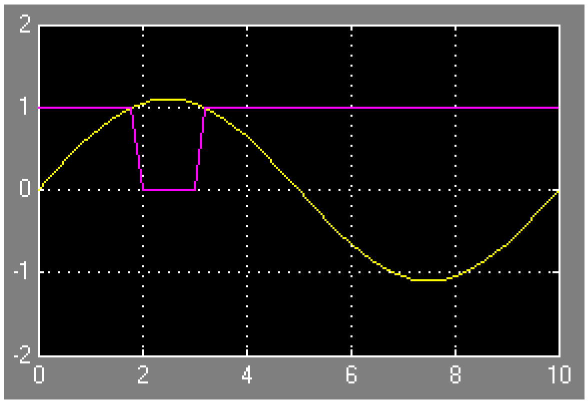
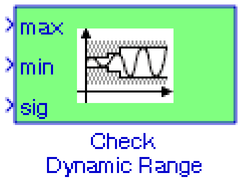


Figure 9.12. Input and output waveforms for the model in Figure 9.11

9.7 The Check Dynamic Range Block



The **Check Dynamic Range** block performs a check to verify that a test signal falls within a range of amplitudes. The width of the range can vary from time step to time step. The input labeled sig is the test signal, and the inputs labeled min and max are the lower and upper bounds respectively of the valid range. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.7

The amplitude of a random waveform may vary $\pm 20\%$ from its nominal value of 1 volt. We will create a model using a **Check Dynamic Range** block to display error messages when the amplitude exceeds ± 1 volt.

In Figure 9.13 the **Signal Generator** block has been selected as a random waveform with amplitude specified at 1.2, frequency at 1 Hz, **Constant** blocks with the values as indicated, in the **Check Dynamic Range** block the Enable assertion and Output assertion signal are checked, and the icon type is selected as graphic. The **Convert** block was inserted to convert the Boolean output of the **Check Dynamic Range** block to double as required by the **Bus Creator** block. The input and output waveforms are shown in Figure 9.14.

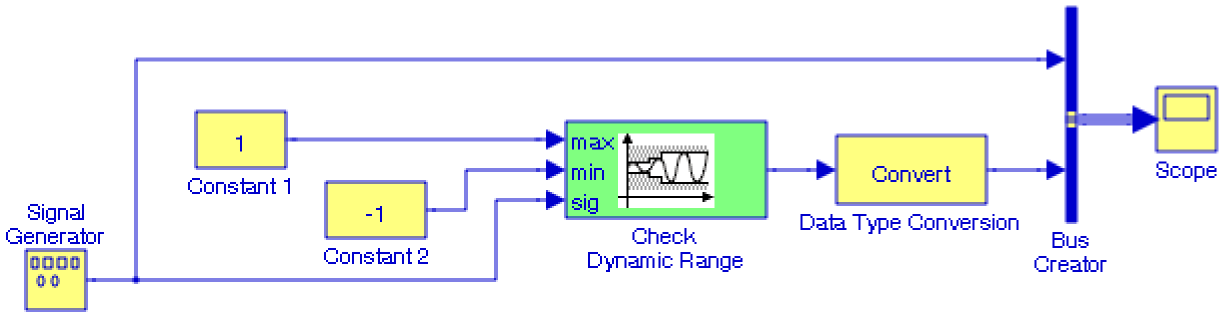


Figure 9.13. Model for Example 9.7

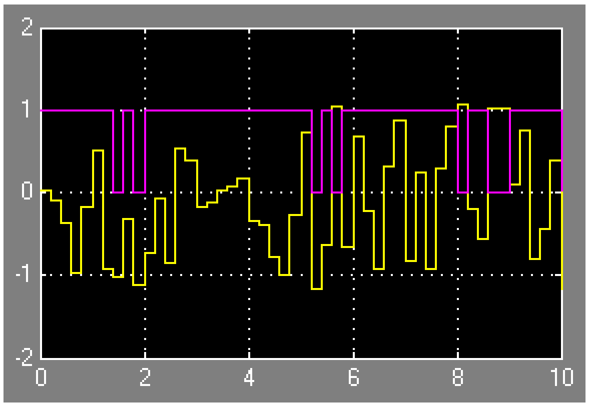
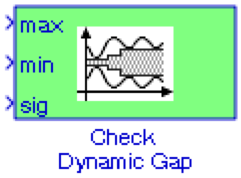


Figure 9.14. Input and output waveforms for the model in Figure 9.13

As stated above this block performs a check to verify that a signal falls inside a range of amplitudes that varies from time step to time step.

9.8 The Check Dynamic Gap Block



The **Check Dynamic Gap** block performs checks to determine whether a gap of possibly varying width occurs in the range of a signal's amplitudes. The test signal is the signal connected to the input labeled sig, and the inputs labeled min and max specify the lower and upper bounds respectively of the dynamic gap. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

Example 9.8

The amplitude of a sinusoidal signal may vary ±10% from its nominal value of 1 volt. We will create a model using a **Check Dynamic Gap** block to display error messages when the amplitude exceeds ±1 volt.

In Figure 9.15, the **Signal Generator** block has been selected as a sine waveform with amplitude set at 1.1, frequency at 0.1 Hz, **Constant** blocks with the values shown, in the **Check Dynamic Gap** block the Enable assertion and Output assertion signal are checked, and the icon type is selected as graphic. The **Convert** block was inserted to convert the Boolean output of the **Check Dynamic Gap** block to double as required by the **Bus Creator** block. The input and output waveforms are shown in Figure 9.16.

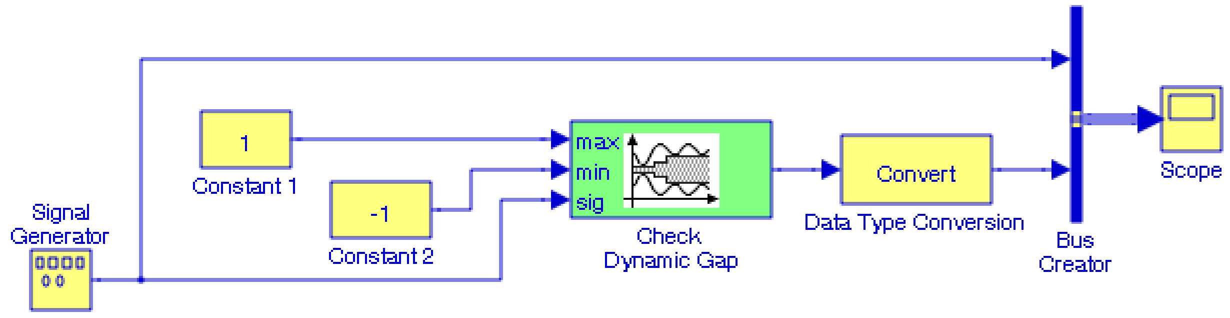


Figure 9.15. Model for Example 9.8

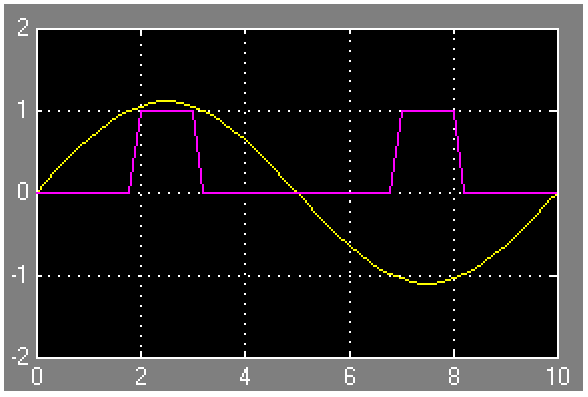
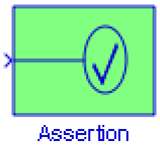


Figure 9.16. Input and output waveforms for the model in Figure 9.15

The Assertion warnings are displayed in MATLAB's Command Window.

9.9 The Assertion Block



The **Assertion** block verifies that the elements of the signal at its input have a non–zero value. If all elements are non–zero, the block takes no action. If any element is zero, the block halts the simulation and displays an error message. The block's parameter dialog box allows us to specify that the block should display an error message when the assertion fails but allows the simulation to continue.

Example 9.9

In the model of Figure 9.17, the **Signal Generator** block was configured for a square waveform, inadvertently the amplitude was specified as 0, and thus the **Scope** block displayed 0 also. To this model we will add an **Assertion** block to display an error message.

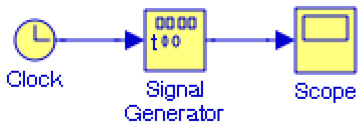


Figure 9.17. Model for Example 9.9 without Assertion block

The model with the addition of an Assertion block is shown in Figure 9.18 where after the simulation command is executed, the following message is displayed:

```
Assertion detected in ‘Figure_9_18/Assertion’ at time 0.000000
```

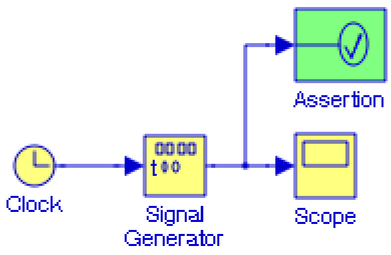
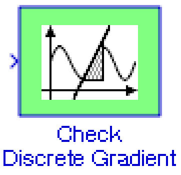


Figure 9.18. Model for Example 9.9 with Assertion block

9.10 The Check Discrete Gradient Block



The **Check Discrete Gradient** block performs a check to determine whether the absolute value of the difference between successive samples of the element is less than an upper bound. The block's parameter dialog box allows us to specify the value of the upper bound whose default value is unity. If the verification condition is true, the block takes no action. Otherwise, the block halts the simulation and displays an error message in the Simulation Diagnostics Viewer.

Example 9.10

In Figure 9.19, the **Digital Clock** block has been set for Sample time 1 as shown on the **Scope** block and thus the difference between successive samples is 1. We will add a **Check Discrete Gradient** block specifying that the value of the upper bound is unity (the default) to determine whether an error message will be displayed.

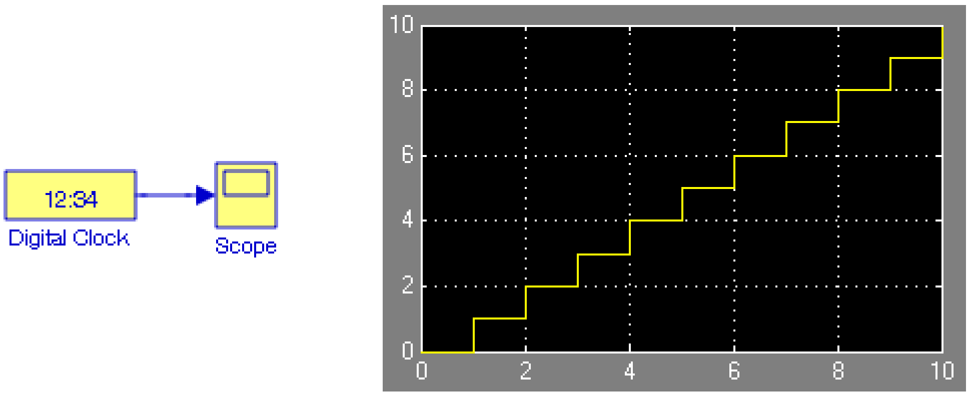


Figure 9.19. Model for Example 9.10 without a Check Discrete Gradient block

The model with the addition of a **Check Discrete Gradient** block where the value of the upper bound is specified as 1 (default), is shown in Figure 9.20. After the simulation command is executed, the following message is displayed:

```
Assertion detected in ‘Figure_9_20/Check Discrete Gradient’ at time
1.000000.
```

However, if the **Digital Clock** block is specified for Sample time less than 1, no error message will be displayed.

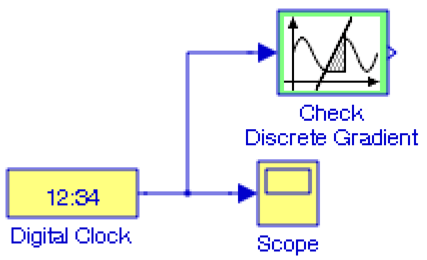
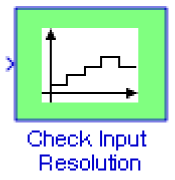


Figure 9.20. Model for Example 9.10 with a Check Discrete Gradient block

9.11 The Check Input Resolution Block



The **Check Input Resolution** block performs a check to determine whether the input signal has a specified scalar or vector resolution.* If the resolution is a scalar, the input signal must be a multiple of the resolution within a 10^{-3} tolerance. If the resolution is a vector, the input signal must equal an element of the resolution vector. If the verification condition is true, the block takes no action. If not, simulation is halted and an error message is displayed.

In general, the resolution of an $n-bit$ analog–to–digital (A/D) converter that spans an input voltage of X volts is given by $X/(2^n-1)$ where n is the number of bit. For instance, an A/D converter with a range of 0 to 12 volts, with $n = 8$ the range is divided to $12/255 \approx 47.1\ mV$ so the resolution is $47.1\ mV$.

Example 9.11

In the model of Figure 9.21, the resolution for both **Check Input Resolution** blocks is specified as the row vector

* *Accuracy and resolution have different meaning. Accuracy is the degree with which an instrument measures a variable in terms of an accepted standard value or true value; usually measured in terms of inaccuracy but expressed as accuracy; often expressed as a percentage of full–scale range. Resolution is the smallest change in the parameter being measured that causes a detectable change in the output of the instrument. For a detailed discussion on accuracy and resolution, please refer to Electronic Devices and Amplifier Circuits with MATLAB Applications, ISBN 0–9709511–7–5.*

$$12 \times \left[\frac{1}{(2^7 - 1)} \quad \frac{1}{(2^8 - 1)} \quad \frac{1}{(2^9 - 1)} \quad \frac{1}{(2^{10} - 1)} \quad \frac{1}{(2^{11} - 1)} \right]$$

and the Enable assertion and Output assertion signal is checked. The values 1 (true) and 0 (false) in the **Display** blocks are justified as follows:

Since the resolution specified in the **Check Input Resolution** blocks is a vector, the input signal must be equal to an element of the resolution vector. The resolution specified in the **Constant 1** block is an element of the resolution vector and thus the output is 1 indicating a True condition. However, the resolution specified in the **Constant 2** block is not an element of the resolution vector and thus the output is 0 indicating a False condition.

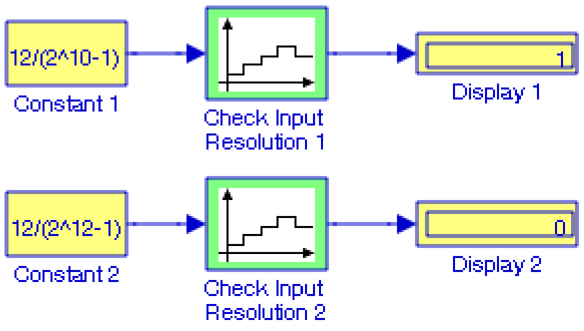


Figure 9.21. Model for Example 9.11

9.12 Summary

The blocks in the Model Verification library are intended to facilitate creation of self–validating models. For instance, we can use model verification blocks to verify that signals do not exceed specified limits during simulation. When we are satisfied that a model is correct, we can turn error checking off by disabling the verification blocks. We need not to physically remove them from the model.

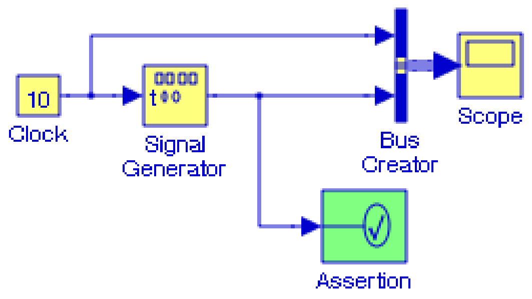
- The **Check Static Lower Bound** block performs a check to verify that each element of the input signal is greater than (or optionally equal to) a specified lower bound at the current time step. The block's parameter dialog box allows us to specify the value of the lower bound and whether the lower bound is inclusive. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Static Upper Bound** block performs a check to verify that each element of the input signal is less than (or optionally equal to) a specified lower bound at the current time step. The block's parameter dialog box allows us to specify the value of the upper bound and whether the bound is inclusive. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Static Range** block performs a check to ascertain that each element of the input signal falls inside the same range of amplitudes at each time step. The block's parameter dialog box allows us to specify the upper and lower bounds of the valid amplitude range and whether the range includes the bounds. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Static Gap** block performs a check to verify that each element of the input signal is less than (or optionally equal to) a static lower bound or greater than (or optionally equal to) a static upper bound at the current time step. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Dynamic Lower Bound** block performs a check to verify that the amplitude of a test signal is less than the amplitude of a reference signal at the current time step. The test signal is the signal connected to the input labeled sig. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Dynamic Upper Bound** block performs a check to verify that the amplitude of a test signal is greater than the amplitude of a reference signal at the current time step. The test signal is the signal connected to the input labeled sig. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Check Dynamic Range** block performs a check to verify that a test signal falls inside a range of amplitudes at each time step. The width of the range can vary from time step to time step. The input labeled sig is the test signal. The inputs labeled min and max are the lower and

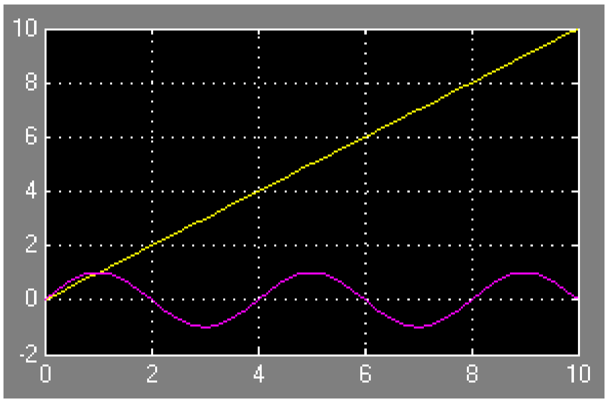
upper bounds of the valid range at the current time step. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.

- The **Check Dynamic Gap** block performs checks to determine whether a gap of possibly varying width occurs in the range of a signal's amplitudes. The test signal is the signal connected to the input labeled sig. The inputs labeled min and max specify the lower and upper bounds of the dynamic gap, respectively. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.
- The **Assertion** block verifies that the elements of the signal at its input have a non–zero value. If all elements are non–zero, the block takes no action. If any element is zero, the block halts the simulation, by default, and displays an error message. The block's parameter dialog box allows us to specify that the block should display an error message when the assertion fails but allows the simulation to continue.
- The **Check Discrete Gradient** block performs a check to determine whether the absolute value of the difference between successive samples of the element is less than an upper bound. The block's parameter dialog box allows us to specify the value of the upper bound (1 by default). If the verification condition is true, the block takes no action. Otherwise, the block halts the simulation and displays an error message in the Simulation Diagnostics Viewer.
- The **Check Input Resolution** block performs a check to determine whether the input signal has a specified scalar or vector resolution. If the resolution is a scalar, the input signal must be a multiple of the resolution within a 10^{-3} tolerance. If the resolution is a vector, the input signal must equal an element of the resolution vector. If the verification condition is true, the block takes no action. If not, the block halts the simulation and displays an error message.

9.13 Exercises

1. Consider the model shown below where the inputs and outputs of the **Signal Generator** block are also shown, and in the parameters for the **Assertion** block the Enable Assertion is checked and the Stop simulation when assertion fails is unchecked. The **Signal Generator** block has been specified for a sine waveform of amplitude 1 and frequency 0.25 Hz to accept an external signal, i.e., the **Clock** block. Under those conditions will the **Assertion** block produce a warning?



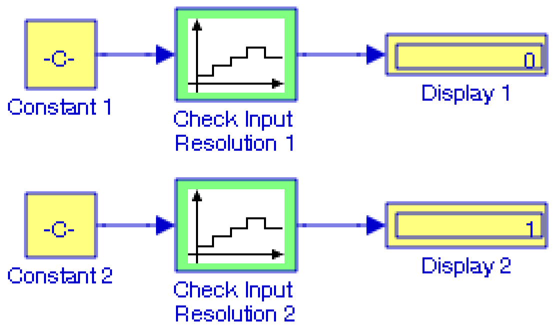


2. It is known that noise voltages generated within the circuitry of an analog–to–digital converter are $0.75\ \mathrm{mv} \pm 10\%$. Create a model using a **Check Dynamic Gap** block to display error messages when the amplitude exceeds this range.

3. For the models shown below, the resolution in both **Check Input Resolution** blocks 1 and 2 has been specified as

$$\frac{12}{(2^n - 1)}$$

with $n = 9$. What is the maximum value that can be specified in **Constant block 1** to cause the **Display 1** block to display 0 (False), and what is the minimum value that will cause the **Display 2** block to display 1 (True)?



9.14 Solutions to End-of-Chapter Exercises

1.

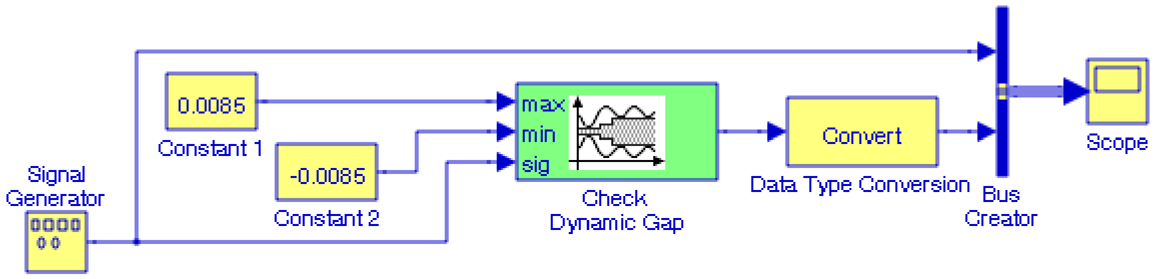
The **Assertion** block detects a 0 value at the start of the simulation time, in this case 10 seconds as shown by the **Clock** block, and thus in MATLAB's Command Window it outputs the message:

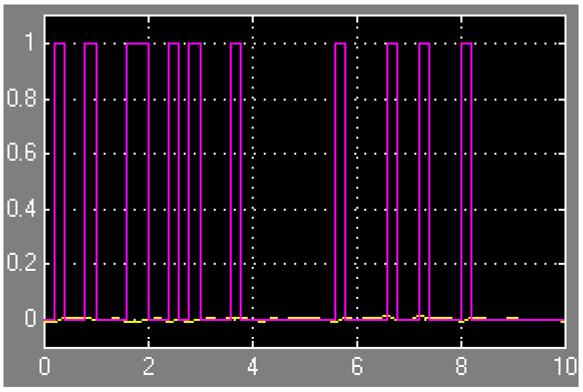
```
Assertion detected in 'Exercise_9_1/Assertion' at time 0.000000.
```

However, the simulation continues for 10 seconds since the **Stop simulation when assertion fails** is unchecked.

2.

The model and input and output waveforms are shown below. Since voltage noise occurs in random, we set the Signal Generator block for Random waveform with amplitude 0.01 and frequency at $0.1\ \mathrm{Hz}$. To allow for the $\pm 10\%$ tolerance from the nominal $0.75\ \mathrm{mv}$ value, we set the Constant blocks for $+0.0085$ and -0.0085.





The output waveform is logic 0 (False) whenever assertions are detected, and jumps to 1 (True) when no assertions are detected. The precise times when assertions are detected are displayed in MATLAB's Command Window.

3.

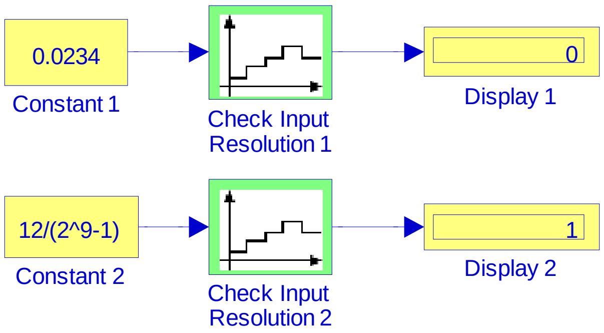
Since the resolution specified in both **Check Input Resolution** blocks is the scalar

$$\frac{12}{(2^9-1)}$$

the input signal must be a multiple of this resolution within a 10^{-3} tolerance. Since,

$$\frac{12}{(2^9-1)} = 0.0235$$

Any value less than $12/(2^9-1)$, e.g., 0.0234 will cause a display of 0 (False) as shown in the models below.

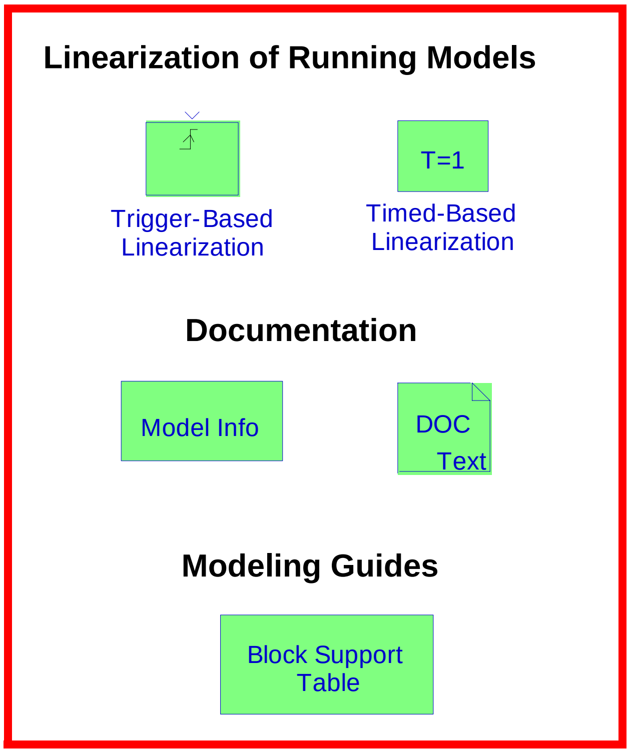


Upon execution of the Simulation command, MATLAB's Command Window displays Assertions detected in the **Check Input Resolution** block 1 from 0 to 10 in steps of 0.2.

Chapter 10

The Model–Wide Utilities Library

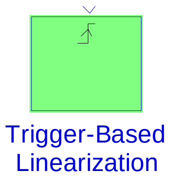
This chapter is an introduction to the **Model–Wide Utilities** library**.** This is the ninth library in the Simulink group of libraries and contains the **Linearization of Running Models Sub–Library**, the **Documentation Sub–Library**, and the **Modeling Guides Sub–Library**. Their functions are illustrated with examples.


Linearization of Running Models
Trigger-Based Linearization
T=1
Timed-Based Linearization
Documentation
Model Info
DOC Text
Modeling Guides
Block Support Table

10.1 The Linearization of Running Models Sub–Library

The **Linearization of Running Models Sub–Library** contains the blocks described in Subsections 10.1.1 and 10.1.2 below.

10.1.1 The Trigger–Based Linearization Block



The **Trigger–Based Linearization** block, when triggered, invokes the MATLAB functions **linmod** or **dlinmod** to create a linear model for the system. No trimming[*] is performed. The linear model is stored in the base workspace as a structure, along with information about the operating point at which the snapshot was taken. Multiple snapshots are appended to form an array of structures.

The name of the structure used to save the snapshots is the name of the model appended by _Trigger_Based_Linearization, for example, vdp_Trigger_Based_Linearization. The structure has the fields shown in the Help menu for this block.

Example 10.1

We will use a **Trigger–Based Linearization** block to extract the linear model for the model shown in Figure 10.1.

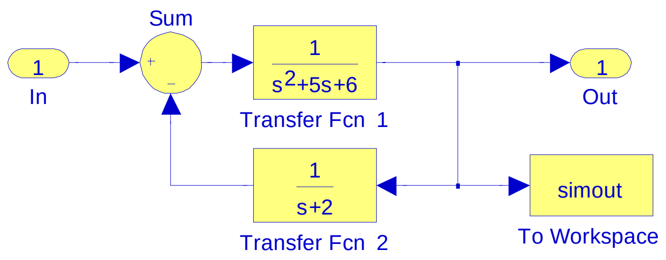


Figure 10.1. Model for Example 10.1

* *The* trim *function uses a Simulink model to determine steady–state points of a dynamic system that satisfy input, output, and state conditions that we can specify. For details please type* help trim *at the MATLAB command prompt.*

This is the same model as that in Figure 3.4, Example 3.3, Chapter 3, Page 3–5, where with the execution of the command [A,B,C,D]=linmod('Figure_3_4') the linear model in the form of the state–space MATLAB displayed the four matrices as

```
A =
     -5      -6     -1
      1       0      0
      0       1     -2
B =
     1
     0
     0
C =
     0     1     0
D =
     0
```

and thus the model of Figure 10.1 can be represented as

$$\dot{x} = \begin{bmatrix} -5 & -6 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & -2 \end{bmatrix} x + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \end{bmatrix} u$$

Next, let us reconsider the model in Figure 10.1 shown as Figure 10.2 where we have included a **Trigger–Based Linearization** block triggered by a **Pulse Generator** block whose period is arbitrarily specified for 10 seconds.

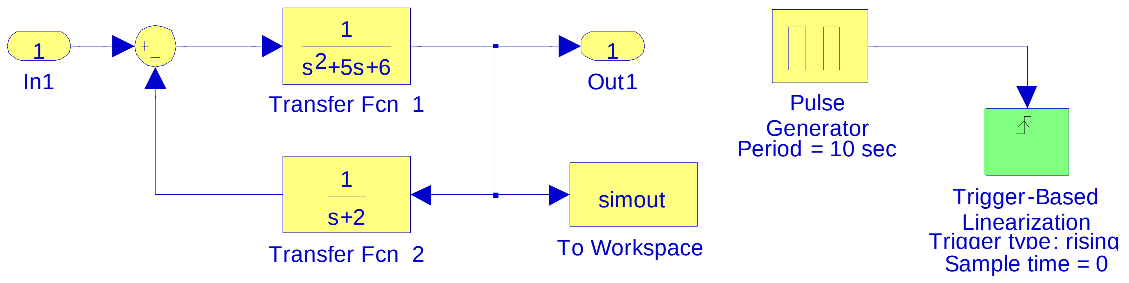


Figure 10.2. Model for Example 10.1 with Trigger–Based Linearization

For the model of Figure 10.2, we execute the simulation command, we save this model as Figure_10_2.mdl, and at the MATLAB command prompt we type and execute the command

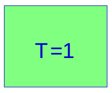
```
Figure_10_2_Trigger_Based_Linearization
```

MATLAB displays the following:

```
Figure_10_2_Trigger_Based_Linearization =
             a: [3x3 double]
             b: [3x1 double]
             c: [0 1 0]
             d: 0
     StateName: {3x1 cell}
    OutputName: {'Figure_10_2/Out1'}
     InputName: {'Figure_10_2/In1'}
     OperPoint: [1x1 struct]
            Ts: 0
```

We observe that a, b, c, and d indicate the sizes of the state−space matrices A, B, C, and D respectively.

10.1.2 The Time−Based Linearization Block



Timed-Based Linearization

The **Time−Based Linearization** block invokes the MATLAB functions **linmod** or **dlinmod** to create a linear model for the system when the simulation clock reaches the time specified by the Linearization time parameter. No trimming is performed. The linear model is stored in the base workspace as a structure, along with information about the operating point at which the snapshot was taken. Multiple snapshots are appended to form an array of structures.

The name of the structure used to save the snapshots is the name of the model appended by _Timed_Based_Linearization, for example, vdp_Timed_Based_Linearization. The structure has the fields shown in the Help menu for this block.

Example 10.2

The model shown in Figure 10.3 is the same model as that of Figure 10.1, Example 10.1. We will use a **Time−Based Linearization** block to extract its linear model.

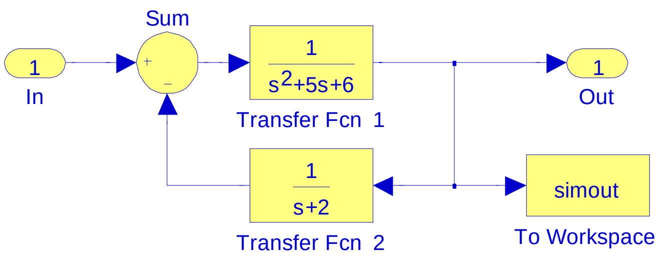


Figure 10.3. Model for Example 10.2

We begin by adding a **Time–Based Linearization** block with the linearization time arbitrarily set for 2 seconds, and the new model is now as shown in Figure 10.4.

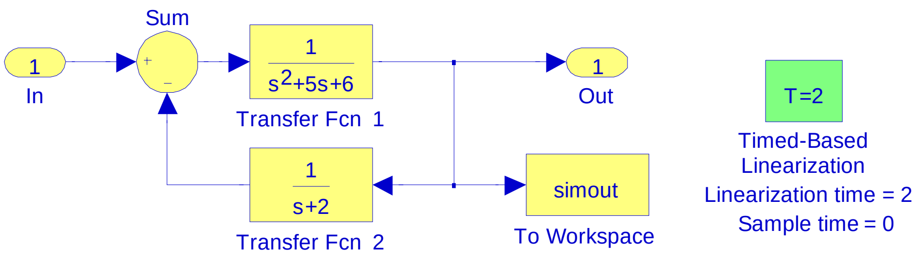


Figure 10.4. Model for Example 10.2 with Timed–Based Linearization block

For the model in Figure 10.4, we execute the simulation command, we save this model as Figure_10_2.mdl, and at the MATLAB command prompt we type

Figure_10_4_Timed_Based_Linearization

and when this command is executed MATLAB displays the following:

```
Figure_10_4_Timed_Based_Linearization =
             a: [3x3 double]
             b: [3x1 double]
             c: [0 1 0]
             d: 0
     StateName: {3x1 cell}
    OutputName: {'Figure_10_4/Out'}
     InputName: {'Figure_10_4/In'}
     OperPoint: [1x1 struct]
            Ts: 0
```

We observe that a, b, c, and d indicate the sizes of the state–space matrices A, B, C, and D respectively.

We can use state and simulation time logging to extract the model states and inputs at operating points. For example, suppose that we want to get the states of the Figure_10_4 model at linearization times of 3 seconds and 7 seconds. This can be done with the following steps:

1. We open the model and drag an instance of this block from the Model–Wide Utilities library and drop the instance into the model.
2. We open the block's parameter dialog box and set the Linearization time to `[3 7]`.The model appears as shown in Figure 10.5.

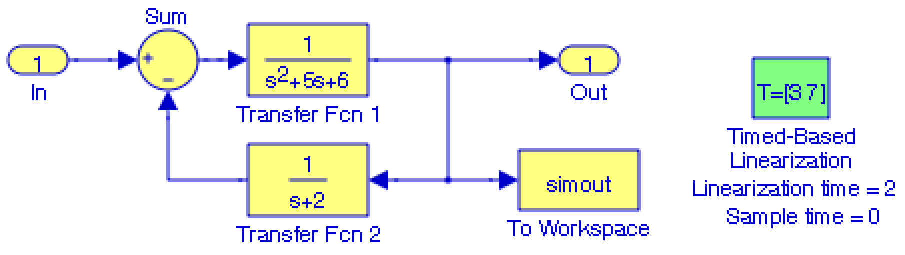


Figure 10.5. Model in Figure 10.4 with linearization times at T= 3 sec and T=7 sec

3. We open the model's Configuration Parameters dialog box from the Simulation drop menu and we select the Data Import/Export pane.
4. We check States and Time on the Save to Workspace control panel, we leave all other parameters in their default state, and we click on OK to confirm the selections and close the dialog box.
5. We start the simulation.
6. At the end of the simulation, we type and execute whos at the MATLAB command prompt, and the following variables appear in the MATLAB workspace:

   `Figure_10_4_Timed_Based_Linearization, tout, and xout.`

7. We obtain the indices to the operating point times by entering and executing the following in MATLAB's Command Window:

```
ind1 = find(Figure_10_4_Timed_Based_Linearization(1).OperPoint.t==tout);
ind2 = find(Figure_10_4_Timed_Based_Linearization(1).OperPoint.t==tout);
```

   We type and execute whos at the MATLAB command prompt, and the indices ind1 and ind2 are now included in the MATLAB workspace:

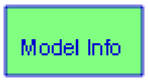
8. We obtain the state vectors at the operating points by entering and executing the following at the MATLAB command prompt:

```
x1 = xout(ind1,:); x2 = xout(ind2,:);
```

10.2 The Documentation Sub–Library

The **Documentation Sub–Library** contains the blocks described in Subsections 10.2.1 and 10.2.2 below.

10.2.1 The Model Info Block



The **Model Info** block displays revision control information about a model as an annotation block in the model's block diagram.

Example 10.3

The model in Figure 10.6 solves the non–linear equation

$$f(z) = z^2 + 4z + 3 + \sin z - z\cos z$$

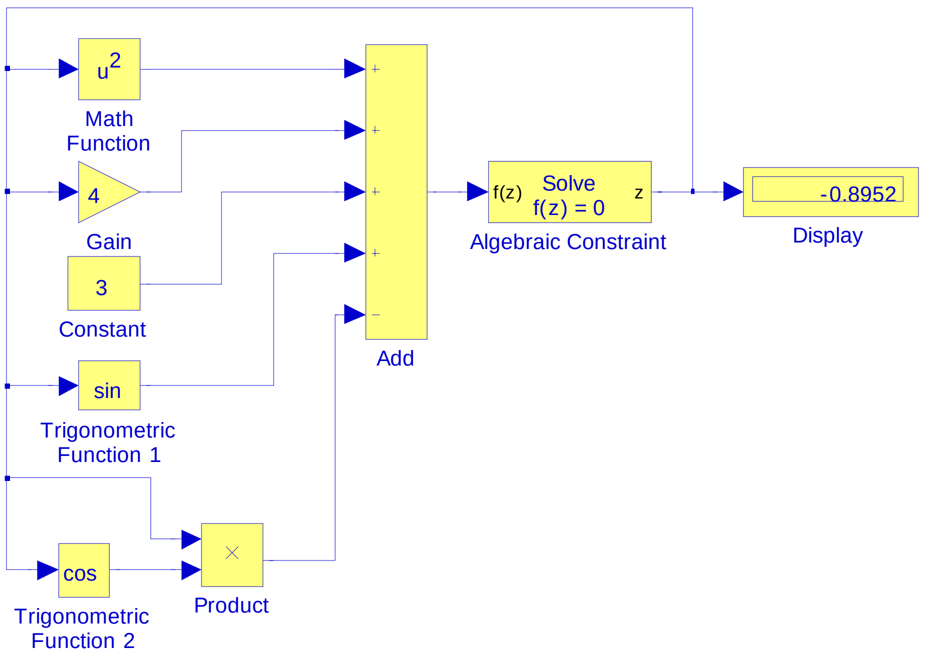
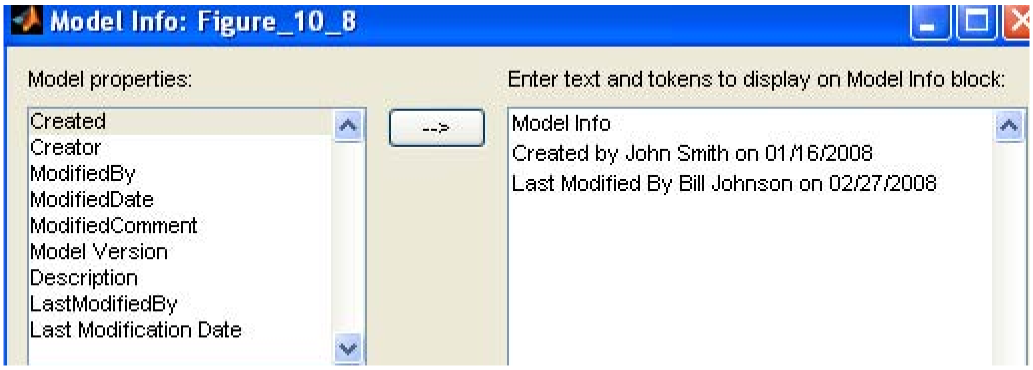


Figure 10.6. Model for Example 10.3

We would like to add a Model Info block to indicate that this model was created by John Smith on 01/16/2008 and was last modified by Bill Johnson on 02/27/2008.

We drag a Model Info block into the model in Figure 10.6, we double–click it, and in the **Model Info** dialog box shown in Figure 10.7 we enter the desired information. The model now appears as shown in Figure 10.8.



Model Info
Created by John Smith on 01/16/2008
Last Modified By Bill Johnson on 02/27/2008

Figure 10.7. Model Properties and Text for the Model Info block

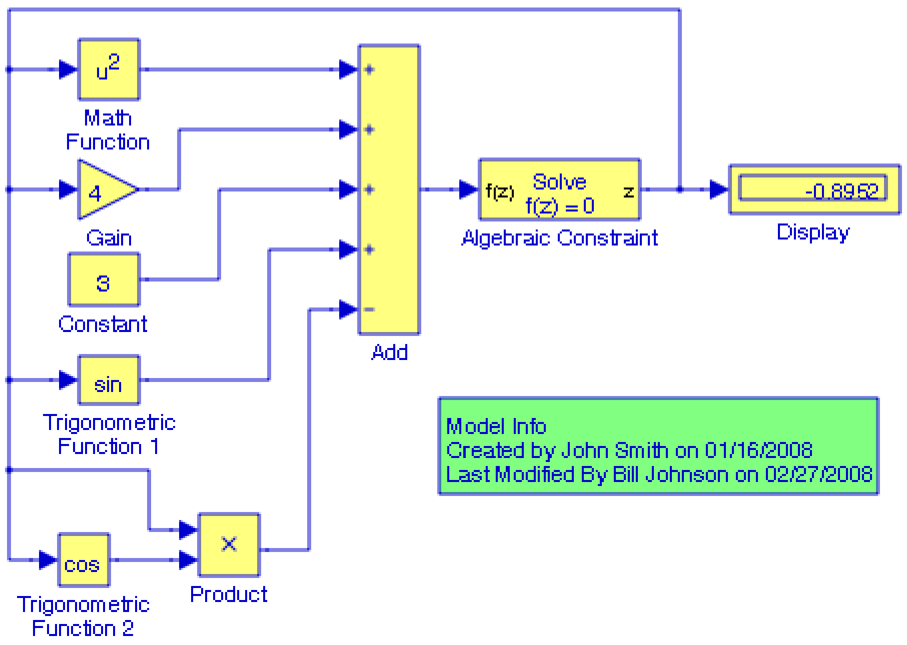


Figure 10.8. Updated model for Example 10.3

10.2.2 The Doc Text Block

The **Doc Text** block or **DocBlock** allows us to create and edit text that documents a model and save that text with the model. To create a file that contains relevant text, we double–click on this block to open the file in the text editor that we have selected in the MATLAB Preferences dialog box. We use the text editor to modify the text and save the file. Simulink stores the contents of the saved file in the model file block.

Example 10.4

In Figure 10.9 the DOC Text block is provided to justify the necessity for the Data Type Conversion block. Let us insert appropriate text for justification.

We double–click on the DOC Text block and in the Text Editor we replace the displayed message with the following text:

The Convert block was inserted to convert the Boolean output of the
Check Dynamic Gap to double as required by the Bus Creator block.

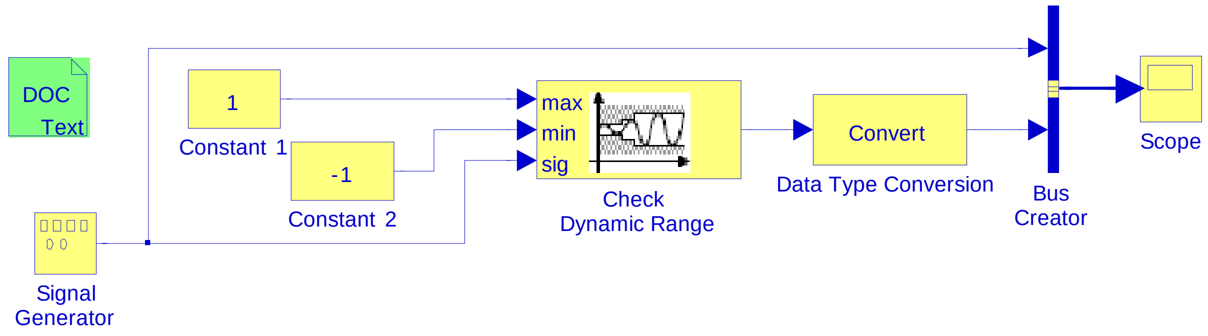


Figure 10.9. Model for Example 10.4

This message will be displayed on MATLAB's Editor Window whenever we double click on the Doc Text block in the model of Figure 10.9.

10.3 The Modeling Guides Sub–Library

The Modeling Guides Sub–Library contains only the **Block Support Table** which is described below.

The **Block Support Table** block includes a table which describes the data types that are supported by blocks in the main Simulink library. All blocks that can generate code contain an "X" in the column titled "Code Generation Support". A subset of these blocks is not recommended for production code as flagged by Note X(4). Guidelines to determine when a block is recommended for production code are listed below the table. Some blocks include caveats and notes that should be taken into account when they are used. Caveats and notes are described below the table.

Example 10.5

For the model in Figure 10.10, we will determine the types of data the **Clock**, **Signal Generator**, and the **Scope** blocks will accept.

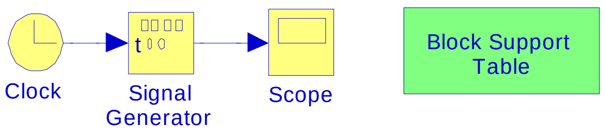


Figure 10.10. Model for Example 10.5

We double–click the **Block Support Table** block and from the table displayed we find that the **Clock** and **Signal Generator** blocks will accept the double data type but as noted by Note X(4) neither is recommended for production code. The **Scope** block will accept all data types listed in the table.

10.4 Summary

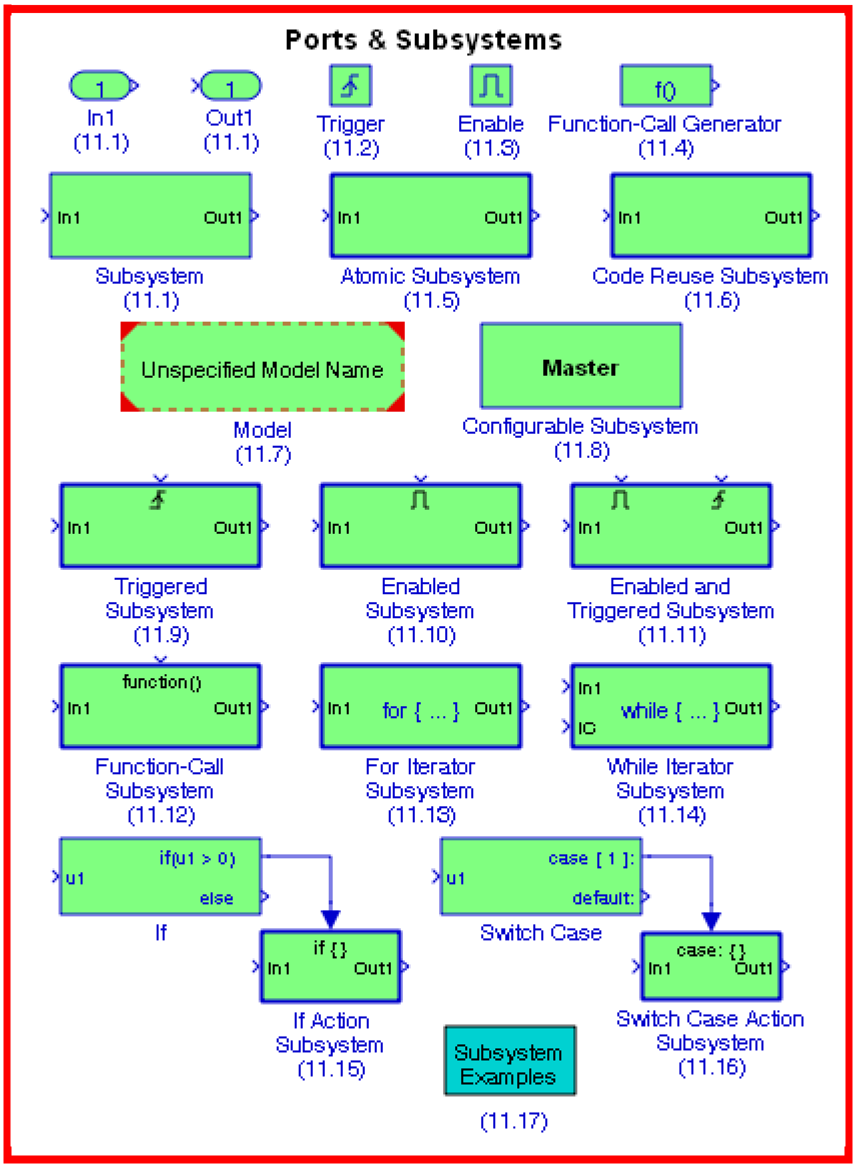
- The **Trigger–Based Linearization** block, when triggered, invokes the MATLAB command **linmod** or **dlinmod** to create a linear model for the system.
- The **Time–Based Linearization** block invokes the MATLAB command **linmod** or **dlinmod** to create a linear model for the system when the simulation clock reaches the time specified by the Linearization time parameter.
- The **Model Info** block The Model Info block displays revision control information about a model as an annotation block in the model's block diagram.
- The **Doc Text** block or **DocBlock** allows us to create and edit text that documents a model and save that text with the model.
- The **Block Support Table** block describes the data types that are supported by blocks in the main Simulink library.

NOTES:

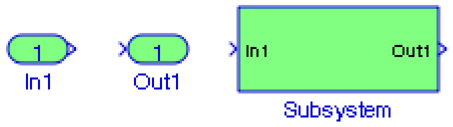
Chapter 11

The Ports & Subsystems Library

This chapter is an introduction to the **Ports & Subsystems** library**.** This is the tenth library in the Simulink group of libraries and contains the blocks shown below. All nonvirtual subsystems, defined in Section 11.17, are shown with a bold border.We will describe the function of each block included in this library and we will perform simulation examples to illustrate their application.

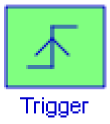

Ports & Subsystems
In1 (11.1)
Out1 (11.1)
Trigger (11.2)
Enable (11.3)
f()
Function-Call Generator (11.4)
Subsystem (11.1)
Atomic Subsystem (11.5)
Code Reuse Subsystem (11.6)
Unspecified Model Name
Model (11.7)
Master
Configurable Subsystem (11.8)
Triggered Subsystem (11.9)
Enabled Subsystem (11.10)
Enabled and Triggered Subsystem (11.11)
function()
Function-Call Subsystem (11.12)
for { ... }
For Iterator Subsystem (11.13)
while { ... }
IC
While Iterator Subsystem (11.14)
if(u1 > 0)
u1
else
If
if { }
If Action Subsystem (11.15)
case [1]:
default:
Switch Case
case: { }
Switch Case Action Subsystem (11.16)
Subsystem Examples (11.17)

11.1 The Inport, Outport, and Subsystem Blocks



Inport blocks are ports that serve as links from outside a system into the system. **Outport** blocks are output ports for a subsystem. A **Subsystem** block represents a subsystem of the system that contains it. These blocks are described in Section 2.1, Chapter 2, Page 2–2.

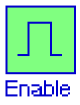
11.2 The Trigger Block



The **Trigger** block is used with a subsystem or a model to allow its execution only when triggered by an external signal provided by the **Trigger** block. We can configure this block to enable a change in the value of the external signal to trigger execution of a subsystem once on each integration step when the value of the signal that passes through the trigger port changes in a specifiable way. We can also configure the **Trigger** block to accept a function–call trigger. This allows a **Function–Call Generator** block or **S–function**[*] to trigger execution of a subsystem or model multiple times during a time step. A subsystem or model can contain only one Trigger block. Examples are presented in Sections 11.9 and 11.11, this chapter, Pages 11–25 and 11–30. For additional information, please refer also to **Triggered Subsystems** in Simulink's documentation.

The Simulink documentation includes the **Block Priority Demonstration** demo and it can be accessed by typing prioritydemo at the MATLAB command prompt.

11.3 The Enable Block



The **Enable** block adds an enable block to a subsystem to make it an enabled subsystem. Enable subsystems are subsystems that execute at each simulation step where the control signal has a positive value. A **Control Signal** is a signal that determines whether a subsystem executes. An enabled subsystem has a single control input which can have a scalar or vector value. If the input is a scalar, the subsystem executes if the input is greater than zero. For instance, if the signal is a waveform (sinusoid, square, sawtooth, etc.), crosses zero, and the slope is positive, the subsystem

* *An introduction and an example of an S–Function is presented in Section 11.18, this Chapter, Page 11–49.*

is enabled. If the signal crosses zero and the slope becomes negative, the subsystem is disabled. If the input is a vector, the subsystem executes if any of the vector elements is greater than zero.

At the start of simulation, Simulink initializes the states of blocks inside an enabled subsystem to their initial conditions. When an enabled subsystem restarts, that is, it executes after having been disabled, the States parameters determine the status of the blocks contained in the enabled subsystem. Thus,

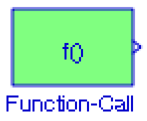
reset resets the states to their initial conditions (zero if not defined).

held holds the states at their previous values.

We can output the enabling signal by selecting the **Show output** port check box in the Block Parameters dialog box. Selecting this option allows the system to process the enabling signal.

To add an Enable block to a subsystem model, we double–click on the subsystem block, and when the subsystem appears, we drag the Enable block into it. An example is presented in Section 11.6, Figure 11.15, this chapter, Page 11–14.

11.4 The Function–Call Generator Block



The **Function–Call Generator** block executes a function–call subsystem at the rate specified by the block's Sample time parameter. We can execute multiple function–call subsystems in a prescribed order by first connecting a Function–Call Generator block to a Demux block that has as many output ports as there are function–call subsystems to be controlled. Then, we can connect the output ports of the Demux block to the systems to be controlled. The system connected to the first demux port executes first, the system connected to the second demux port executes second, and so on. We can configure Stateflow®* blocks to execute function–call subsystems, thereby extending the capabilities of the blocks. For more information on their use in Stateflow, please refer to the Stateflow documentation.

Example 11.1

The model of Figure 11.1 shows how a **Function–Call Generator** block and a **Demux** block can be used to control four different **Function–Call Subsystem** blocks. The **Function–Call Subsystem** block is described in Section 11.12, this chapter, Page 11–34.

* *For an introduction to Stateflow, please refer to Introduction to Stateflow with Applications, ISBN 978–1–934404–07–2.*

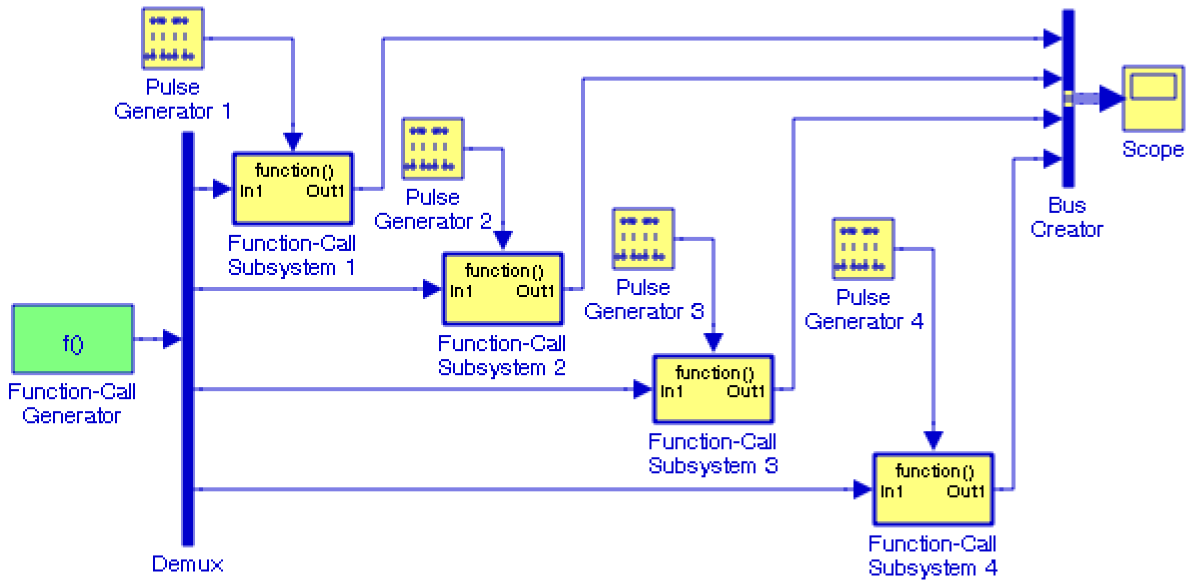
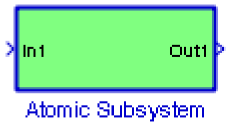


Figure 11.1. Model for Example 11.1

The Simulink documentation includes the **Subsystem Semantics** demo, the **Model Reference Function Call** demo, and the **Function Call Counter** demo. They can be accessed by entering sl_subsys_semantics, sldemo_mdlref_fcncall, and sldemo_mdlref_fcncall_cntr at the MATLAB command prompt respectively.

11.5 The Atomic Subsystem Block



In Chapter 2, Section 2.1, Page 2–2, we described the **Subsystem**, **Inport**, and **Outport** blocks. As we recall, we select the blocks and lines which will become parts of the subsystem using a bounding box, then we choose **Create Subsystem** from the **Edit** menu. Simulink replaces the blocks with a Subsystem block. When we double–click the subsystem block, a model appears which displays the blocks that we have selected, and adds **Inport** and **Outport** blocks to indicate the signals entering and leaving the subsystem.

We can also create a subsystem using the **Atomic Subsystem** block. This is done by copying the **Atomic Subsystem** block from the **Ports & Subsystems** library into our model. Then we can add blocks to the subsystem by opening the **Subsystem** block and copying blocks into it.

Example 11.2

Figure 11.2 shows a four–line–to–one–line digital multiplexer whose truth table is shown as Table 11.1 below. This model is saved as Figure_11_2.

TABLE 11.1 Truth table for Example 11.2

Inport 6	Inport 5	Output
0	0	D
0	1	C
1	0	B
1	1	A

We will use an **Atomic Subsystem** block to create a subsystem for this multiplexer. We do so by selecting all blocks in this model and copying them into new model which we name Figure_11_2S. From the **Ports & Subsystems** library, we drag the **Atomic Subsystem** block into model Figure_11_2S and we save it with the same name. It is shown as Figure 11.3, and it is annotated as Saved as Figure_11_2S.

Next, we double–click the **Atomic Subsystem** block in Figure 11.3, and we observe that it is now displayed with an **Inport** block and an **Outport** block connected by a straight line as shown in Figure 11.4. It is annotated as Figure_11_2S/Atomic Subsystem, and it is saved with this name.

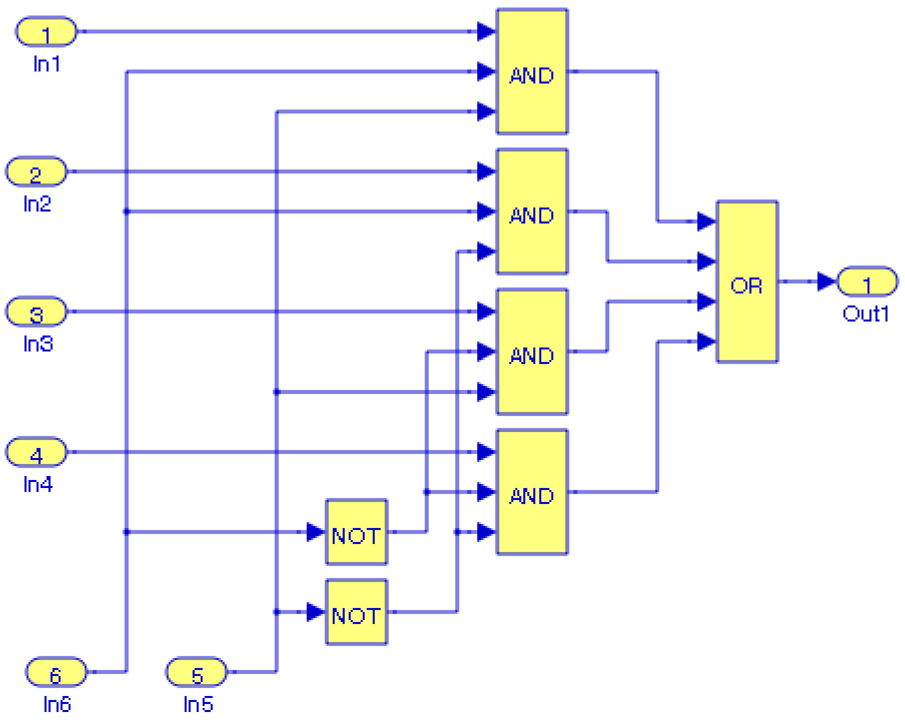


Figure 11.2. Digital multiplexer circuit for Example 11.2

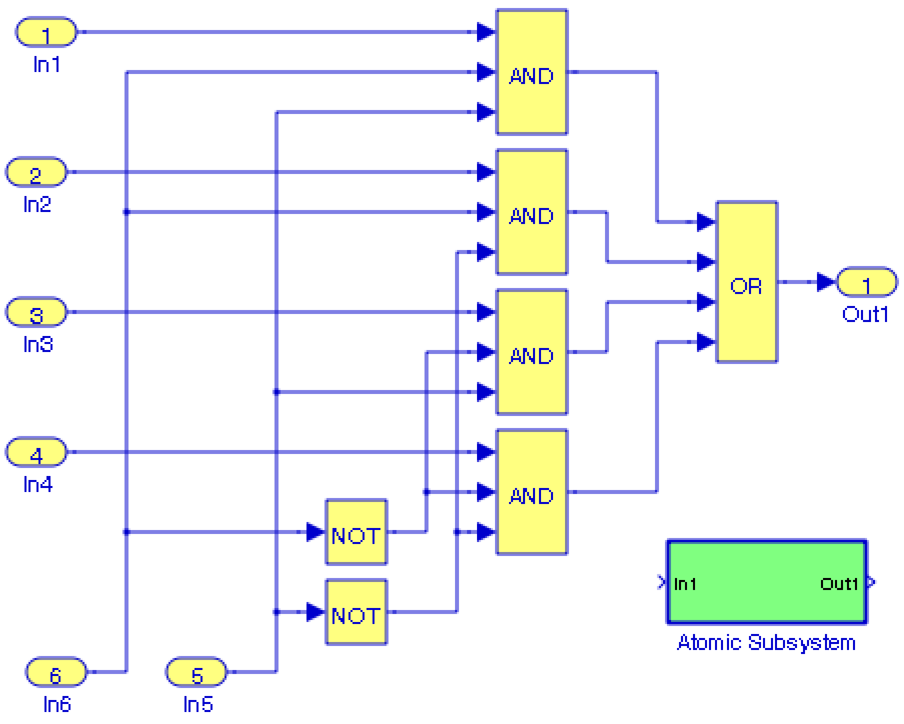


Figure 11.3. Model in Figure 11.2 saved as Figure_11_2S

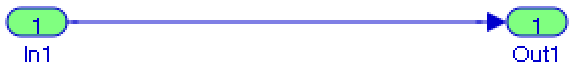


Figure 11.4. The updated appearance of the Atomic Subsystem block of Figure 11.3

We open the model of Figure 11.2, we saved it as Figure_11_2, we choose **Select All** from the **Edit** menu, and we drag it into the model of Figure 11.4 which now appears as in Figure 11.5. We save the model of Figure 11.5 with the same name as that of Figure 11.4, i.e., Figure_11_2S/ Atomic Subsystem.

Now, we reopen the model of Figure 11.3 and we observe that the Atomic Subsystem block appears as shown in Figure 11.6. We double−click the **Atomic Subsystem** block of Figure 11.6 and we observe that it has the appearance of Figure 11.5.

We no longer need the **In1** and **Out1** blocks shown on top of the model of Figure 11.5, so we delete them, and we also delete the interconnecting line. We also relabel the **In** and **Out** blocks as In 1, In 2,..., In 6, and Out, and we save this model with the same name. We return to the model with the Atomic Subsystem block, we copy it into a new model, we expand it, and we save it. It is shown as Figure 11.7.

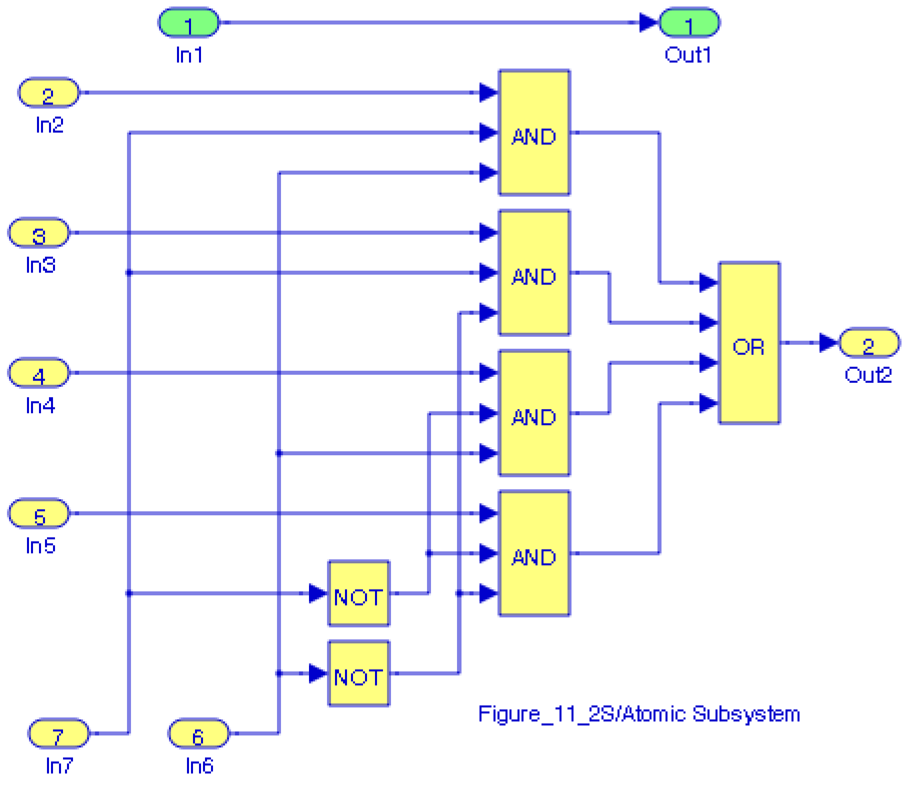


Figure 11.5. The model in Figure 11.2 copied into the model in Figure 11.4

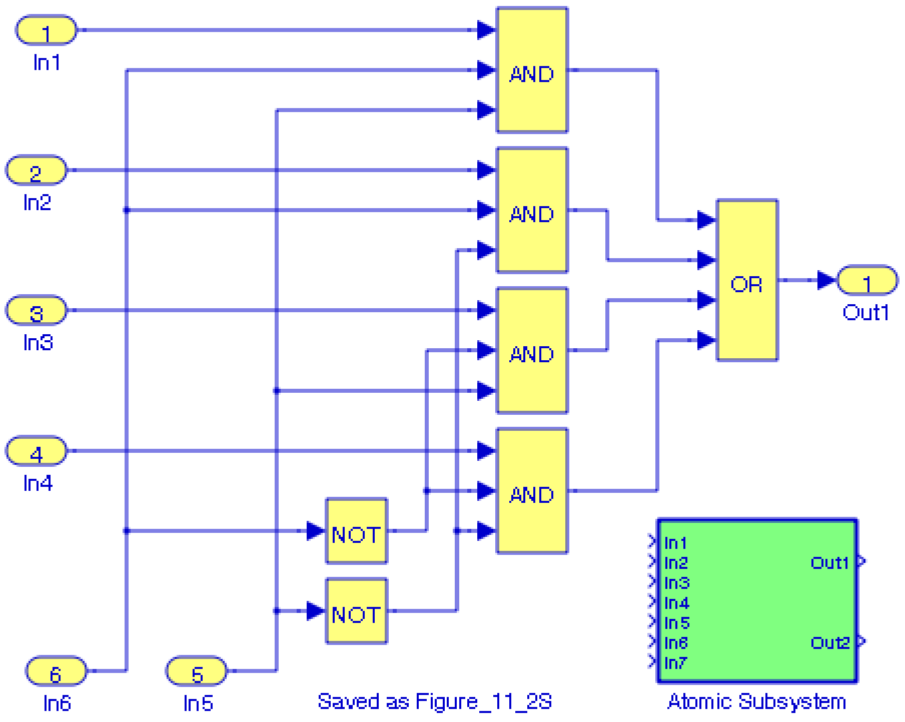


Figure 11.6. Updated appearance of the Atomic Subsystem block

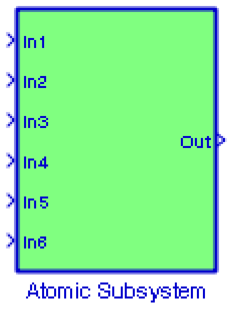


Figure 11.7. The multiplexer in Figure 11.2 shown as an Atomic Subsystem.

To verify that the Atomic Subsystem of Figure 11.7 performs in accordance with the truth table, we assign the variables A, B, C, and D and control lines C0 and C1 as shown in Figure 11.8 and successively we assign the values shown below at the MATLAB command prompt. With these values, the output of the digital multiplexer is logical 1 (True).

```
A=1; C0=1; C1=1;
B=1; C0=0; C1=1;
C=1; C0=1; C1=0;
D=1; C0=0; C1=0;
```

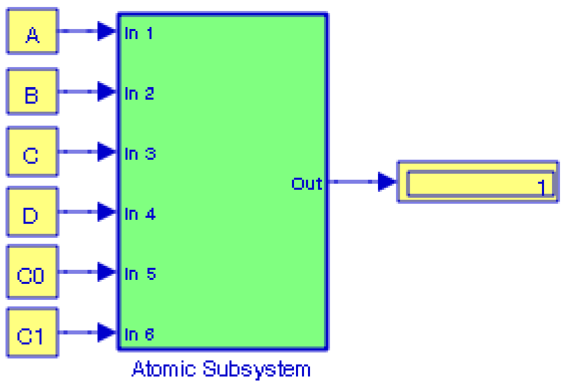
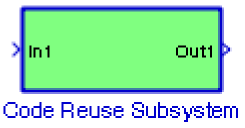


Figure 11.8. The Atomic Subsystem with inputs and output to verify the truth table in Example 11.2

11.6 The Code Reuse Subsystem Block



The **Code Reuse Subsystem** block is a Subsystem block that represents a subsystem of the system that contains it. It is very similar to the Atomic Subsystem which we discussed in the previous section. We can create a subsystem either by copying the **Subsystem** (or **Atomic Subsystem**) block from the **Ports & Subsystems** library into our model and add blocks to the subsystem by opening the **Subsystem** block and copying blocks into its window, or by selecting the blocks and lines that are to make up the subsystem using a bounding box, then choosing **Create Subsystem** from the **Edit** menu. Simulink replaces the blocks with a **Subsystem** block. When we double–click the block, the window displays the blocks which we selected.

Example 11.3

Figure 11.9 is a block diagram of a decimal–to–BCD encoder digital circuit. We will use the truth table of Table 11.2 below to create a model for the decimal–to–BCD encoder circuit.

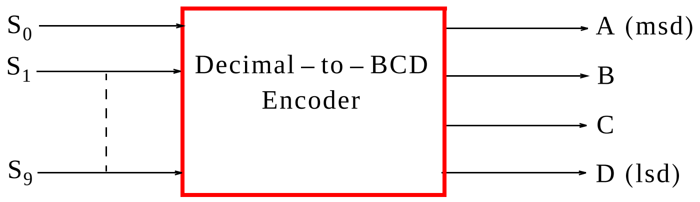


Figure 11.9. Block diagram for decimal–to–BCD encoder

TABLE 11.2 Truth table for decimal–to–BCD encoder

Inputs										Outputs			
S_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	A	B	C	D
1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	1
0	0	1	0	0	0	0	0	0	0	0	0	1	0
0	0	0	1	0	0	0	0	0	0	0	0	1	1
0	0	0	0	1	0	0	0	0	0	0	1	0	0
0	0	0	0	0	1	0	0	0	0	0	1	0	1
0	0	0	0	0	0	1	0	0	0	0	1	1	0
0	0	0	0	0	0	0	1	0	0	0	1	1	1
0	0	0	0	0	0	0	0	1	0	1	0	0	0
0	0	0	0	0	0	0	0	0	1	1	0	0	1

From the truth table above we derive the following relations:

$$\begin{aligned} A &= S_8 + S_9 \\ B &= S_4 + S_5 + S_6 + S_7 \\ C &= S_2 + S_3 + S_6 + S_7 \\ D &= S_1 + S_3 + S_5 + S_7 + S_9 \end{aligned} \tag{11.1}$$

where A is the most significant bit and D is the least significant bit. We can implement the decimal–to–BCD encoder with either the circuit of Figure 11.10 or the circuit of Figure 11.11. The latter is more practical since five–input OR gates are not standard IC devices. In both circuits the input S_0 is terminated inside the circuit since it does not appear in the relations of (11.1).

The problem statement instructs us to design a logic circuit whose inputs are the decimal numbers 0 through 9 denoted as switches S_0 through S_9, and the output is the BCD code, that is, the logic circuit has ten input lines and four output lines as shown in Figures 11.10 and 11.11. Obviously, only one of the ten switches S_0 through S_9 will be closed (will be logical 1) at any time and thus the truth table is as presented above.

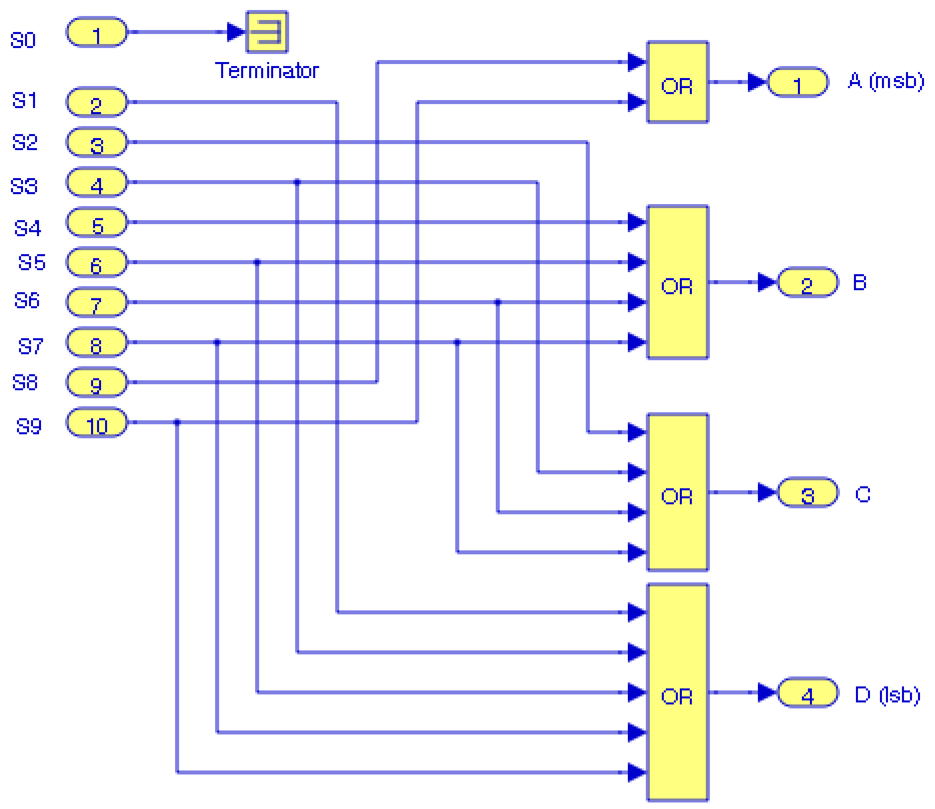


Figure 11.10. Decimal−to−BCD encoder circuit with non−standard OR gates

We save the model in Figure 11.10 as Figure_11_10, and we save the model in Figure 11.11 as Figure_11_11. Next, we open a new model and we name it Figure_11_12. From the **Ports & Subsystems** library we drag a **Code Reuse Subsystem** block into model Figure_11_12 and we label it Code Reuse Subsystem 1. We double−click on the **Code Reuse Subsystem 1** block and in the Figure_11_12/Code Reuse Subsystem 1 window we drag the model of Figure_11_10, and we save it. Now, we double−click on the **Code Reuse Subsystem 1** block in the model Figure_11_12 and the encoder circuit in Figure 11.10 appears.

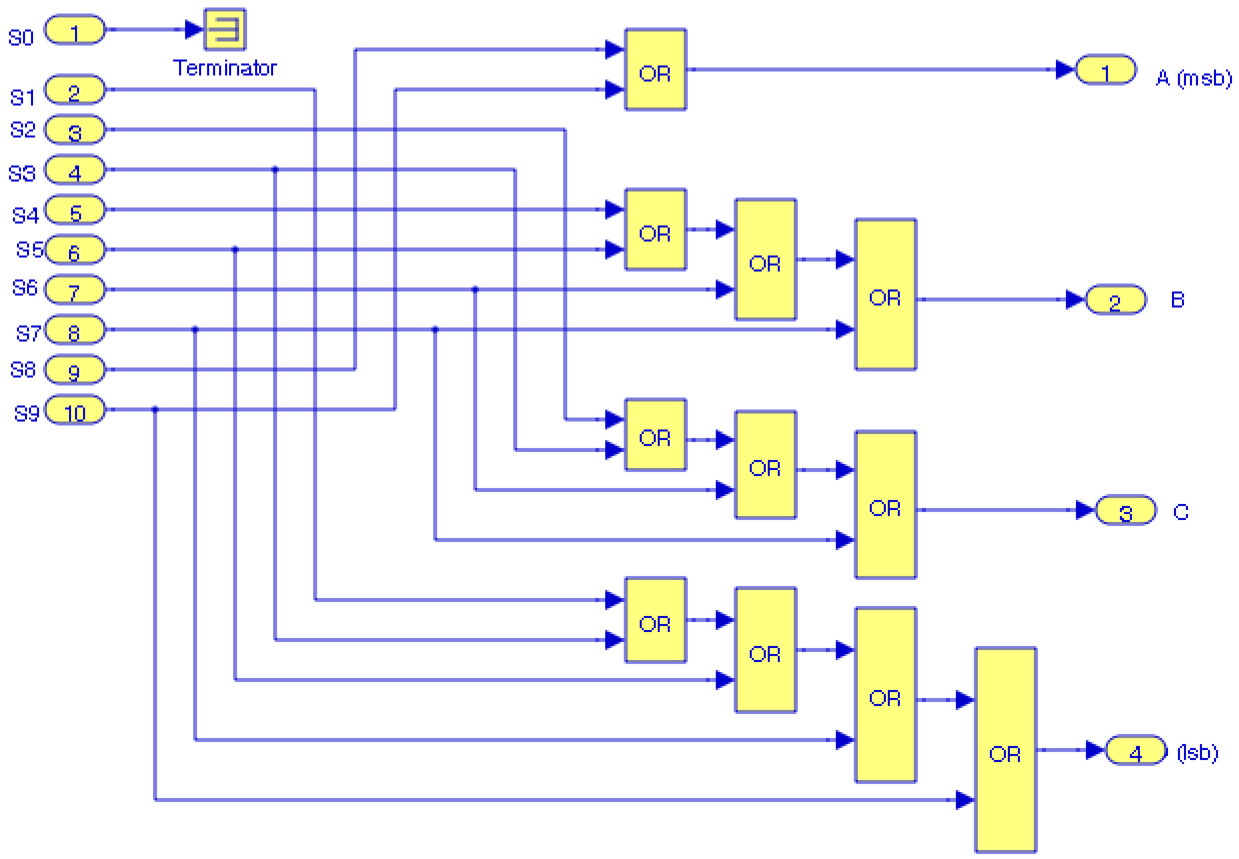


Figure 11.11. Decimal–to–BCD encoder with standard 2–input OR gates

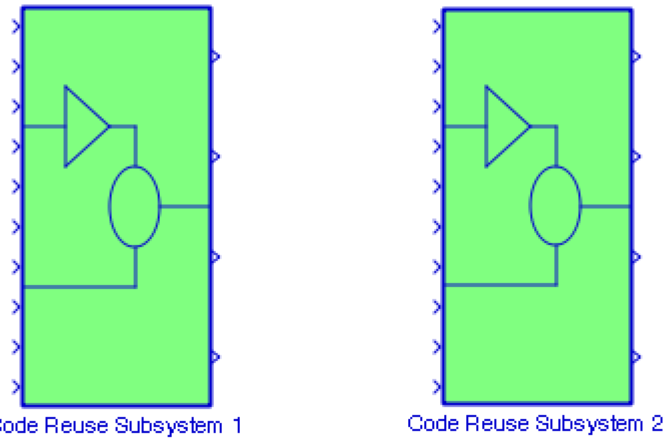


Figure 11.12. Models in Figures 11.10 and 11.11 shown as subsystems

We repeat these steps for model Figure_11_11 shown in Figure 11.11 and we label it Code Reuse Subsystem 2 as shown in Figure 11.12.

We can verify that the outputs of both subsystems in Figure 11.12 are as specified in the given truth table. With the inputs and outputs labeled as shown in Figure 11.13, we can verify the BCD codes 0000 0001 0010 … 1001 by entering the values of S_1, S_2, …, S_9 at the MATLAB command prompt as follows:

```
S0=0; S1=0; S2=0; S3=0; S4=0; S5=0; S6=0; S7=0; S8=0; S9=0;
S0=0; S1=0; S2=1; S3=0; S4=0; S5=0; S6=0; S7=0; S8=0; S9=0;
S0=0; S1=0; S2=0; S3=1; S4=0; S5=0; S6=0; S7=0; S8=0; S9=0;
S0=0; S1=0; S2=0; S3=0; S4=0; S5=0; S6=0; S7=0; S8=0; S9=1;
```

The MATLAB script above defines the BCD value 1001 which is equivalent to decimal number 9 and it is displayed by both subsystems in Figure 11.13.

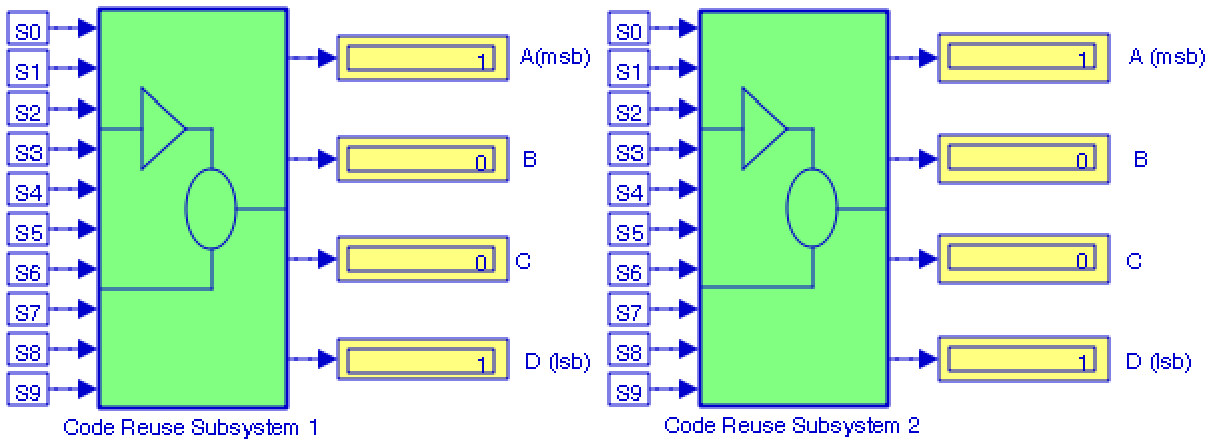


Figure 11.13. Subsystems for truth table verification of Table 11.2, Example 11.3

Example 11.4

In this example, we will add an **Enable** block to **Code Reuse Subsystem 1** in Figure 11.13 which now is shown in Figure 11.14. We will use a **Pulse Generator** block to generate the enable control signal.

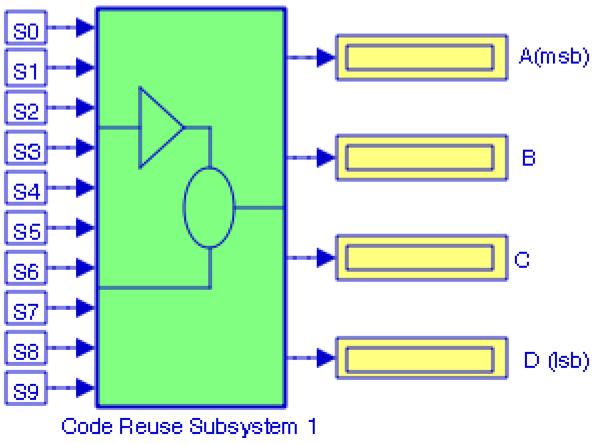


Figure 11.14. Subsystem for Example 11.4

We cannot drag the **Enable** block into the subsystem model of Figure 11.14; we must double–click it, and when its subsystem appears as in Figure 11.10, from the **Ports & Subsystems** library we drag the **Enable** block which now appears as shown in Figure 11.15.

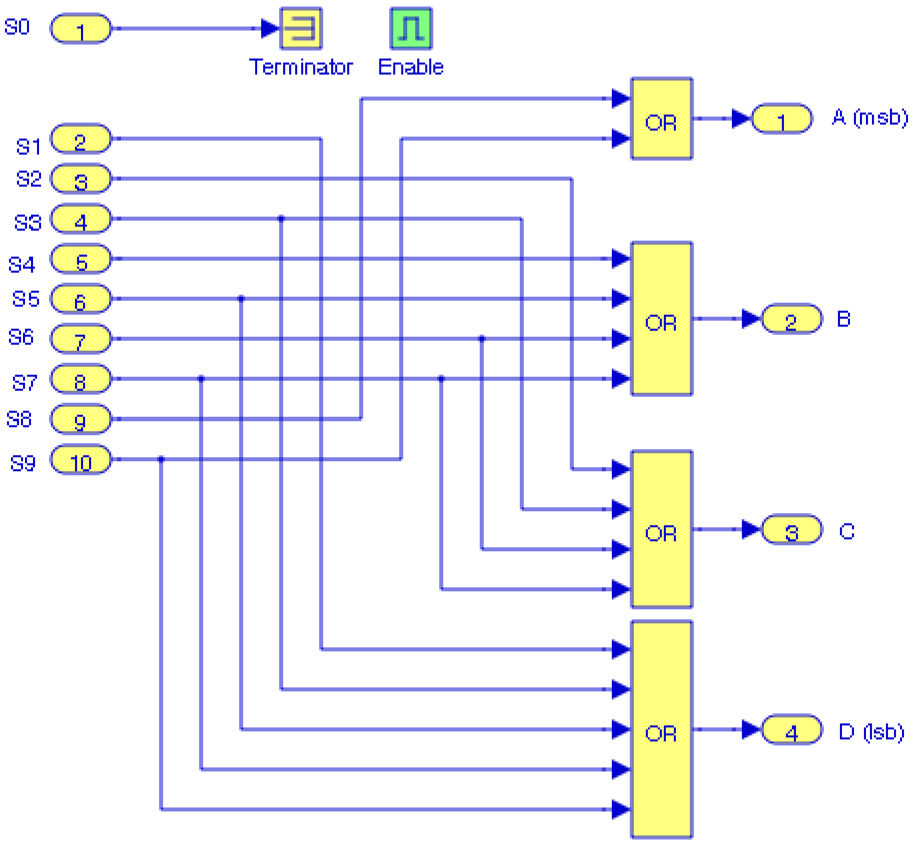


Figure 11.15. Model for Example 11.4 with Enable block

We save it as Figure_11_15.

The subsystem of Figure 11.14 now appears as shown in Figure 11.16 with another input on top of it for the **Enable** control signal. To this input we connect a **Pulse Generator** block as shown in Figure 11.17.

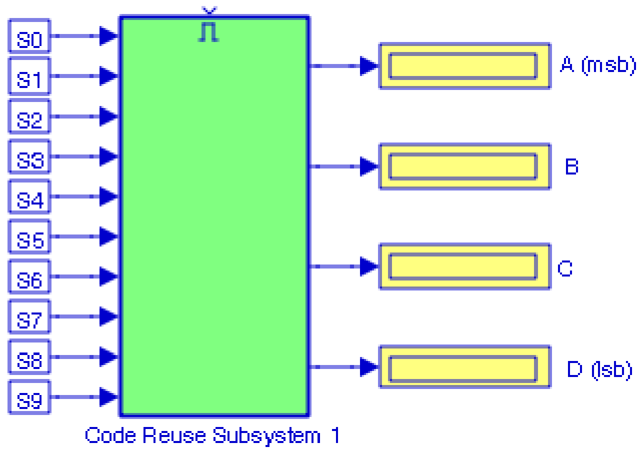


Figure 11.16. The Code Reuse Subsystem 1 block with the Enable input on top

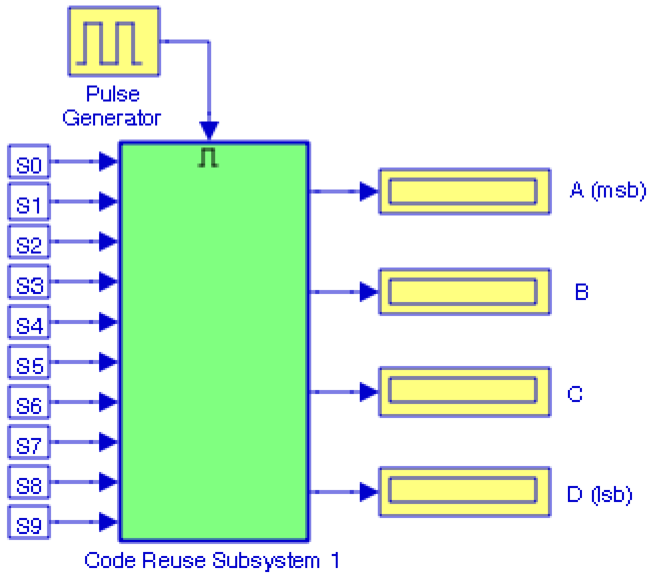


Figure 11.17. The Code Reuse Subsystem 1 block with Pulse Generator block connected to Enable port

When the Simulation command is executed, the outputs are $A = 1$, $B = 0$, $C = 0$, and $D = 1$ since the last entry into MATLAB's Command Window was as follows:

```
S0=0; S1=0; S2=0; S3=0; S4=0; S5=0; S6=0; S7=0; S8=0; S9=1;
```

Next, we remove the **Pulse Generator** block from the model of Figure 11.17 and reissue the Simulate command. We observe that all four outputs are now zero as shown in Figure 11.18 even though at the MATLAB command prompt the last entry was:

```
S0=0; S1=0; S2=0; S3=0; S4=0; S5=0; S6=0; S7=0; S8=0; S9=1;
```

This occurred because the **Enable** Control Signal provided by the **Pulse Generator** block was removed.

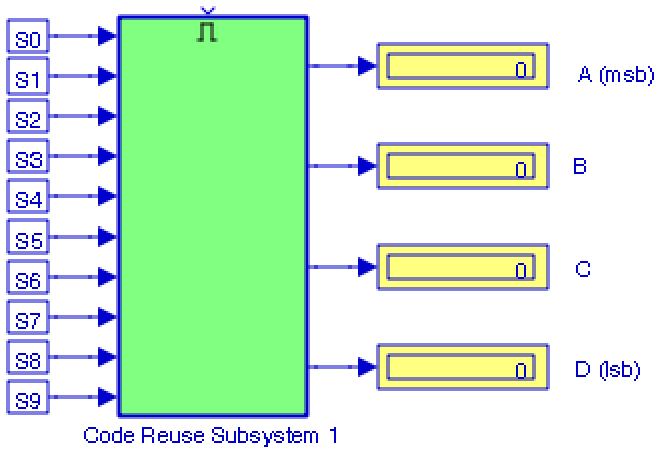


Figure 11.18. Outputs when the Pulse Generator block is removed from the subsystem of Figure 11.17

As stated earlier, we can output the enabling signal by selecting the **Show** output port check box. When we choose this option we allow the subsystem to display the status the **Enable** signal. The subsystem then appears as shown in Figure 11.19 assuming that the **Pulse Generator** block is connected as shown in Figure 11.17.

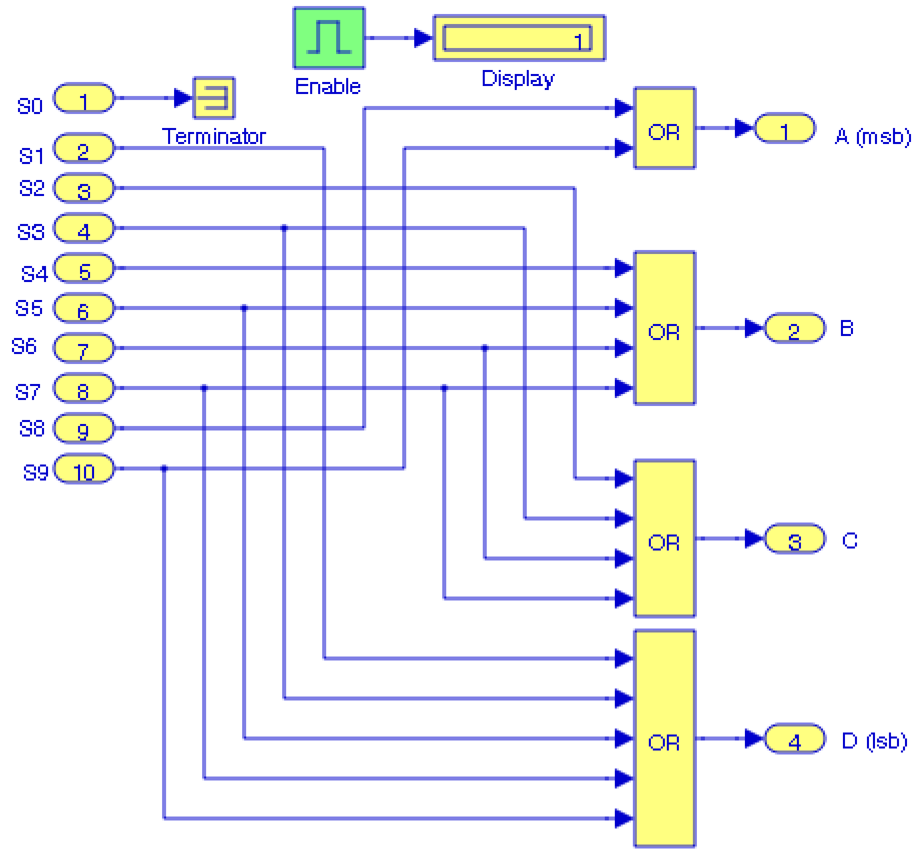
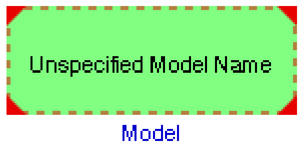


Figure 11.19. The Enable block with the Show output selected

11.7 The Model Block



The **Model** block is used to specify the name of a Simulink model. The name must be a valid MATLAB identifier. The model must exist on the MATLAB path and the MATLAB path must contain no other model having the same name. To add the name of a saved model on the MATLAB path, we open the Command Window, we choose **Set Path** from the **File** menu, we click the **Add Folder field**, we select the path to be added from the **Browse for Folder**, and we click **OK**.

Example 11.5

We will use the **Model** block to specify the model Figure_11_11 which we saved by this name in Example 11.3.

We open a new model and we drag a **Model** block into it. The Model block appears as shown in Figure 11.20.

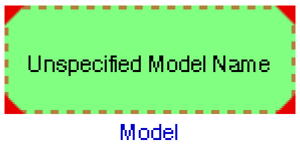


Figure 11.20. The first appearance of a Model block in a new model

We double click the **Model** block and in the **Parameters** dialog box we enter the saved model name without the < and the > symbols and without the .mdl extension. The **Model** block now appears as shown in Figure 11.21.

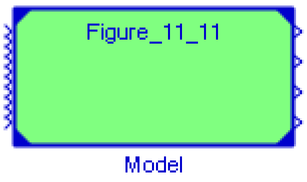


Figure 11.21. The appearance of a Model block with a saved model name

Next, we double–click the Model block in Figure 11.21 and the model Figure_11_11 appears as shown in Figure 11.22. This is the same model as that shown in Figure 11.11.

The Simulink documentation includes the **Component–Based Modeling with Model Reference** demo, the **Parameterizing Model Reference** demo, and the **Converting Subsystems to Model Reference** demo. They can be accessed by entering at the MATLAB command prompt sldemo_mdlref_basic, sldemo_mdlref_paramargs, and sldemo_mdlref_conversion respectively.

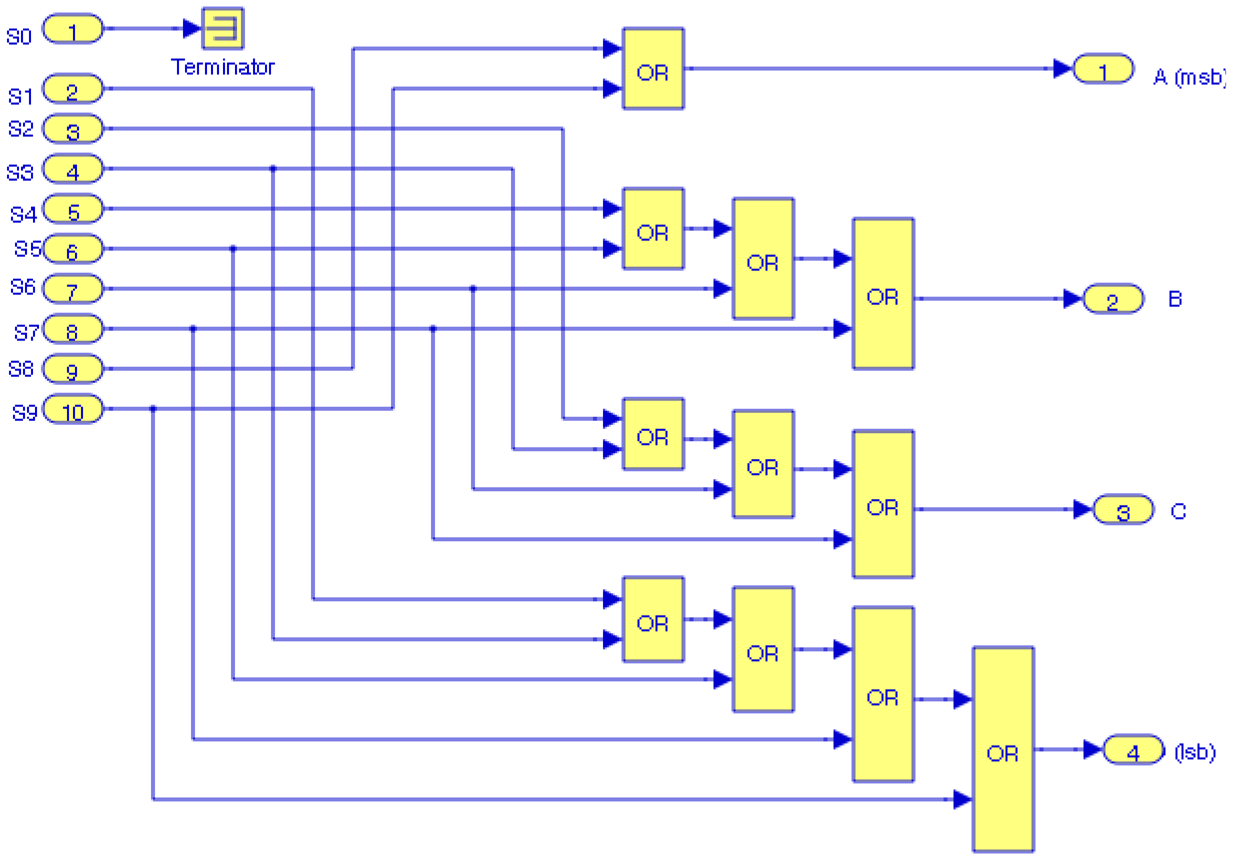
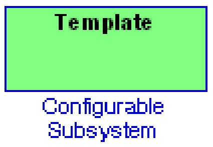


Figure 11.22. Model displayed by the Model block in Figure 11.21

11.8 The Configurable Subsystem Block



The **Configurable Subsystem** block[*] represents one of a set of blocks contained in a specified library of blocks. The block's context menu lets us choose which block the configurable subsystem represents. A configurable Subsystem block simplifies the creation of models that represent families of designs.

* *We cannot insert this block to a new model window. This block must be placed in a library to be used. We create a new library by choosing* ***New Library*** *from the* ***File*** *menu.*

For example, suppose that we want to model a full adder[*] digital circuit that offers a choice of logic gates, e.g., NAND, NOR, AND, OR and NOT, or by the combination of two half–adders. To model such a design, we must first create a library of models of the logic gates available. We would then use a **Configurable Subsystem** block in our model to represent the choice of the logic. To model a particular variant of the basic design, a user needs only choose the logic gate type, using the configurable block's dialog box.

To create a configurable subsystem in a model, we must first create a library containing a master configurable subsystem and the blocks that it represents. We can then create configurable instances of the master subsystem by dragging copies of the master subsystem from the library and dropping them into models. We can add any type of block to a master configurable subsystem library. Simulink derives the port names for the configurable subsystem by making a unique list from the port names of all the choices. Simulink uses default port names for non–subsystem block choices.

Example 11.6

We will create a new library with two binary full–adder circuits. The first will be designed with a combination of AND, OR, and NOT gates as shown in Figure 11.23, and the second will be formed by cascading two half–adders as shown in Figure 11.24. We will create a subsystem for each, and these subsystems will constitute the blocks of the new library where **Subsystem 1** will represent the full–adder of Figure 11.23, and **Subsystem 2** will represent the full adder of Figure 11.24. Then, we will create a model for a four–bit binary adder by cascading four one–bit full adder blocks of the **Subsystem 1**.

In both models of Figures 11.23 and 11.24 the first output represents the Sum bit and the second output represents the Carry bit. It is not necessary to assign **Outport** blocks but it is necessary to assign **Inport** blocks as shown, otherwise the inputs would be shown as unconnected lines. Next, we create subsystems for each by enclosing all blocks except the Inport blocks, and we choose **Create Subsystem** from the **Edit** menu. The created subsystems are as shown on the left side of Figures 11.25 and 11.26. The **Inport** blocks are no longer required and are deleted. The subsystem blocks are thus simplified as shown on the right side of Figures 11.25 and 11.26.

We will now create a new library. This is done by clicking on **File>New>Library**, and we name it Library_Example_11_6. From the subsystem model of Figure 11.25 we drag the **Subsystem 1A** block into this new library. We also drag the **Subsystem 2A** block from the model of Figure 11.26 into this library. Our library now looks as shown in Figure 11.27 where **Subsystem 1A** block represents the full–adder implemented with AND, OR, and NOT gates, and **Subsystem 2A** block represents the full–adder implemented with two half–adders.

[*] *For a detailed discussion and design of a full adder digital circuit please refer to Digital Circuit Analysis and Design with Simulink Modeling and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–05–8.*

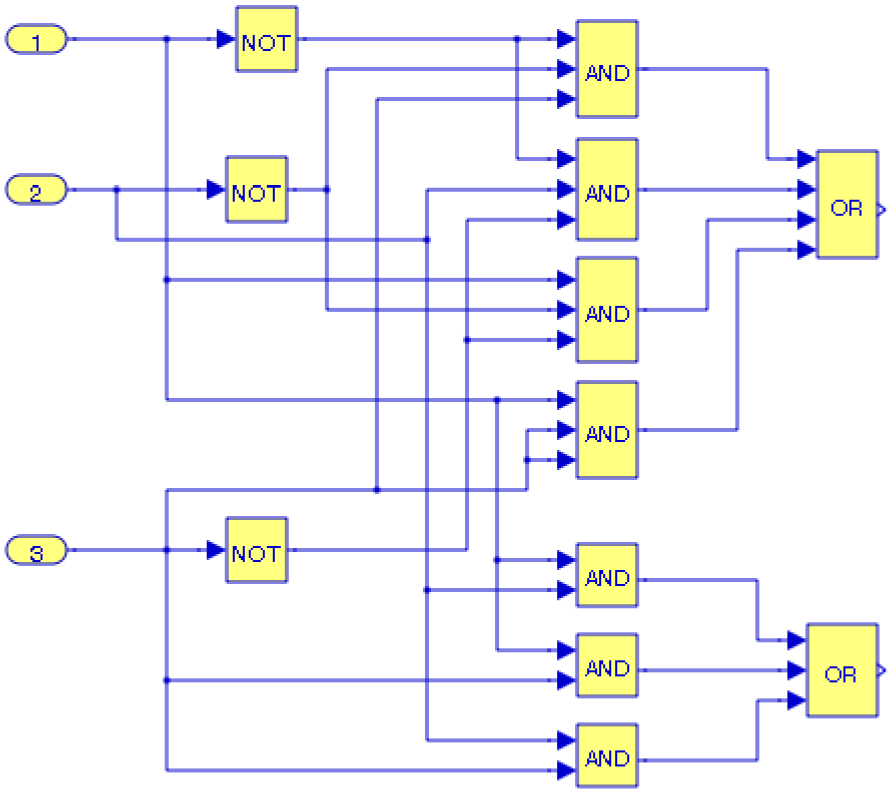


Figure 11.23. Full−Adder circuit for Subsystem 1 in Example 11.6

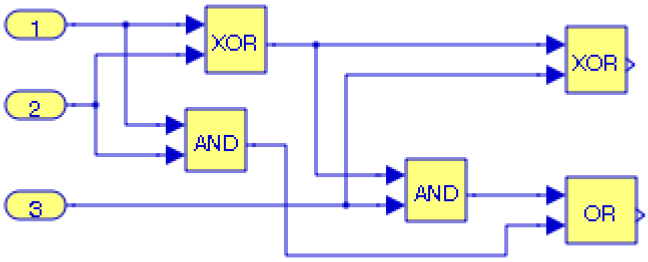


Figure 11.24. Full−Adder circuit for Subsystem 2 in Example 11.6

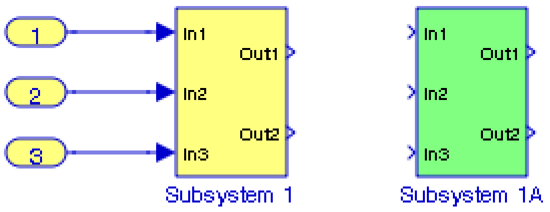


Figure 11.25. The model in Figure 11.23 shown as a subsystem

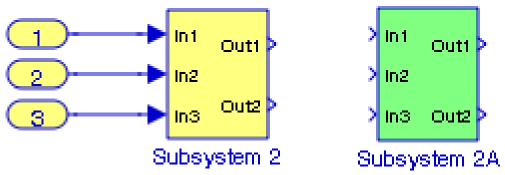


Figure 11.26. The model in Figure 11.24 shown as a subsystem

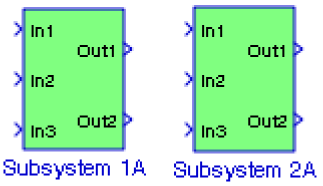


Figure 11.27. Library with Subsystems 1A and 2A blocks

We save the library, and then we drag a **Configurable Subsystem** block in the library. The library now appears as shown in Figure 11.28.

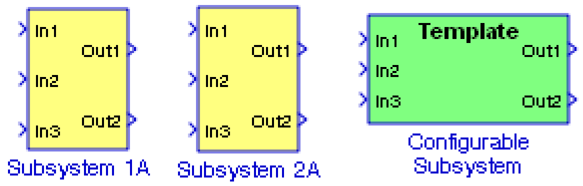
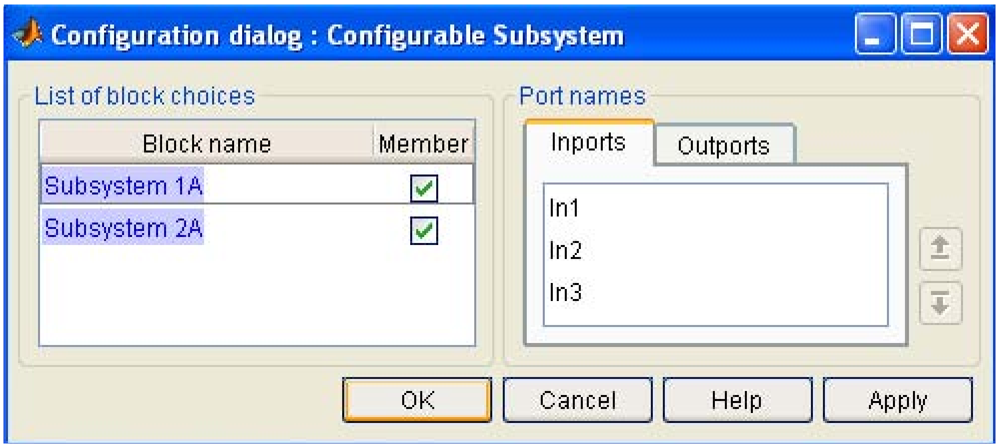


Figure 11.28. The library with the addition of the Configurable Subsystem

We double click on **Configurable Subsystem** block and in the **Configuration dialog** box we place check marks in the **Member** squares as shown in Figure 11.29. The Port names pane shows the inputs indicated as **Inports**. To see the outputs, we click the **Outports** tab.


Configuration dialog : Configurable Subsystem

List of block choices

Block name	Member
Subsystem 1A	✓
Subsystem 2A	✓

Port names

Inports | Outports

In1
In2
In3

Figure 11.29. The Configuration dialog for the library of Example 11.6

We can now select either Subsystem 1A or Subsystem 2A from the Configuration dialog to implement the 4–bit Adder by cascading four one–bit adders. For this example we choose Subsystem 1A. This is done by unselecting Subsystem 2A on the Configuration dialog box of Figure 11.29.

We create a new model by dragging the Configurable Subsystem block from this library into this model, copy and paste this block three times, and we interconnect these as shown in Figure 11.30.

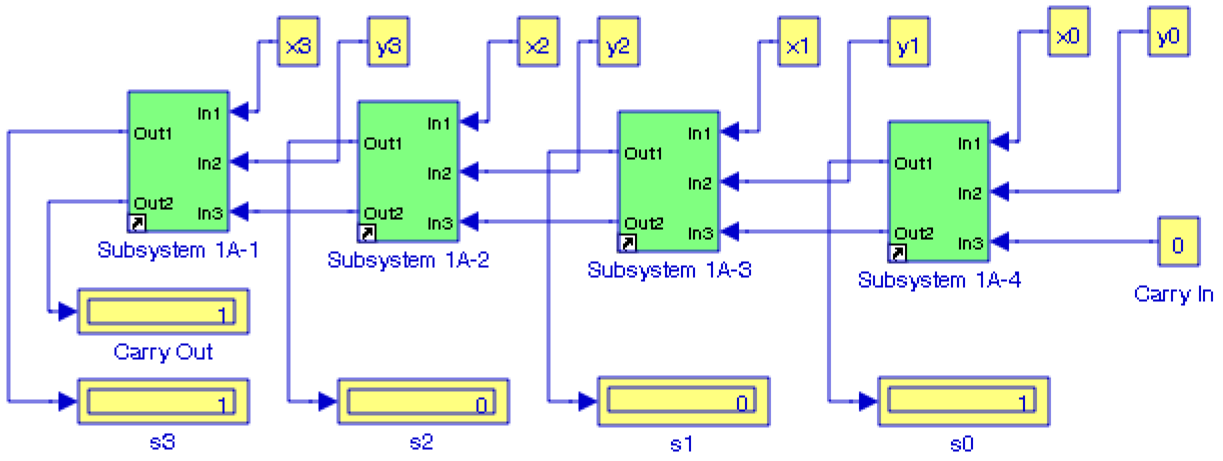


Figure 11.30. Four–bit binary adder for Example 11.6 with Subsystem 1A blocks

In the model of Figure 11.30, the carry bit of the right–most one–bit adder is set to zero since there is no previous one–bit adder. We observe that Simulink displays small arrows on the bottom left corner of each of the subsystem blocks. A small arrow indicates that each subsystem block represents a library link in the model, and it is only visible if the **Link Library Display** option of the **Format** menu is selected **All**.

To verify that the 4–bit adder of Figure 11.30 operates properly, let us perform the binary addition

$$\begin{array}{r} 1011 \\ +\ 1110 \\ \hline 11001 \end{array}$$

At the MATLAB command prompt we enter:

```
x0=1; y0=0; x1=1; y1=1; x2=0; y2=1; x3=1; y3=0;
```

and the addition is verified where the most significant bit of the sum is displayed as Carry Out.

Should we, later decide to replace the Subsystem 1A blocks with Subsystem 2A blocks, we return to our library, we click the **Configurable Subsystem** block, on the Configuration dialog of Figure 11.29 we unselect **Subsystem 1A** block and we select the **Subsystem 2A** block. We copy this block into our model of Figure 11.30 and we replace the **Subsystem 1A** blocks with **Subsystem 2A** blocks. The new model is now as shown in Figure 11.31.

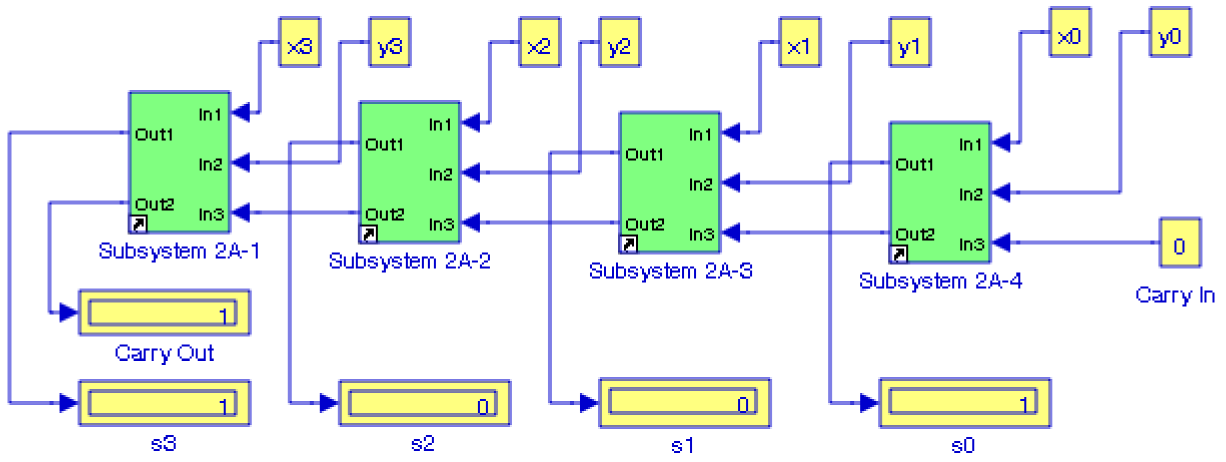


Figure 11.31. Four−bit binary adder for Example 11.1 with Subsystem 2 blocks

Using the **Subsystem 1** or **Subsystem 2** blocks in Figure 11.30 or Figure 11.31 we can create another library with subsystems representing a 4−bit adder block as shown in Figure 11.32. Of course, we can next combine four 4−bit adder blocks to form a 16−bit adder subsystems, and so on.

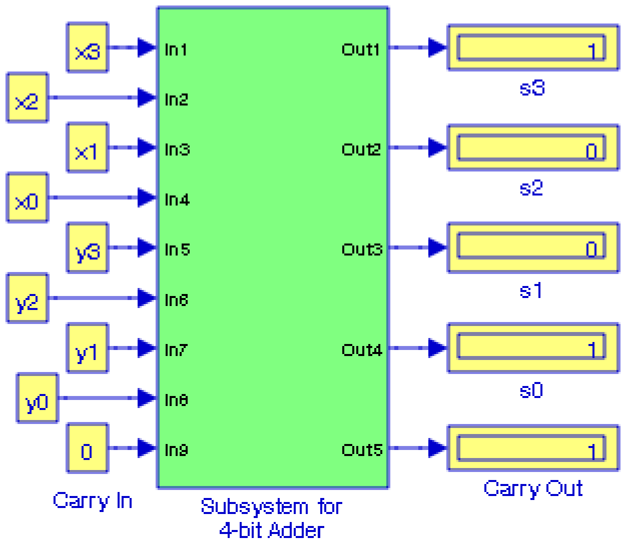
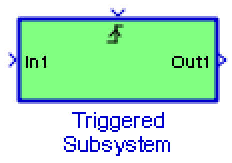


Figure 11.32. A 4−bit Adder Subsystem

For more details on Creating a Master **Configurable Subsystem** please refer to the Help menu for the **Configurable Subsystem** block.

11.9 The Triggered Subsystem Block



A **Triggered Subsystem** block is used to represent a subsystem whose execution is triggered by an external input.

Example 11.7

Let us reconsider the **Atomic Subsystem** block of Figure 11.8, Example 11.2, Section 11.5, this chapter which is repeated below as Figure 11.33, and add a **Trigger** block to it. We will use a **Pulse Generator** block to generate the trigger control signal. The **Display** block indicates the value 1, provided that at the MATLAB command prompt we have entered the following script:

```
A=1; C0=1; C1=1;
B=1; C0=0; C1=1;
C=1; C0=1; C1=0;
D=1; C0=0; C1=0;
```

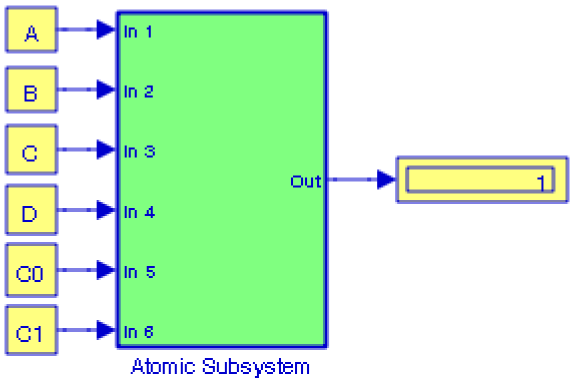


Figure 11.33. The Atomic Subsystem block for a four–line–to–one–line digital multiplexer

We cannot drag the **Trigger** block into the subsystem model of Figure 11.33; we must double click it, and when its subsystem appears, from the **Ports & Subsystems** library we drag the **Trigger** block which now appears as shown in Figure 11.34. We save it as Figure_11_34.

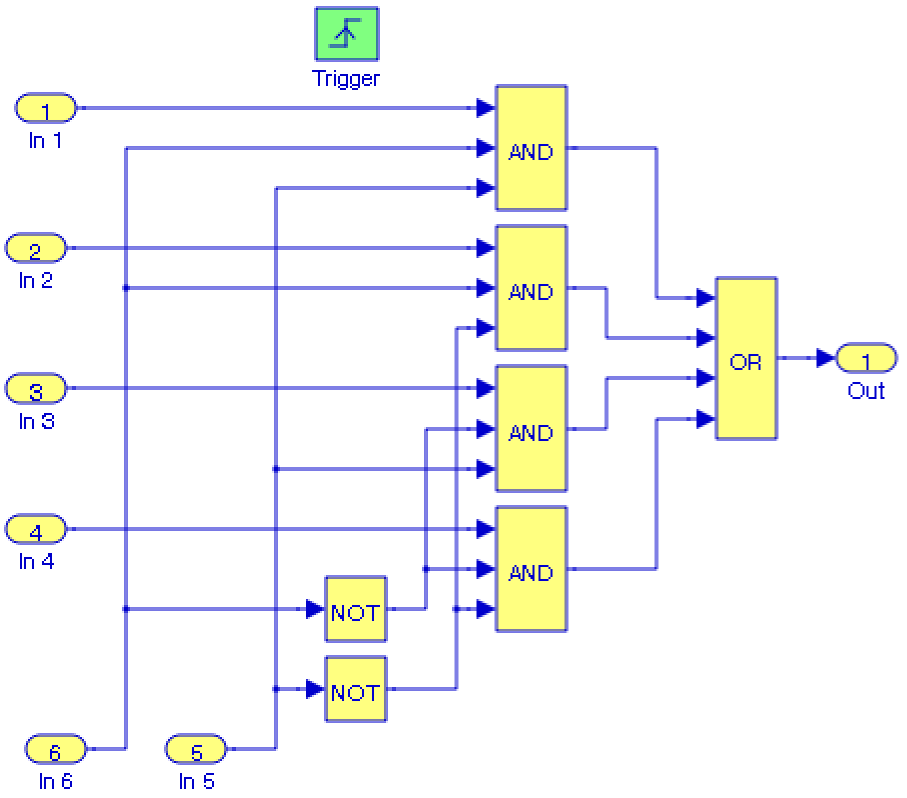


Figure 11.34. Model for Example 11.7 with Trigger block

The Atomic Subsystem in Figure 11.33 now appears as shown in Figure 11.35 with another input on top of it for the Trigger control signal. We observe that the Display block now indicates the value 0; this is because with the addition of the Trigger control input without a signal, the subsystem block is disabled. To this input we connect a **Pulse Generator** block as shown in Figure 11.36.

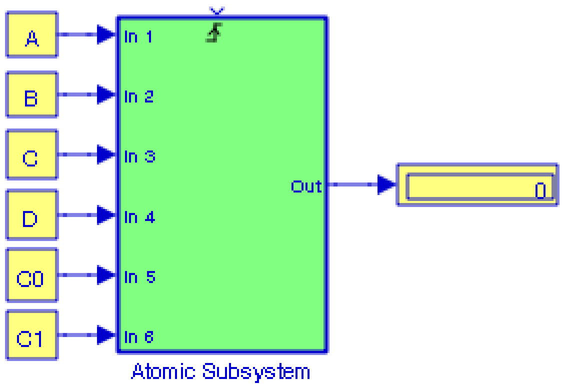


Figure 11.35. The Atomic Subsystem block with the Trigger input on top

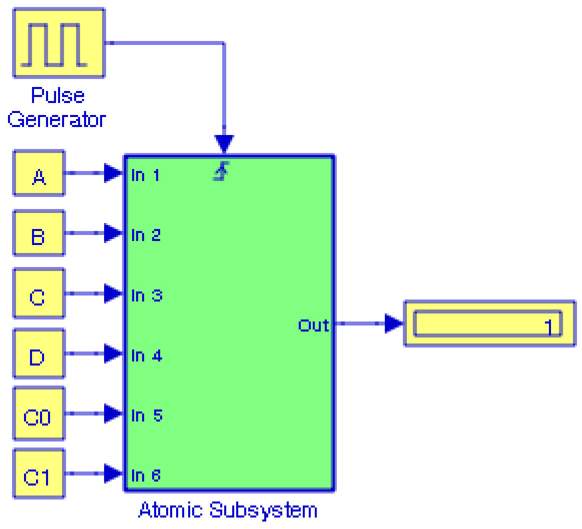


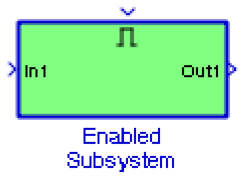
Figure 11.36. The Atomic Subsystem block with Pulse Generator connected to Trigger port

We observe that, because the subsystem is now enabled, the **Display** block indicates the value 1, provided that at the MATLAB command prompt we have entered the following script:

```
A=1; C0=1; C1=1;
B=1; C0=0; C1=1;
C=1; C0=1; C1=0;
D=1; C0=0; C1=0;
```

The Simulink documentation includes the **Triggered Subsystem Demonstration** demo, and the **Counters Using Conditionally Executed Subsystems** demo. They can be accessed by entering at the MATLAB command prompt triggeredsub, and sldemo_counters respectively.

11.10 The Enabled Subsystem Block



The **Enable Subsystem** block represents a subsystem whose execution is enabled by an external input which can be a scalar or a vector. If the input is a scalar, the subsystem executes if the input value is greater than zero. If the input is a vector, the subsystem executes if any of the vector elements is greater than zero. Consider the waveform of Figure 11.37 where an up arrow denotes an enable condition, and a down arrow denotes a disable condition.

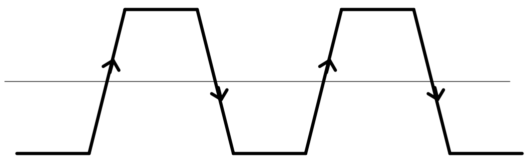


Figure 11.37. An alternating waveform that can cause alternate enable and disable conditions

Thus, when the control input signal is alternating, the subsystem will be alternately enabled and disabled. Simulink uses the zero–crossing slope method to determine whether an enable is to occur. Thus, if the signal crosses zero and the slope is positive, the subsystem is enabled, and if the slope is negative at the zero crossing, the subsystem is disabled.

We create an enabled subsystem by copying an **Enable** block from the **Ports & Subsystems** library into a subsystem. Simulink adds an enable symbol and an enable control input port to the **Subsystem** block, and although an enabled subsystem does not execute while it is disabled, the output signal is still available to other blocks. While an enabled subsystem is disabled, we can choose to hold the subsystem outputs at their previous values or reset them to their initial conditions. We choose held to cause the output to maintain its most recent value and we choose reset to cause the output to revert to its initial condition.

Example 11.8

The model of Figure 11.38 is the same as that of Figure 2.29, Example 2.14, Section 2.14, Chapter 2, Page 2–26. We will create a subsystem using an **Enabled Subsystem** block by grouping all blocks except the **Step** and the **Scope** blocks, then we add an appropriate Enable control input to the created subsystem block.

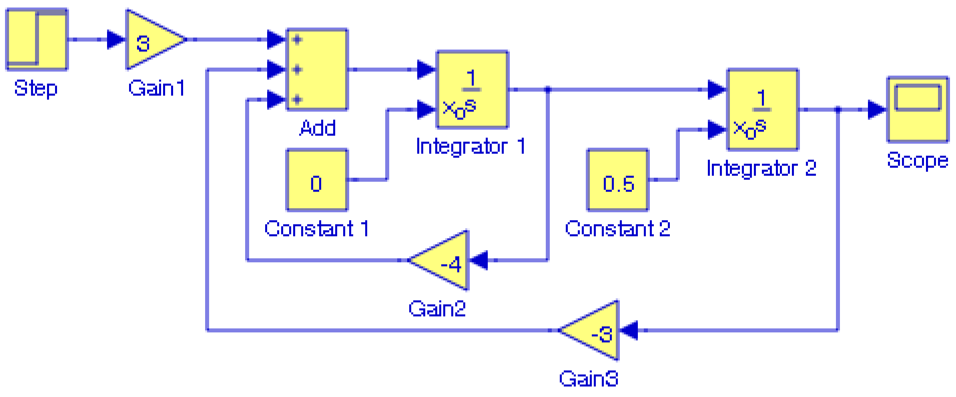


Figure 11.38. Model for Example 11.8

We open a new model, and from the **Ports & Subsystems** library we drag the **Enabled Subsystem** shown in Figure 11.39.

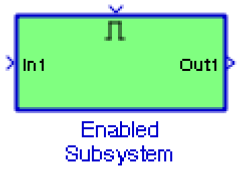


Figure 11.39. The Enable and Triggered Subsystem for replacing the model of Figure 11.38

We double–click the **Enabled Subsystem** block of Figure 11.39, we drag the entire model of Figure 11.38 into the **Enable Subsystem** window, we replace the **Step** and **Scope** blocks with the **In** and **Out** ports, for the **Enable** block we select the **Show** output port check box, and we connect its output to a **Display** block as shown in Figure 11.40.

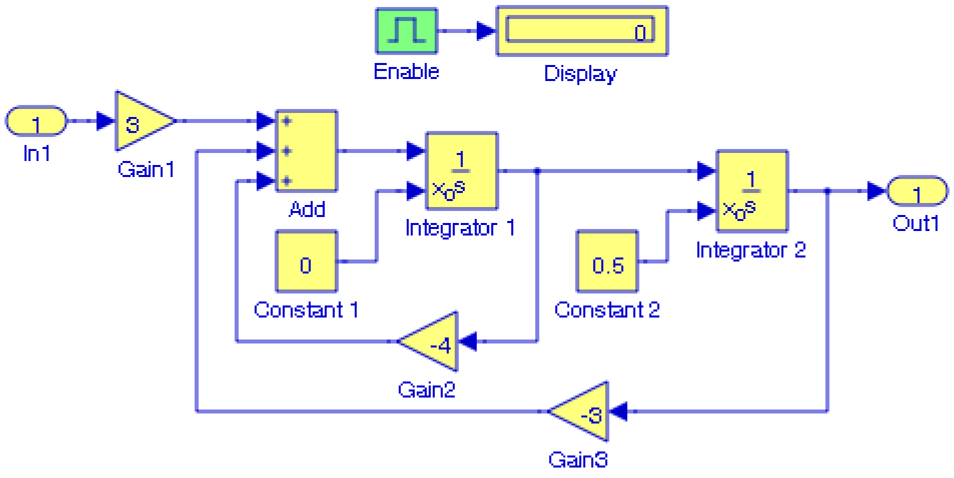


Figure 11.40. Contents of the Enable Subsystem block for the Subsystem of Figure 11.39

We return to the **Enabled and Triggered Subsystem** in Figure 11.39, we drag the **Pulse Generator** and **Step** blocks from the **Sources** library, and we connect them to the Enable and to the input of the subsystem. We also add a **Bus Creator** block and a **Scope** block by dragging them from the **Commonly Used Blocks** Library. The model now is as shown in Figure 11.41.

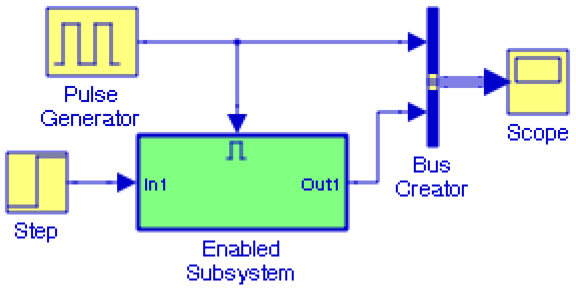


Figure 11.41. The model of Figure 11.40 replaced with an Enabled Subsystem block

After execution of the Simulation command for the model of Figure 11.41, the **Enable** signal and **Subsystem** outputs are displayed on the **Scope** block as shown in Figure 11.42.

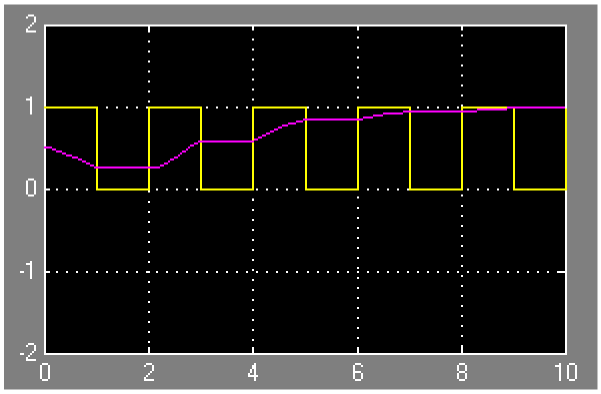
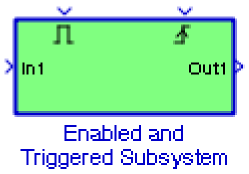


Figure 11.42. The Enable signal and Subsystem block outputs for the model in Figure 11.38

The Simulink documentation includes the **Enabled Subsystem Demonstration** demo, the **Enabled Subsystems in Simulink** demo, the **Merge Block Demonstration** demo, the **Counters Using Conditionally Executed Subsystems** demo, and the **Modeling Engine Timing Using Triggered Subsystems** demo. They can be accessed by entering at the MATLAB command prompt enablesub, enabsubs, mergedemo, sldemo_counters, and sldemo_engine respectively.

11.11 The Enabled and Triggered Subsystem Block



The **Enabled and Triggered Subsystem** block is a combination of the enabled subsystem and the triggered subsystem. When the trigger occurs, Simulink checks the enable input port to evaluate the enable control signal. If its value is greater than zero, Simulink executes the subsystem. If both inputs are vectors, the subsystem executes if at least one element of each vector is nonzero. The subsystem executes once at the time step at which the trigger event occurs. We create a triggered and enabled subsystem by dragging both the Enable and Trigger blocks from the Ports & Subsystems library into an existing subsystem. Simulink adds enable and trigger symbols and enable and trigger and enable control inputs to the Subsystem block.

Example 11.9

Figure 11.43 is a model for the second–order, discrete–time transfer function

$$H(z) = \frac{0.5(1 + 0.25z^{-2})}{1 + 0.1z^{-1} - 0.75z^{-2}} \qquad (11.2)$$

We will create a subsystem using an **Enabled and Triggered Subsystem** block by grouping all blocks except the **Pulse Generator** and the **Scope** blocks, and we will add appropriate Enable and Trigger control inputs to the created subsystem block. The delay blocks `1/Z` are specified for Sample time –1 (Inherited).

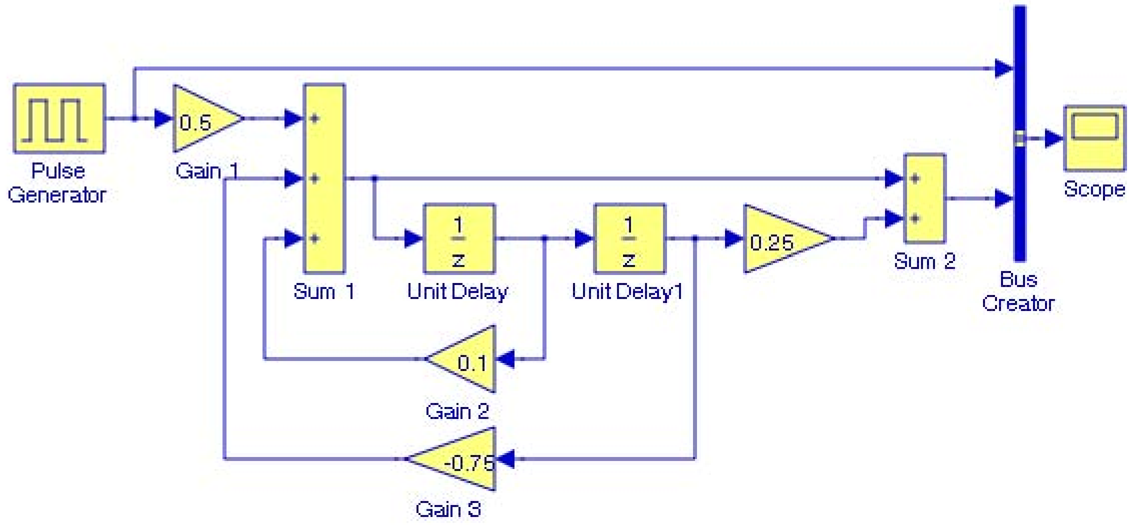


Figure 11.43. Model for Example11.9

We open a new model, and from the **Ports & Subsystems** library we drag the **Enabled and Triggered Subsystem** block shown in Figure 11.44.

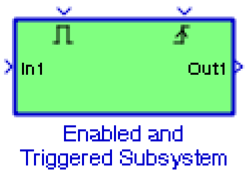


Figure 11.44. The Enable and Triggered Subsystem for replacing the model in Figure 11.43

We double–click the **Enabled and Triggered** block of Figure 11.44, we drag the entire model of Figure 11.43 into the **Enable and Triggered Subsystem** window, we replace the **Pulse Generator** and **Scope** blocks with the **In** and **Out** ports, for the **Trigger and Enable** blocks we select the **Show** output port check box, and we connect their outputs to **Display** blocks as shown in Figure 11.45.

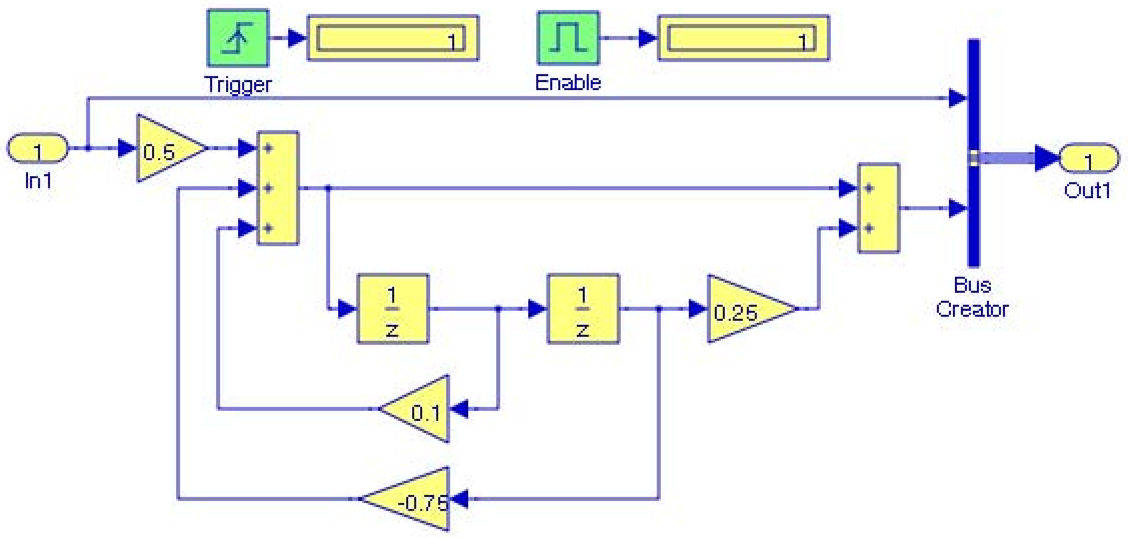


Figure 11.45. Contents for the Enable and Triggered Subsystem block for the Subsystem in Figure 11.44

We return to the **Enabled and Triggered Subsystem** in Figure 11.44, we drag the **Pulse Generator** and **Step** blocks from the Sources library and we connect them to the Enable and Triggered inputs of the subsystem. We also connect a **Sine Wave** block to its input and a **Scope** block to its output as shown in Figure 11.46 where the Sine Wave block is specified for Sample time 0.2.

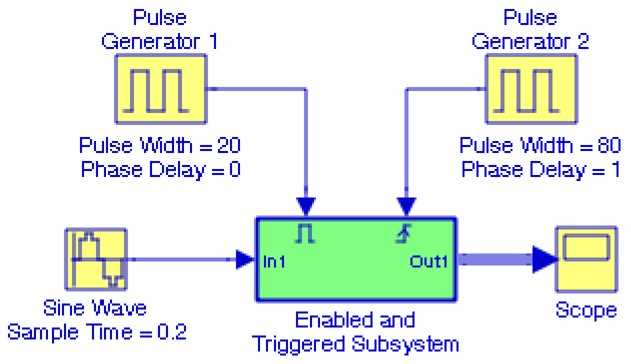


Figure 11.46. The model in Figure 11.43 replaced with an Enabled and Triggered Subsystem block

After execution of the Simulation command for the model of Figure 11.46, the **Enable and Triggered Subsystem** block output is as shown in Figure 11.47.

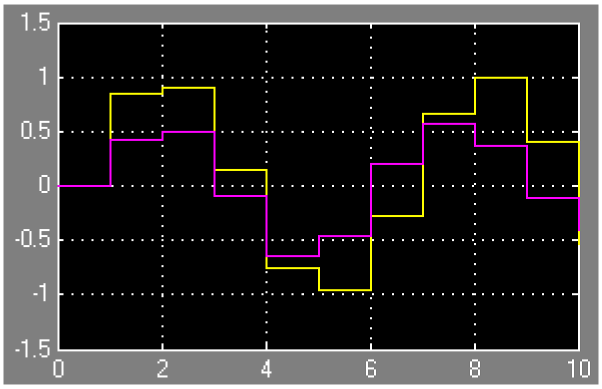


Figure 11.47. Output waveforms for the Enabled and Triggered Subsystem of Figure 11.46

We also observe that the outputs of Trigger and Enable blocks in Figure 11.45 are now as shown in Figure 11.48 indicating that the trigger and enable commands were issued.

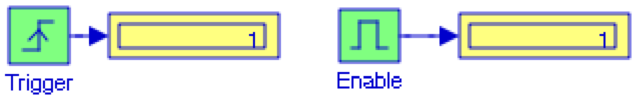


Figure 11.48. The outputs of the Trigger and Enable blocks after the Simulation command is issued

The model shown in Figure 11.49 below is the model of Figure 11.46 with execution context to which a block belongs and ***execution context indicators***.[*] The **execution context** is the sorted order index for each block and it is shown in the upper right corner of each block. It is shown as **s:b** where is **s** denotes the subsystem and **b** denotes the block's sorted order. Thus, the execution context 0:0 shown inside the **Sine Wave** block indicates that this block is the first block[†] in the subsystem's execution context, and the **Pulse Generator 1** block is the next. The execution context 0:2 is not shown; that would be the Enable input in the **Subsystem** block. The execution context 0:4 is not shown either; that would be the Trigger input in the **Subsystem** block. In the execution context 0:5{1} 0 indicates that the **Enabled and Triggered Subsystem** block resides in the model's root system, 5 indicates that the subsystem is the fifth block on the root subsystem's sorted list, and {1} indicates that the index of the enabled subsystem is 1.

* *To see the context indicators, we invoke Format>Block Displays>Sorted order*

† *We must remember that the default indexing in Simulink is the zero–based indexing.*

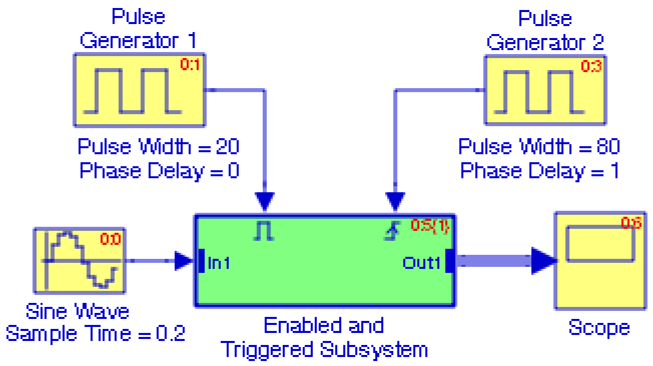
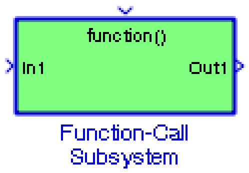


Figure 11.49. The model of Figure 11.46 with Execution Context and context indicators

The Enabled and Triggered Subsystem block in Figure 11.49 also shows two vertical bars at the input and output ports referred to as ***execution context bars***.[*] These bars indicate that at these ports execution contexts will not be propagated.

11.12 The Function–Call Subsystem Block



The **Function–Call Subsystem** block is used to represent a subsystem that can be invoked as a function by another block. With a **Function–Call Subsystem** block we can create a triggered subsystem whose execution is determined by logic internal to an **S–function**[†] instead of by the value of a signal. A subsystem so configured is called a **Function–Call subsystem**.

To implement a **Function–Call Subsystem** we can use a **Trigger** block – as in Example 11.7, Section 11.9, in which we select **function–call** as the Trigger type parameter. Another method is to connect an **S–Function** block output directly to the trigger port. A third method is to use an S–Function using the **ssEnableSystemWithTid** and **ssDisableSystemWithTid** to enable or disable the triggered subsystem, and the **ssCallSystemWithTid** macro to call the triggered subsystem. These are discussed in the Simulink documentation.

All blocks in a triggered subsystem must have either inherited (–1) or constant (inf) sample time. This is to indicate that the blocks in the triggered subsystem run only when the triggered subsystem is triggered. A triggered subsystem cannot contain continuous blocks, such as an Integrator block.

* *To see the execution context bars, we invoke Format>Block Displays>Execution Context Indicator.*
† *S–Functions are discussed in Section 11.18, this chapter.*

Function–Call subsystems implement callable functions using Simulink blocks. They are executed by a **function–call initiator**. **S–Functions**, **Function–Call Generators**, and **Stateflow** charts, the latter being the most common, are all function–call initiators.

Example 11.10

The model shown in Figure 11.50 is the same as in Example 11.9. The **Delay** blocks 1/Z are specified for Sample time –1 (Inherited). We will create a subsystem using a **Function–Call Subsystem** block by grouping all blocks in Figure 11.50 except the **Pulse Generator** and the **Scope** blocks. We will add a Trigger control input to the created subsystem block.

We open a new model, and from the **Ports & Subsystems** library we drag the **Function–Call Subsystem** shown in Figure 11.51.

We double–click on the block of Figure 11.51, we drag the entire model of Figure 11.50 into the Function–Call Subsystem window, we replace the **Pulse Generator** and **Scope** blocks with the **In** and **Out** ports, for the **Trigger** block we select the **Show** output port check box, and we connect their outputs to **Display** blocks as shown in Figure 11.52.

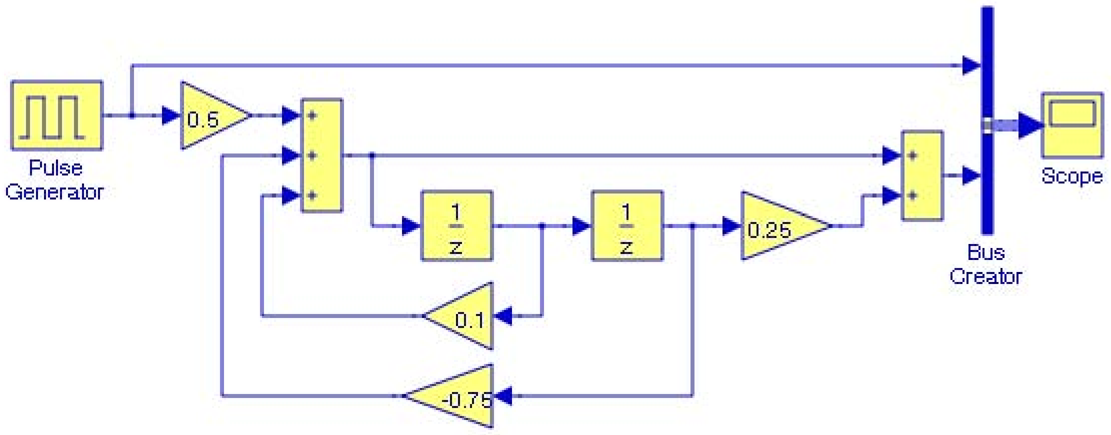


Figure 11.50. Model for Example 11.10

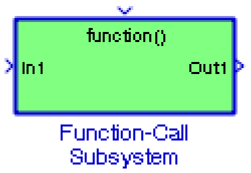


Figure 11.51. The Function–Call Subsystem for replacing the model in Figure 11.50

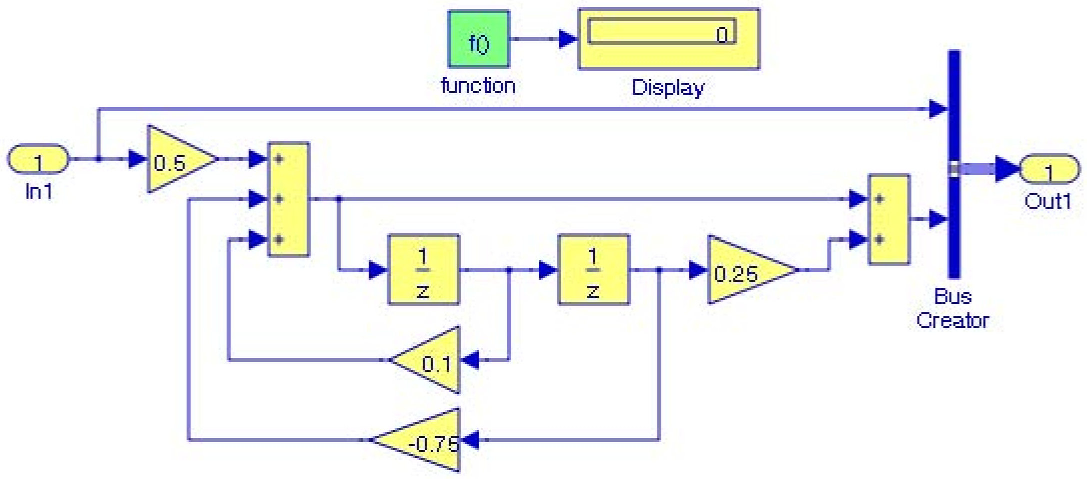


Figure 11.52. Contents for the Function–Call Subsystem block for the Subsystem in Figure 11.51

We return to the **Function–Call Subsystem** in Figure 11.51, to the Function input on top of the block we connect a **Function–Call Generator** block, to the **In1** block output we connect a **Rate Transition**[*] block, to the **Function–Call Subsystem** output we connect another **Rate Transition** block, and the updated model is now as shown in Figure 11.53.

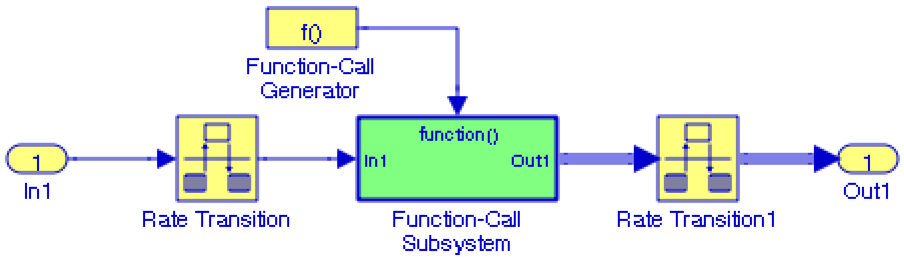


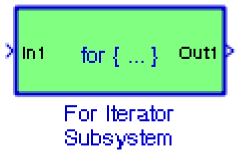
Figure 11.53. The model of Figure 11.50 replaced with a Function–Call Subsystem block

The model of Figure 11.53 does not illustrate the full power of a **Function–Call Subsystem**. Function–Call Subsystems are not executed directly by Simulink; the S–function determines when to execute the subsystem. When the subsystem completes execution, control returns to the S–function. For a detailed description for this block, and an illustration of the interaction between a Function–Call Subsystem and an S–function, please refer to Simulink's Help menu for this block.

* *The Rate Transition block is described in Subsection 12.1.8, Chapter 12.*

Function–Call subsystems are a powerful modeling construct. We can configure Stateflow® blocks to execute function–call subsystems, thereby extending the capabilities of the blocks. For more information on their use in Stateflow, please refer to the Stateflow documentation*.

11.13 The For Iterator Subsystem Block



The **For Iterator Subsystem** block is a subsystem that executes repeatedly during a simulation time step until an iteration variable exceeds a specified iteration limit. We can use this block the same way as a for loop in MATLAB.

Example 11.11

The components of the **For Iterator Subsystem** in Figure 11.54 are shown in Figure 11.55 and this subsystem was created following the steps in Examples 11.2 and 11.3. The **Display** block in Figure 11.55 shows the constant assigned to the input of the **For Iterator Subsystem** in Figure 11.54. The **XY Graph** block† appears in Simulink's **Sink** library and displays an X–Y plot of its inputs in a MATLAB figure window. We will assign an appropriate value to the **Memory** block in Figure 11.55 so that the XY Graph block will display a linear segment for the equation $y = -x+5$.

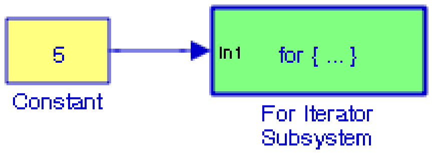


Figure 11.54. For Iterator Subsystem for Example 11.11

* *For an Introduction to Stateflow, please refer to Introduction to Stateflow with Applications, ISBN 978–1–934404–07–2.*

† *The XY Graph block is described in Subsection 14–2–3, Chapter 14.*

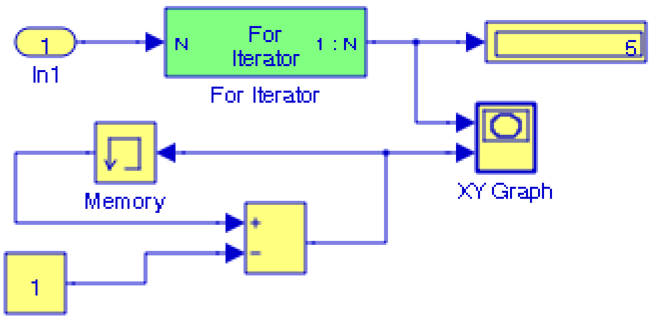


Figure 11.55. Contents of the For Iterator Subsystem block for the Subsystem in Figure 11.54

The straight line equation $y = -x+5$ has slope $m = -1$, and y–intercept $b = 5$. Since the slope is negative, we want the y values to decrease with increasing values of x, and since the y–intercept is 5, we set the initial value in the **Memory** block to 5. Next, we double click the **XY Graph** block, and on the Block parameters we set $x-\min = 1$, $x-\max = 5$, $y-\min = 0$, and $y-\max = 4$. After execution of the Simulation command the **XY Graph** block displays the straight line shown in Figure 11.56.

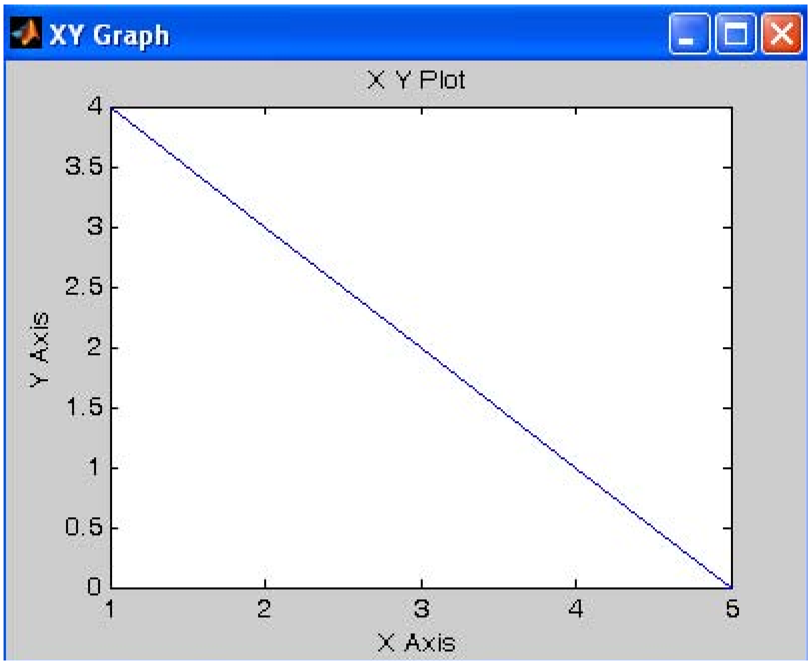


Figure 11.56. XY plot for the model in Figure 11.55

11.14 The While Iterator Subsystem Block

In1
IC
while { ... }
Out1

While Iterator
Subsystem

The **While Iterator Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem that executes repeatedly while a condition is satisfied during a simulation time step. The **While Iterator Subsystem** block, when placed in a subsystem, repeatedly executes the contents of the subsystem at the current time step while a specified condition is true. If a **While Iterator Subsystem** block is placed within a subsystem, it makes it an atomic subsystem.

We can use this block to implement the block–diagram equivalent of a C program while or do–while loop. In particular, the block's While loop style parameter allows us to choose either the do–while mode, or the while mode.

In the do–while mode, the **While Iterator Subsystem** block has one input, the while condition input, whose source must reside in the subsystem. At each time step, the block runs all the blocks in the subsystem once and then checks whether the while condition input is true. If the input is true, the iterator block runs the blocks in the subsystem again. This process continues as long as the while condition input is true and the number of iterations is less than or equal to the iterator block's Maximum number of iterations parameter.

In the while mode, the iterator block has two inputs: a while condition input and an initial condition (IC) input. The source of the initial condition signal must be external to the while subsystem. At the beginning of the time step, if the IC input is true, the iterator block executes the contents of the subsystem and then checks the while condition input. If the while condition input is true, the iterator executes the subsystem again. This process continues as long as the while condition input is true and the number of iterations is less than or equal to the iterator block's Maximum number of iterations parameter. If the IC input is false at the beginning of a time step, the iterator does not execute the contents of the subsystem during the time step.

Example 11.12

We will create a model to compute the sum of the first N integers where the sum should be equal to or less than 1000.

We begin by dragging a **While Iterator Subsystem** block into a new model as shown in Figure 11.57. We double–click it and the subsystem now appears as shown in Figure 11.58. We add and interconnect **In1**, **Out1**, **Sum**, **Memory**, and **Relational Operator** blocks, and the model of Figure 11.58 is now as shown in Figure 11.59. This example is similar to the example given in Simulink's Help menu for the **While Iterator Subsystem** block.

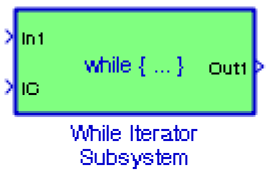


Figure 11.57. The While Iterator Subsystem block before configuration, Example 11.12

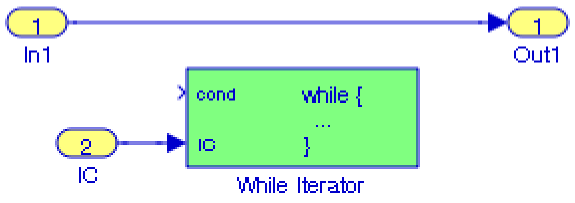


Figure 11.58. The While Iterator block for the While Iterator Subsystem block in Figure 11.57

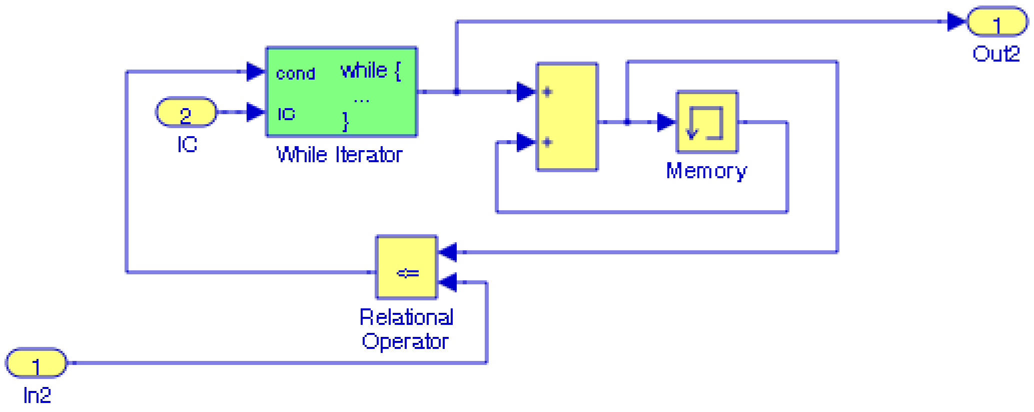


Figure 11.59. The contents of the While Iterator Subsystem of Figure 11.57

We return to the **While Iterator Subsystem** of Figure 11.57 and we add the **Constant** and **Display** blocks as shown in Figure 11.60. The output of the **Relational Operator** block is True (logical one) and this establishes the Initial Condition (IC) input to the **While Iterator Subsystem** block. As noted below the **Display** block in the model of Figure 11.60, the number of iterations is specified in the While Iterator is 5. The **Display** block in the model of Figure 11.61 indicates that the sum of the first N integers after 5 iterations is 765.

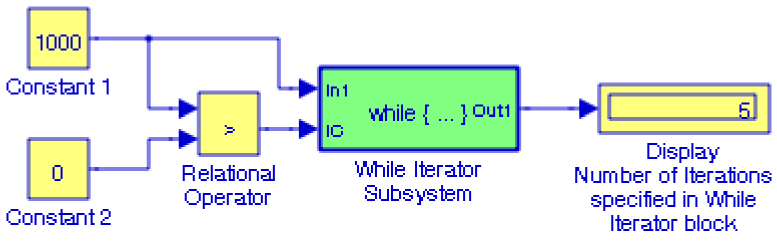


Figure 11.60. Final form for the model for Example 11.12

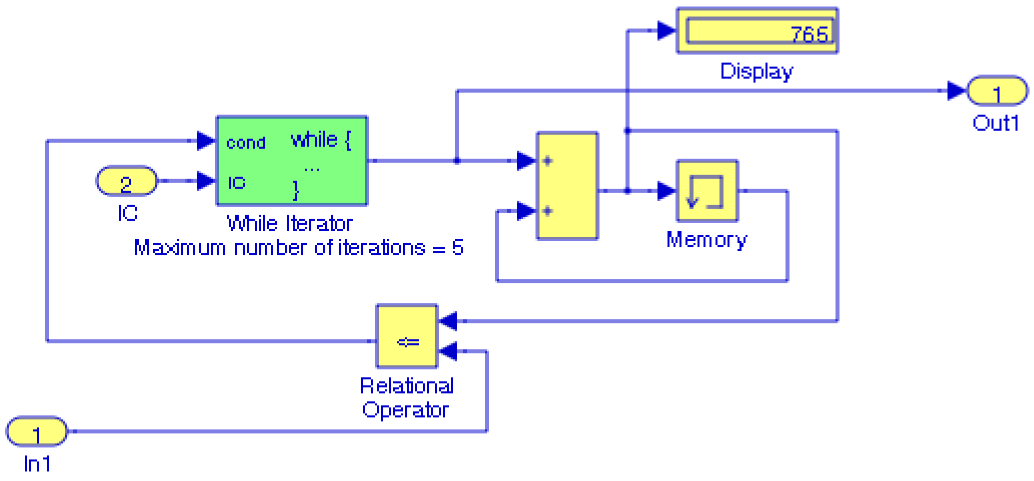
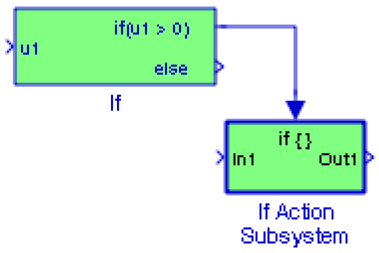


Figure 11.61. Model for Example 11.12 to indicate the sum of the first N integers

11.15 The If and If Action Subsystem Blocks



The **If** block, along with an **If Action** subsystem, implements standard C–like if–else logic. The **If Action Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem whose execution is triggered by an **If** block.

Example 11.13

From analytic geometry we know that two straight line segments L_1 and L_2 are orthogonal (perpendicular) to each other if their slopes m_1 and m_2 satisfy the relation $m_1m_2 = -1$ as shown in Figure 11.62 below.

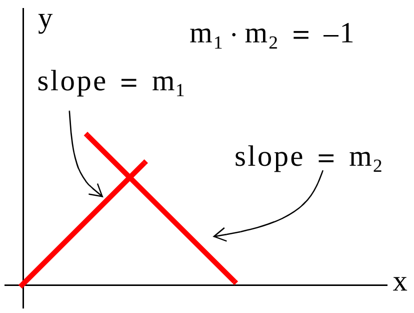


Figure 11.62. Orthogonal straight line segments

In the model in Figure 11.63, we specified the value of the slope m_1 as constant a and at the MATLAB command prompt we specified that constant as $a = -1.2$.

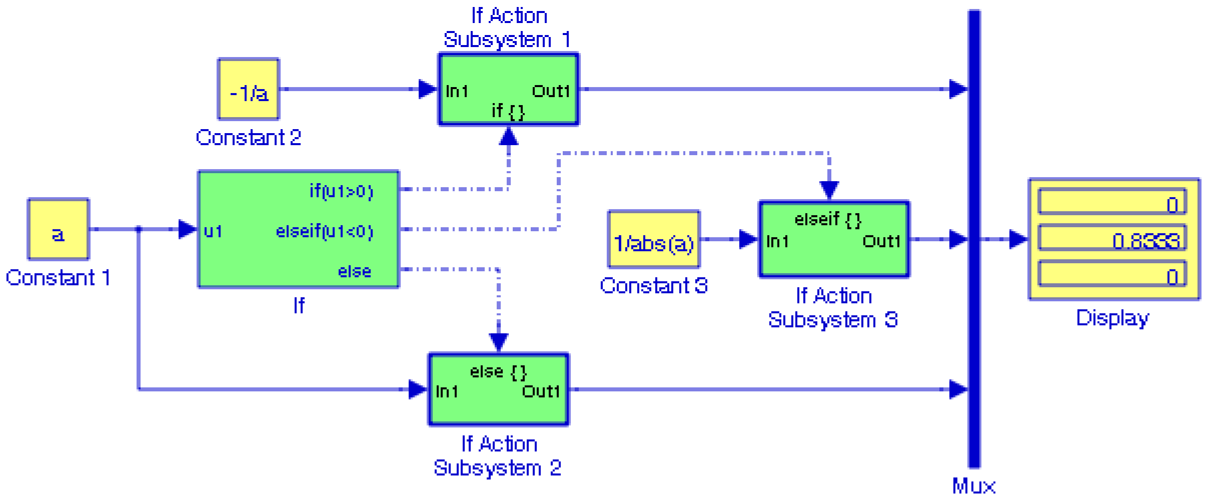
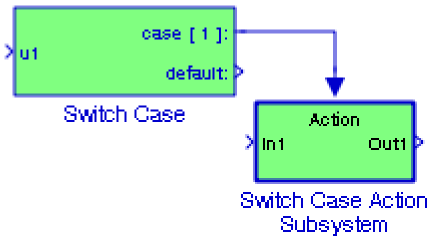


Figure 11.63. Model for Example 11.13

Refer also the Simulink documentation for the **Clutch Simulation** demo by typing sldemo_clutch_if at the MATLAB command prompt, and the **If Block Demonstration** demo by typing sldemo_ifsub at the MATLAB command prompt.

For another example, please refer to the Help menu for the **If** block which includes also a pseudocode.[*]

11.16 The Switch Case and The Switch Case Action Subsystem Blocks



The **Switch Case** block implement a C–like switch control flow statement. The **Switch Case Action Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem whose execution is triggered by a **Switch Case** block.

Example 11.14

Let us first review the **Switch–Case constructions** in MATLAB which have the following form:

```
switch expression
    case test_expression1
        commands1...
    case {test_expression2, test_expression3, test_expressions4}
        commands2...
    otherwise
        commands3...
end
```

The MATLAB script below is an illustrative example for converting x miles per hour to:

a. kilometers per hour

b. feet per second

c. centimeters per second

d. meters per minute

[*] *Abbreviated p–code. A machine language for a nonexistent processor (a pseudomachine). Such code is executed by a software interpreter. The major advantage of p–code is that it is portable to all computers for which a p–code interpreter exists. The p–code approach has been tried several times in the microcomputer industry, with mixed success. The best known attempt was the UCSD p–System.*

```
%
x=65;
%
% Conversion of miles per hour to other units
% x is number of miles, e.g., 65, and must be
% specified at the MATLAB command prompt
units = 'ft';
%
switch units
   case {'km/hr','km'}
        y=x*1.6093;
   case {'ft/sec','ft'}
        y=x*1.4667;
   case {'cm/sec','cm'}
        y=x*44.704;
   case {'m/min', 'm'}
        y=x*26.8224;
   otherwise
        disp('Unknown units')
end
```

Now, we type y at the MATLAB command prompt and MATLAB outputs

```
y =
   95.3355
```

and this correspponts to the Case 2 indicating that 65 miles per hour when converted to feet per second yields 95.34 feet per second. The same result is obtained with the model in Figure 11.64 below where in the **Function Block Parameters** for the **Switch Case** block we have made the entries shown in Figure 11.65, and at the MATLAB command prompt we have entered;

```
a=2; x=65;
```

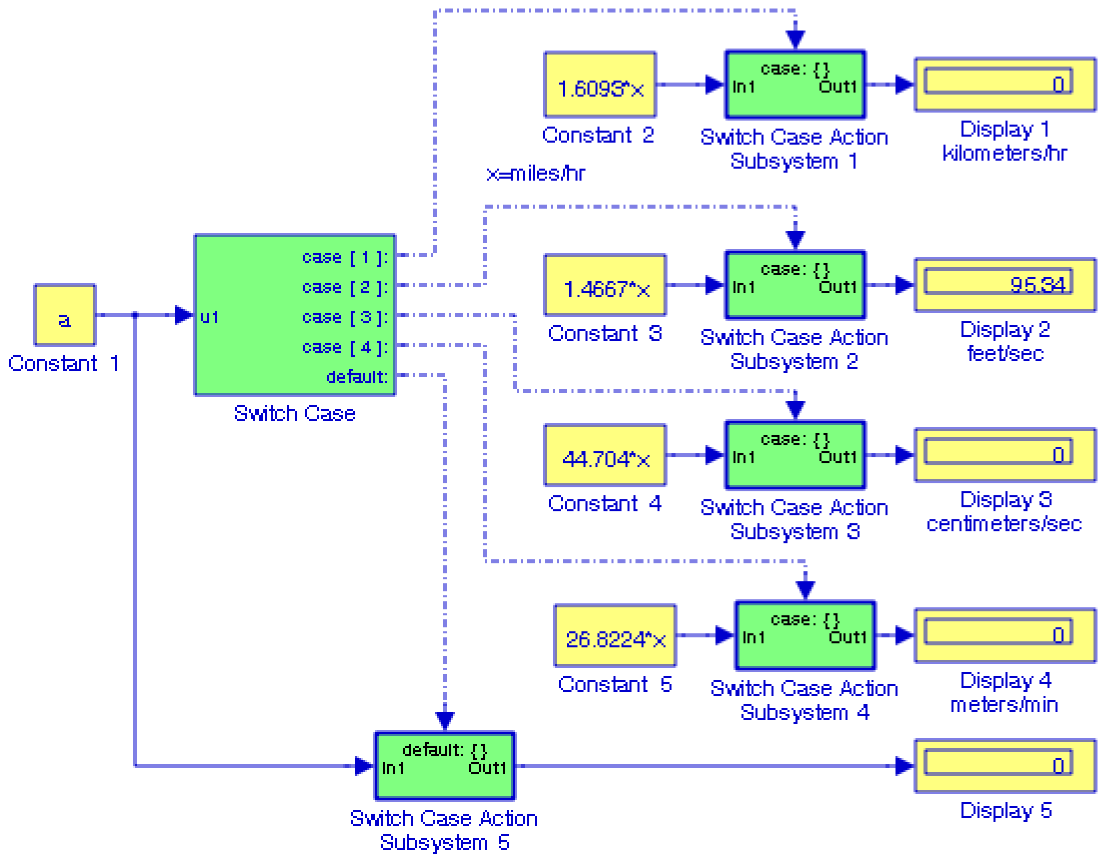
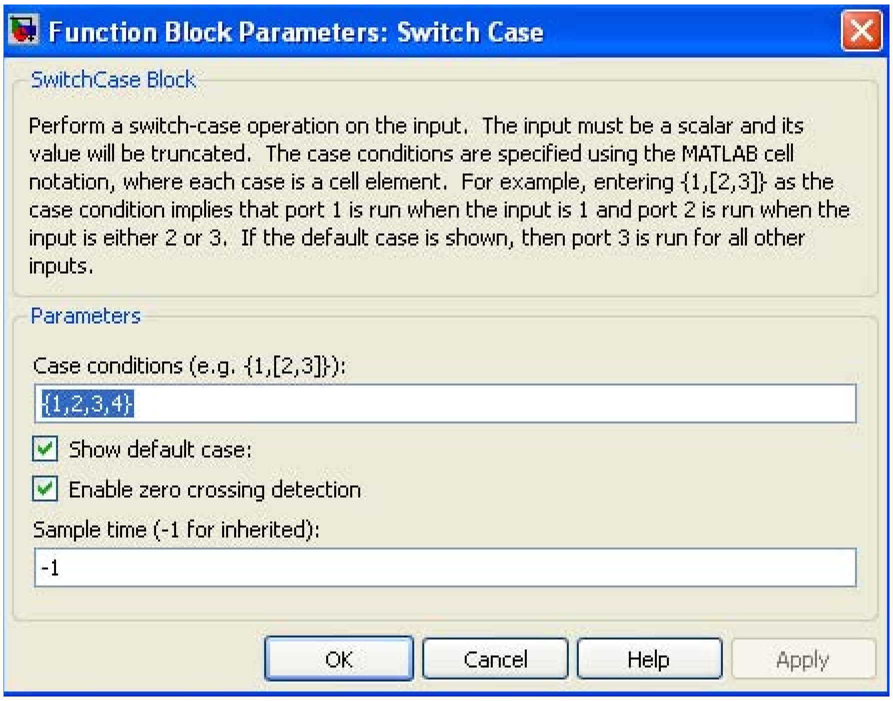


Figure 11.64. Model for Example 11.14



Perform a switch-case operation on the input. The input must be a scalar and its value will be truncated. The case conditions are specified using the MATLAB cell notation, where each case is a cell element. For example, entering {1,[2,3]} as the case condition implies that port 1 is run when the input is 1 and port 2 is run when the input is either 2 or 3. If the default case is shown, then port 3 is run for all other inputs.

Case conditions (e.g. {1,[2,3]}): {1,2,3,4}

[✓] Show default case:

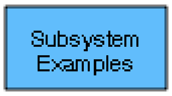
[✓] Enable zero crossing detection

Sample time (-1 for inherited): -1

Figure 11.65. Parameter settings for the Switch Case block in Figure 11.65

For another example, please refer to the Help menu for the **Switch Case** block that includes also a pseudocode.

11.17 The Subsystem Examples Block



The **Subsystem Examples** block includes a library of S–functions. To run an example, at the MATLAB command prompt we type:

```
sfundemos
```

and MATLAB will display the S–Function directory blocks shown in Figure 11.66. In this text we will be concerned with the M–file S–Functions only. An introduction to S–functions with an example is presented in the next section.

Next, we double–click the M–file S–Functions block of Figure 11.66 and MATLAB displays the Level–1 and Level–2 M–file S–Functions shown in Figure 11.67.

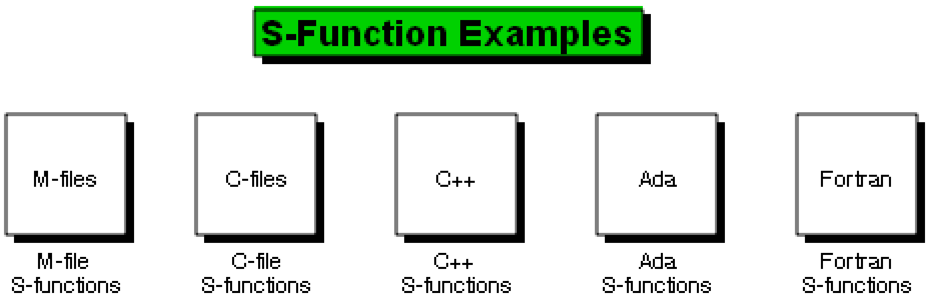


Figure 11.66. S−Function directory blocks

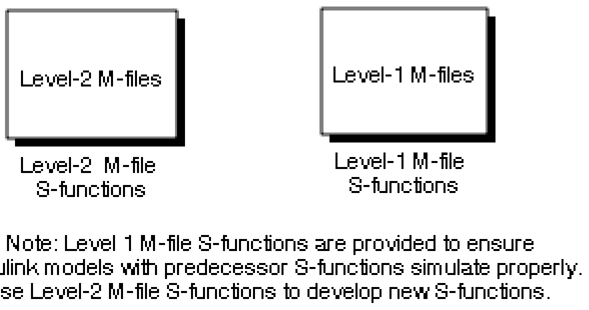

Level-2 M-files
Level-2 M-file S-functions
Level-1 M-files
Level-1 M-file S-functions
Note: Level 1 M-file S-functions are provided to ensure Simulink models with predecessor S-functions simulate properly. Use Level-2 M-file S-functions to develop new S-functions.

Figure 11.67. Levels of M−file S−Functions

The Level−1 M−file S−Functions are shown in Figure 11.68 and the Level−2 M−file S−Functions are shown in Figure 11.69.

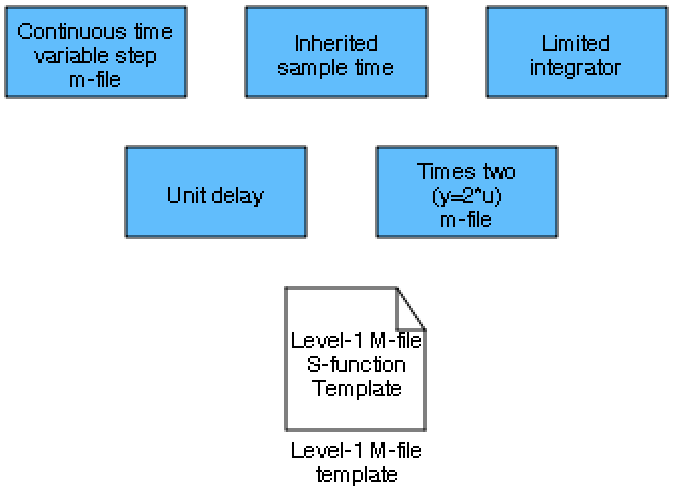


Figure 11.68. List of Level−1 M−file S−Functions

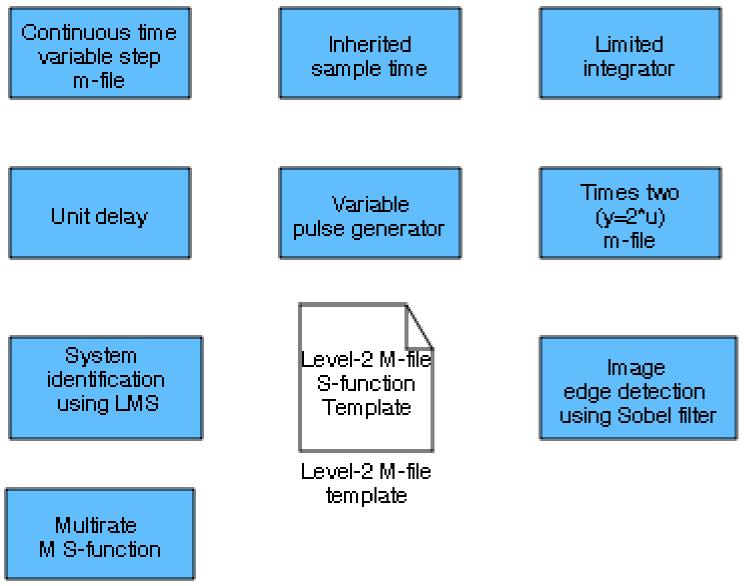


Figure 11.69. List of Level−2 M−file S−Functions

Figure 11.70 shows the Subsystem Semantics (Definitions) for the Simulink family of subsystems.

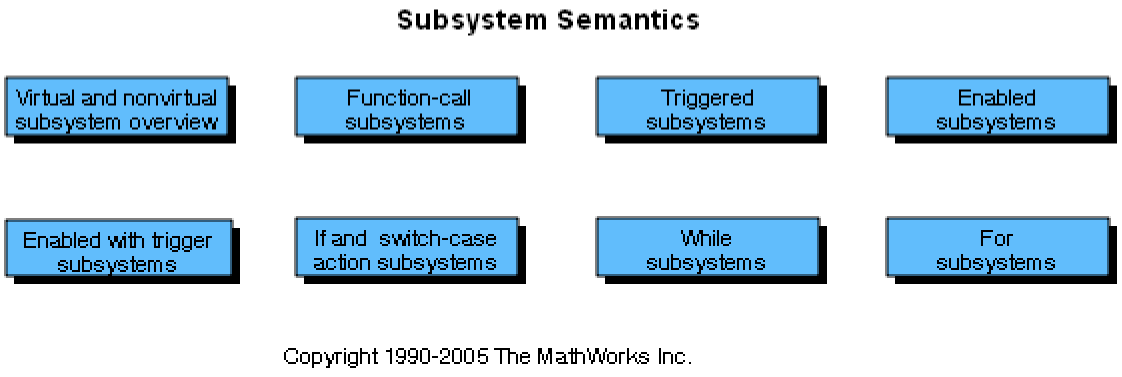

Subsystem Semantics
Virtual and nonvirtual subsystem overview
Function-call subsystems
Triggered subsystems
Enabled subsystems
Enabled with trigger subsystems
If and switch-case action subsystems
While subsystems
For subsystems
Copyright 1990-2005 The MathWorks Inc.

Figure 11.70. Classes and types of Simulink subsystems

Simulink consists of two classes of subsystems, Virtual subsystems and Nonvirtual subsystems. **Virtual subsystems** provide graphical hierarchy in models and do not impact execution. **Nonvirtual subsystems** are executed as a single unit (atomic execution) by Simulink. The blocks within a nonvirtual subsystem execute only when all subsystems inputs are valid. All nonvirtual subsystems are drawn with a bold border.

It is highly recommended that each of the subsystem blocks shown in Figure 11.66 be explored to become familiar with them.

11.18 S–Functions in Simulink

An **S–function** is a computer language description of a Simulink block. S–functions can be written in MATLAB, C, C++, Ada, or Fortran. Files in C, C++, Ada, and Fortran S–functions are compiled as mex–files using the mex utility.[*] S–functions use a special calling syntax that enables us to interact with Simulink's equation solvers. The form of an S–function is very general and applies to continuous, discrete, and hybrid systems.

S–functions allow us to add our own blocks to Simulink models. After we write our S–function and place its name in an S–Function block. We can also use S–functions with the **Real–Time Workshop**.[†] With m–file S–Functions we can define our own ordinary differential equations, discrete–time system equations and any type of algorithm that can be used with Simulink block diagrams.

To become familiar with S–Functions, we begin our discussion with an example.

Example 11.15

For the simple RC circuit of Figure 11.71 it can be shown[‡] that the state–space equations are

$$\begin{aligned}\frac{dx}{dt} &= \left(-\frac{1}{RC}\right)x + V_S \\ y &= x\end{aligned} \tag{11.3}$$

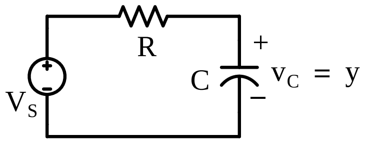


Figure 11.71. RC circuit for Example 11.15

We will create an S–**Function** block that implements the relations of (11.3). We begin by writing the function m–file below and we save it as RCckt.m

* *For a discussion on mex–files please refer to in the online MATLAB documentation. These files are dynamically linked into MATLAB when specified. In this text we will only be concerned with m–files.*

† *Real–Time Workshop® is an extension of the capabilities provided by MATLAB and Simulink. It generates, and compiles source code from Simulink models to create real–time software applications on a variety of systems. Refer to Writing S–Functions for Real–Time Workshop and the Real–Time Workshop documentation for more information.*

‡ *For a detailed discussion on state variables, please refer to Signals and Systems with MATLAB Computing and Simulink Modeling, ISBN 978–0–9744239–9–9.*

```
function dx = RCckt(t,x,Vs)
%
% Model for RC series circuit, function m-file RCckt.m
%
% Define circuit constants
%
R = 10^6;                % Resistance in Ohms
C = 10^(-6);             % Capacitance in Farads

dx = -1/(R*C)*x+Vs;      % The arguments x and dx are column vectors
                         % for state and derivative respectively. The
                         % variable t on the first line above specifies
                         % the simulation time. The default is [0 10].
```

To test this function m–file for correctness, at the MATLAB command prompt we execute the following statement:

[t,x,Vs]=ode45(@RCckt, [0 10], 0, [ ], 1)

This statement specifies a simulation time interval [0 10], an initial condition value of 0, the null vector [ ] can be used for options, and the input value is set to 1. Upon execution of this statement MATLAB displays several values for t, x, and Vs.

Next, we write the **S–function** m–file shown below, and we save it as RCckt_sfun.m

An explanation for each line of this file is provided afterwards.

```
function [sys,x0,str,ts]=...
           RCckt_sfcn(t,x,u,flag,xinit)
%
% This is the m-file S-Function RCckt_sfcn.m
%
switch flag

    case 0                      % Initialize

        str = [];
        ts = [0 0];
        x0 = xinit;

% Alternately, the three lines above can be combined into a single line as
% [sys,x0,str,ts]=mdlInitializeSizes(t,x,u)

        sizes = simsizes;

            sizes.NumContStates = 1;
            sizes.NumDiscStates = 0;
            sizes.NumOutputs = 1;
            sizes.NumInputs = 1;
            sizes.DirFeedthrough = 0;
            sizes.NumSampleTimes = 1;

        sys =simsizes(sizes);
    case 1                        % Derivatives

        Vs = u;

        sys = RCckt(t,x,Vs);

    case 3                        % Output

        sys = x;

    case {2 4 9}                  % 2:discrete
                                  % 3:calcTimeHit
                                  % 9:termination
        sys = [];

    otherwise

        error(['unhandled flag =',num2str(flag)]);

end
```

The first line of the S–function m–file RCckt_sfun.m is written as

```
function [sys,x0,str,ts]=...
           RCckt_sfcn(t,x,u,flag,xinit)
```

This specifies the input and output arguments.

a. Input arguments

t – time variable

x – column vector for the state variables

u – column vector for the input variables; will be supplied by other Simulink blocks

flag – an indication of which group of information and calculations. Table 11.3 below lists the integer numbers assigned to an S–function routine.

TABLE 11.3 Flags used in S–function m–files

Flag	S–Function Routine	Simulation Stage
0	mdlInitializeSizes	Initialization – sets input and output vector sizes and specifies initial conditions for the state variables.
1	mdlDerivatives	Calculation of derivatives
2	mdlUpdate	Update of discrete states – not used for this example
3	mdlOutputs	Calculation of outputs
4	mdlGetTimeOfNextVarHit	Calculation of next sample hit – not used for this example
9	mdlTerminate	End of simulation tasks

`xinit` – additional supplied parameter; in this example the initial condition

a. Output arguments

sys – a vector of information requested by Simulink. This vector will hold different information depending on the **flag** value as shown in Table 11.4 below.

TABLE 11.4 Information for vector sys for different flag values

Flag	Information requested
0	sys = [a, b, c, d, e, f, g] a = number of continuous time states b = number of discrete time states c = number of outputs d= number of inputs e = not used but must be set to 0 if requested f = applies to direct algebraic feed through of input to output, 0 for No, 1 for Yes. It is relevant if during flag=3, the output variables depend on the input variables. g = number of sample times. For continuous systems must be set to 1.
1	sys = column vector of the state variables derivatives
3	sys = column vector of output variables
2,4,9	sys = [ ] (null vector) if not applicable

x0 – a column vector of initial conditions. Applies only to **flag** = 0

str – reserved for future use; for m–file S–functions it must be set to null vector. Applies only to **flag** = 0

ts – an array of two columns to specify sample time and time offsets. For continuous–time systems it is set to [0 0]. If it is desired that S–function should run at the same rate as the block to which it is connected (inherited sample time), we must set **ts** to [–1 0]. If we want to run at discrete sample time, say 0.25 seconds starting at 0.1 seconds after the start of simulation time, we must set **ts** to [0.25 0.1]. Applies only to **flag** = 0.

Let us now review the m–file S–function RCckt_sfcn structure.

We begin with the function RCckt_sfcn defined as follows:

```
function [sys,x0,str,ts]=...
              RCckt_sfcn(t,x,u,flag,xinit)
%
% This is the m-file S-Function RCckt_sfun.m
%
```

Next, we use flag; this specifies an integer value that indicates the task to be performed by the S–function and begins with the statement

```
switch flag
```

Initialization begins with

```
    case 0                    % Initialize

        str = [];             % Must be set to null. Reserved for future use
        ts = [0 0];           % Specify sampling time. For continuous-time
                              % systems is always set to [0 0]
        x0 = xinit;           % Column vector for initial conditions
```

Simulink will not recognize our m–file S–function unless we provide specific information about number of inputs, number of outputs, states, and other characteristics. This information is provided with the simsizes function. This function returns an initialized structure of the variables in which we can assign the required values. Thus, in MATLAB's Command Window we invoke this command as shown below and we manually enter the values shown.

```
        sizes = simsizes;

            sizes.NumContStates = 1;
            sizes.NumDiscStates = 0;
            sizes.NumOutputs = 1;
            sizes.NumInputs = 1;
            sizes.DirFeedthrough = 0;
            sizes.NumSampleTimes = 1;
```

Direct Feedthrough in line 5 above implies that the output is controlled by the value of the input. Generally, if an S–Function has an input port, it has direct feedthrough if the input u is accessed in mdlOutputs. For instance, if $y = ku$ where u is the input, k is the gain, and y is the output, the system has direct feedthrough only if *flag=3*.

After we initialize the sizes structure we invoke simsizes again as shown below

```
        sys =simsizes(sizes);
```

and this passes the information in the sizes structure to sys which is a vector that holds the information required by Simulink.[*]

For **case 1** (derivatives) we assign V_S to the input u and then we apply it to the RCckt.m file. Thus,

```
    case 1                        % Derivatives

        Vs = u;

        sys = RCckt(t,x,Vs);
```

For **case 3** (output) we assign the output x to the input sys. Thus,

```
    case 3                        % Output
        sys = x;
```

[*] *Upon execution of the statement* sys=simsizes(sizes), *MATLAB displays a row vector of seven 0s, one for each of the* simsizes *function above. Sys(5) is reserved for root finding and for the present must be set to 0.*

Flags 2, 4, and 9 are not used so they output the null vector `sys = []` shown below.

```
    case {2 4 9}                    % 2:discrete
                                    % 3:calcTimeHit
                                    % 9:termination
        sys = [];

    otherwise
        error(['unhandled flag =',num2str(flag)]);

end
```

Next, we open a window to create a new model, from the **User–Defined Functions** library we drag an S–Function block into it, in the Function Block Parameters dialog box we assign the S–function name RCckt_sfcn to it, we type the initial condition 0, and we add the other blocks shown in Figure 11.72. The parameter values can be constants, names of variables defined in the model's workspace, or MATLAB expressions. The input and output waveforms are shown in Figure 11.73.

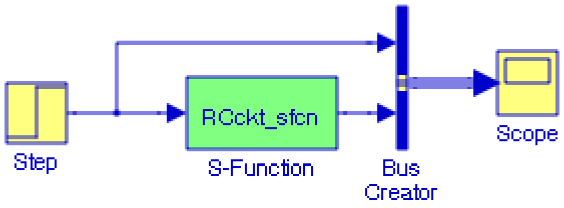


Figure 11.72. Model for Example 11.15

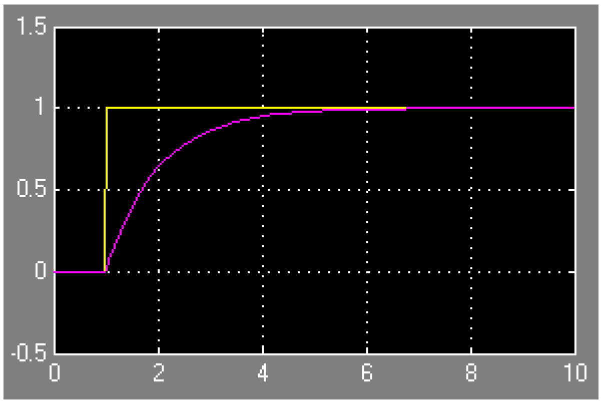


Figure 11.73. Input and output waveforms for the model in Figure 11.72

Two more examples using **S–Function** blocks are presented in Chapter 20, this text.

11.19 Summary

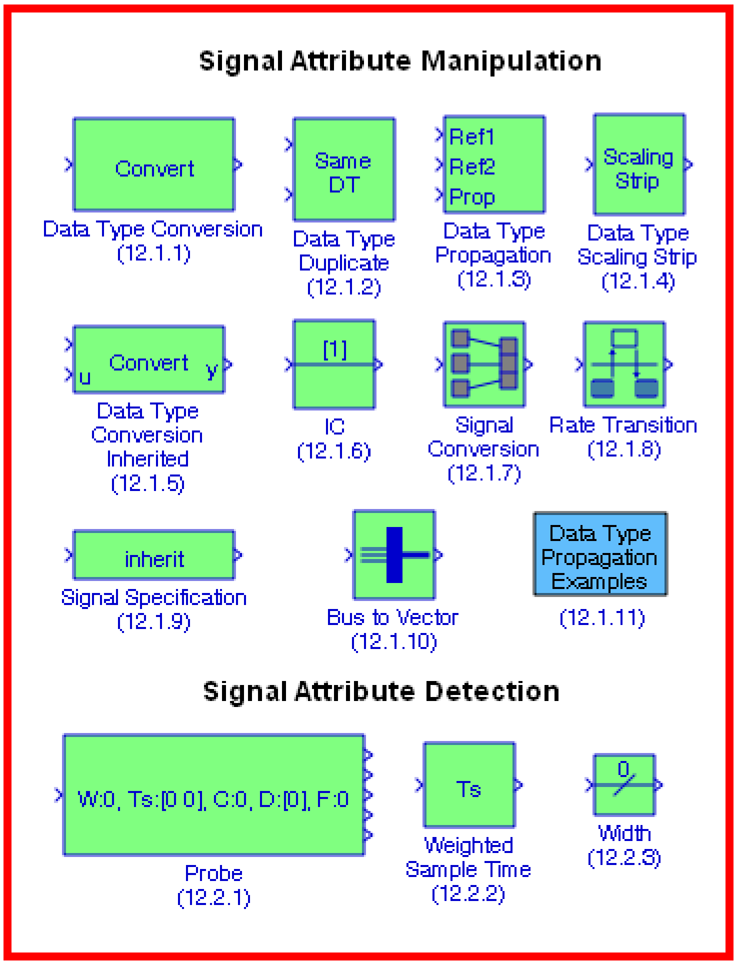
- A **Subsystem** block represents a subsystem of the system that contains it. We use subsystems to group blocks together in our model to manage model complexity.
- **Inport** blocks are ports that serve as links from outside a system into a subsystem.
- **Outport** blocks are output ports for a subsystem.
- The **Trigger** block is used with a subsystem or a model allowing its execution to be triggered by an external signal.
- The **Enable** block adds an external enable block to a subsystem to make it an enabled subsystem.
- The **Function–Call Generator** block executes a function–call subsystem at the rate specified by the block's Sample time parameter.
- The **Atomic Subsystem** block can be used as an alternate method of creating a subsystem in lieu of the method of selecting blocks and lines that are to make up the subsystem using a bounding box and choosing Create Subsystem from the Edit menu.
- The **Code Reuse Subsystem** block is a Subsystem block that represents a subsystem of the system that contains it. It is very similar to the Atomic Subsystem block.
- The **Model** block is used to specify the name of a Simulink model. The name must be a valid MATLAB identifier. The model must exist on the MATLAB path and the MATLAB path must contain no other model having the same name.
- The **Configurable Subsystem** block represents one of a set of blocks contained in a specified library of blocks. The block's context menu lets us choose which block the configurable subsystem represents. A configurable Subsystem block simplifies the creation of models that represent families of designs.
- The **Triggered Subsystem** block is used to represent a subsystem whose execution is triggered by external input.
- The **Enable Subsystem** block represents a subsystem whose execution is enabled by an external input.
- The **Enabled and Triggered Subsystem** block is a combination of the enabled subsystem and the triggered subsystem.
- The **Function–Call Subsystem** block is used to represent a subsystem that can be invoked as a function by another block.
- The **For Iterator Subsystem** block is a subsystem that executes repeatedly during a simulation time step until an iteration variable exceeds a specified iteration limit.

- The **While Iterator Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem that executes repeatedly while a condition is satisfied during a simulation time step.
- The **If** block, along with an **If Action** subsystem, implements standard C–like if–else logic. The **If Action Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem whose execution is triggered by an If block.
- The **Switch Case** block implement a C–like switch control flow statement. The **Switch Action Subsystem** block is a Subsystem block that is pre–configured to serve as a starting point for creating a subsystem whose execution is triggered by a **Switch Case** block.
- The **Subsystem Examples** block includes a library of S–functions.
- An **S–function** is a computer language description of a Simulink block. S–functions can be written in MATLAB, C, C++, Ada, or Fortran. Files in C, C++, Ada, and Fortran S–functions are compiled as mex–files using the mex utility.

Chapter 12

The Signal Attributes Library

This chapter is an introduction to the **Signal Attributes** library**.** This is the eleventh library in the Simulink group of libraries and consists of two sub–libraries, the **Signal Attribute Manipulation Sub–Library**, and the **Signal Attribute Detection Sub–Library** blocks shown below. We will describe the function of each block included in this library and we will perform simulation examples to illustrate their application.

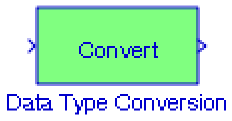


Signal Attribute Manipulation
Convert
Data Type Conversion (12.1.1)
Same DT
Data Type Duplicate (12.1.2)
Ref1
Ref2
Prop
Data Type Propagation (12.1.3)
Scaling Strip
Data Type Scaling Strip (12.1.4)
u Convert y
Data Type Conversion Inherited (12.1.5)
[1]
IC (12.1.6)
Signal Conversion (12.1.7)
Rate Transition (12.1.8)
inherit
Signal Specification (12.1.9)
Bus to Vector (12.1.10)
Data Type Propagation Examples
(12.1.11)
Signal Attribute Detection
W:0, Ts:[0 0], C:0, D:[0], F:0
Probe (12.2.1)
Ts
Weighted Sample Time (12.2.2)
0
Width (12.2.3)

12.1 The Signal Attribute Manipulation Sub–Library

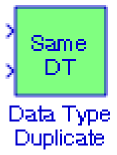
The **Signal Attribute Manipulation Sub–Library** contains the blocks described in Subsections 12.1.1 through 12.1.11 below.

12.1.1 The Data Type Conversion Block



The **Data Type Conversion block** converts an input signal of any Simulink data type to the data type and scaling specified by the block's Output data type mode, Output data type, and / or Output scaling parameters. The input can be any real– or complex–valued signal. If the input is real, the output is real, and if the input is complex, the output is complex. When using this block, we must specify the data type and / or scaling for the conversion. The data types and the **Data Type Conversion** block are described in Section 2.17, Chapter 2.

12.1.2 The Data Type Duplicate Block



The **Data Type Duplicate** block is used to ascertain that all inputs have the same data type. We use the **Data Type Duplicate** block to check for consistency of data types among blocks. If all signals do not have the same data type, the block returns an error message. The **Data Type Duplicate** block is typically used in such a way that one signal to the block controls the data type for all other blocks. The other blocks are set to inherit their data types via back propagation. The block is also used in a user created library. These library blocks can be placed in any model, and the data type for all library blocks are configured according to the usage in the model. To create a library block with more complex data type rules than duplication, we use the **Data Type Propagation** block which is described in Subsection 12.1.3, this chapter, Page 12–4.

Example 12.1

Let us consider the model of Figure 12.1. In all three **Gain** blocks the Signal data types have been specified as Inherit via back propagation. The gains in **Gain 2** and **Gain 3** blocks are very high and thus the **Display 2** and **Display 3** blocks output the value of 0 indicating an overflow condition. To obtain the true values in **Display 2** and **Display 3** blocks, we change the Signal data types from Inherit via back propagation to uint(16) and uint(32) respectively as shown in Figure 12.2.

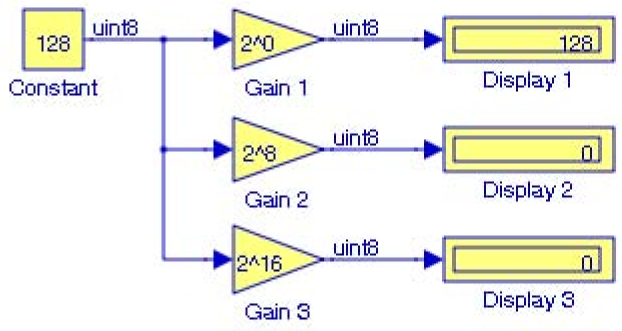


Figure 12.1. Model 1 for Example 12.1

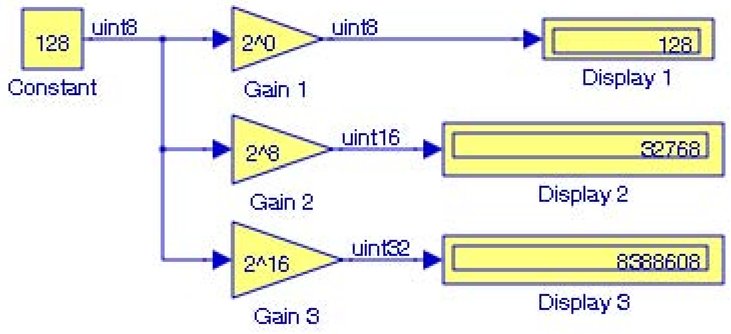


Figure 12.2. Model 2 for Example 12.1

Next, we return to the model of Figure 12.1, we add a **Data Type Duplicate** block, and we specify the Signal data type for the **Constant** block as uint(32), and now our model appears as shown in Figure 12.3.

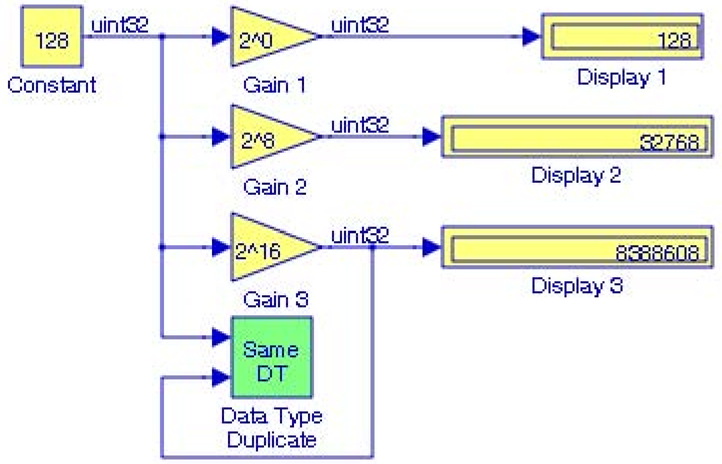
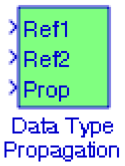


Figure 12.3. Model 3 for Example 12.1

The advantage with the model in Figure 12.3 is that we can specify any Signal data type and that will be inherited by all three **Gain** blocks.

12.1.3 The Data Type Propagation Block



The **Data Type Propagation** block allows us to control the data type and scaling of signals in our model. We can use this block in conjunction with fixed–point blocks that have their Specify data type and scaling parameter configured to Inherit via back propagation. The block has three inputs: Ref1 and Ref2 are the reference inputs, while the Prop input back propagates the data type and scaling information gathered from the reference inputs. This information is subsequently passed on to other fixed–point blocks.

Example 12.2

The model in Figure 12.4 performs the arithmetic operation $2.5(5.75 + 2.375 + 1.8125)$. The Ref1 signal represents the sum of the terms, the Ref2 signal represents the multiplier, and the Prop signal is the product. For all four **Constant** blocks the parameter Signal data types is specified as Inherit from “Constant value”, and for the **Sum** and **Product** blocks the parameter Signal data types is specified as Inherit via back propagation. The **Display** block Format is specified as decimal (Stored Integer.)

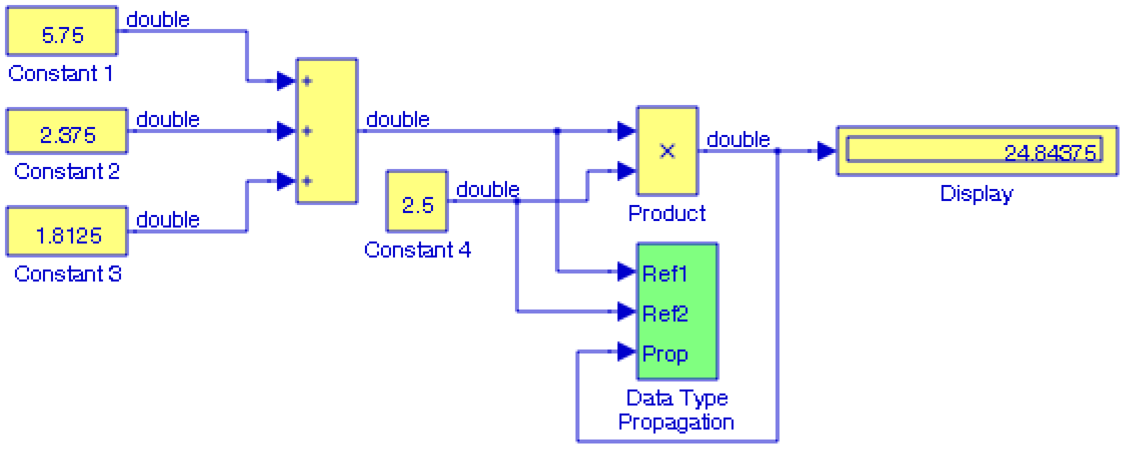
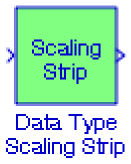


Figure 12.4. Model for Example 12.2

12.1.4 The Data Type Scaling Strip Block



The **Data Type Scaling Strip** block removes the scaling off a fixed–point signal. It maps the input data type to the smallest built in data type that has enough data bits to hold the input. The stored integer value of the input is the value of the output. The output always has nominal scaling (slope = 1.0 and bias = 0.0), so the output does not make a distinction between real world value and stored integer value.

Example 12.3

For the model in Figure 12.5, the parameters for the **Constant** block the Signal data types were specified as Output data type ufix(8) and output scaling value 2^{-3}. Accordingly, the binary presentation of the constant 5.875 is

$$(00101.111)_2 = 1\times 2^2 + 1\times 2^0 + 1\times 2^{-1} + 1\times 2^{-2} + 1\times 2^{-3} = (5.875)_{10}$$

The **Scaling Strip** block removes the scaling and thus it outputs the value

$$(00101111)_2 = 1\times 2^5 + 1\times 2^3 + 1\times 2^2 + 1\times 2^1 + 1\times 2^0 = (47)_{10}$$

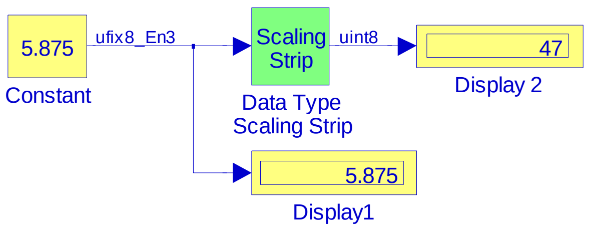
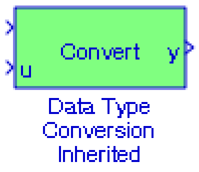


Figure 12.5. Model for Example 12.3

12.1.5 The Data Conversion Inherited Block



The **Data Type Conversion Inherited** block converts one data type to another using inherited data types. In other words, this block dictates that different types of data be converted to be all the same. The first input is used as the reference signal and the second input is converted to the reference type by inheriting the data type and scaling information. Either input is scalar expanded such that the output has the same width as the widest input.

Example 12.4

I the model in Figure 12.6, the input at u from the **Constant 2** block appears at the output y but the signal has been converted to that specified by the first input, i.e., ufix(8) 2^{-3}.

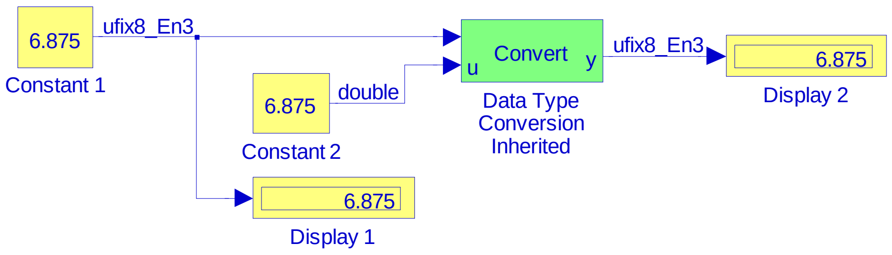
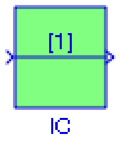


Figure 12.6. Model for Example 12.4

12.1.6 The IC (Initial Condition) Block



The **IC (Initial Condition)** block sets the initial condition of the signal at its input port, i.e., the value of the signal at t=0. The block does this by outputting the specified initial condition at t=0, regardless of the actual value of the input signal. Thereafter, the block outputs the actual value of the input signal. This block is useful for providing an initial guess for the algebraic state variables in the loop.

Example 12.5

In the model 1n Figure 12.7, the **Memory** block introduces a delay of 1 second while the **IC** block establishes an initial condition of 2. The output waveforms with and without the initial condition are shown in Figure 12.8.

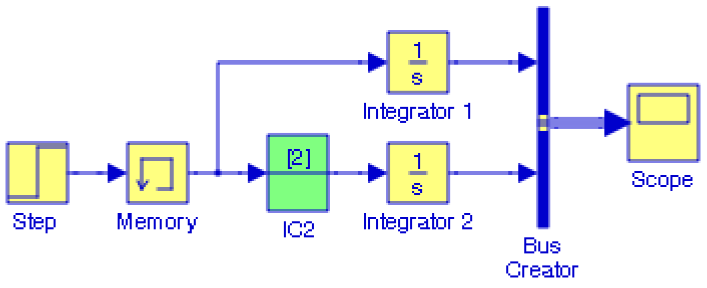


Figure 12.7. Model for Example 12.5

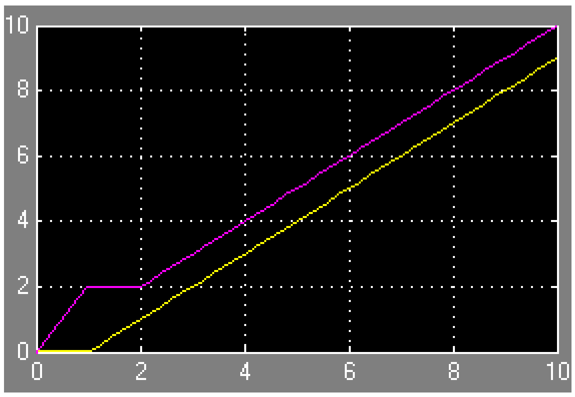
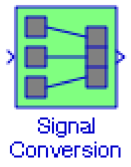


Figure 12.8. Output waveforms for the model in Figure 12.7

12.1.7 The Signal Conversion Block



The **Signal Conversion** block converts a signal from one type to another. The block's Output parameter allows us to choose the type of conversion to be performed. We can choose one of the four types listed below:

Contiguous copy – Converts a muxed signal whose elements occupy discontiguous areas of memory to a vector signal whose elements occupy contiguous areas of memory. The block does this by allocating a contiguous area of memory for the elements of the muxed signal and copying the values from the discontiguous areas (represented by the block's input) to the contiguous areas (represented by the block's output) at each time step.

Bus copy – Outputs a copy of the bus connected to the block's input.

Virtual bus – Converts a nonvirtual bus to a virtual bus. This option enables us to combine an originally nonvirtual bus with a virtual bus.

Nonvirtual bus – Converts a virtual bus to a nonvirtual bus.

Example 12.6

In the model in Figure 12.9, the **Signal Conversion** block's output is specified as **Contiguous** copy. Accordingly the numbers 5.878 and 5.879 originally occupying discontiguous areas of memory, are converted to a vector signal whose elements occupy contiguous areas of memory as indicated in the **Display** block.

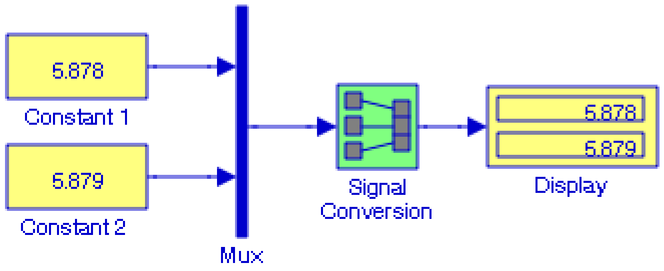
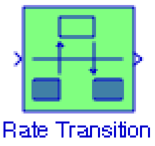


Figure 12.9. Model for Example 12.6

12.1.8 The Rate Transition Block



The **Rate Transition** block transfers data from the output of a block operating at one rate to the input of another block operating at a different rate. Systems containing blocks that are sampled at different rates are referred to as **multirate systems**. The **Rate Transition** block's parameters allow us to specify options that trade data integrity and deterministic transfer for faster response and / or lower memory requirements.

Example 12.7

In the model of Figure 12.10, the parameters for the **Discrete Zero–Pole** blocks 1 and 2 are specified as Zeros: –0.2, Poles: 0.5. The Sample time for the **Discrete Zero–Pole block 1** is specified as $[1 \quad 0.5]$ where 1 is the sample time, and 0.5 is the offset. Since the initial condition is zero, the offset causes no output until $t = 0.5$. The Sample time for the **Discrete Zero–Pole block 2** is specified as 0.75 with no offset. Accordingly, the model of Figure 12.10 is a multirate system and the output waveforms are shown in Figure 12.11.

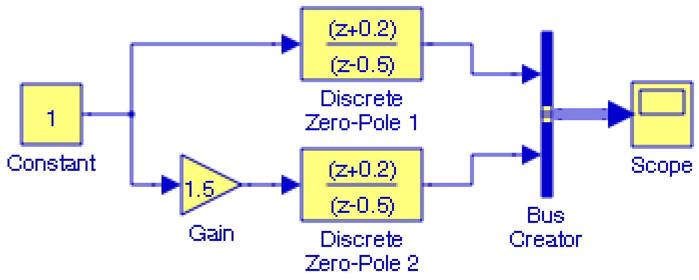


Figure 12.10. Model for Example 12.7

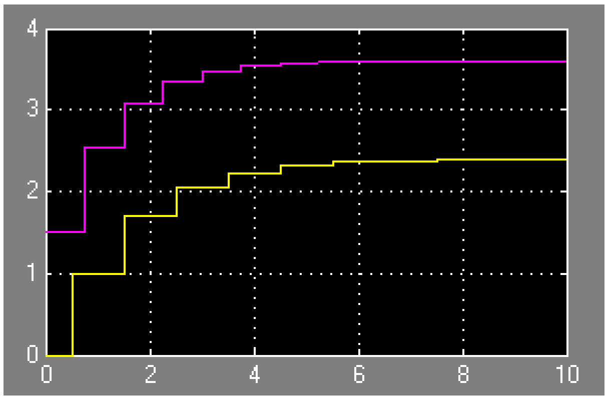


Figure 12.11. Output waveforms for the multirate model in Figure 12.10

Another application of the **Rate Transition** block is illustrated with the next example.

Example 12.8

The model of Figure 12.12 shows three multirate systems where the sample times are as indicated. The **Rate Transition 1** block behaves as a **Zero–Order Hold** block in a fast–to–slow transition, while the **Rate Transition 2** block behaves as a **Unit Delay** block in a slow–to–fast transition. After the simulation command is executed, a label appears on the upper left of the block to indicate its behavior. Since the **Rate Transition 1** block behaves as a **Zero–Order Hold** block, it is indicated as ZOH. Likewise, since the **Rate Transition 2** block behaves as a **Unit Delay** block it is indicated as $1/z$. The **Unit Delay** block is described in Section 2.15, Chapter 2, and the **Zero–Order Hold** block is described in Subsection 5.2.3, Chapter 5. For other behaviors of the **Rate Transition** block, please refer to the Help menu for this block.

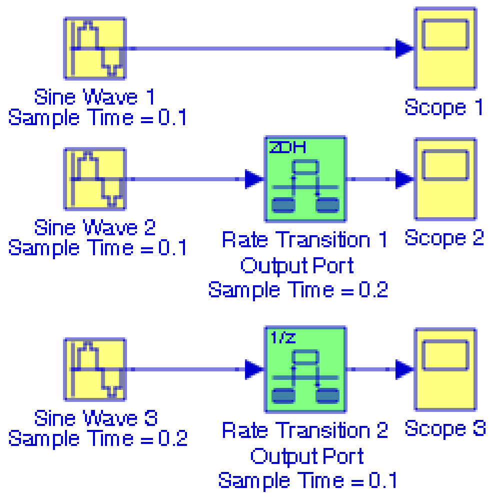


Figure 12.12. Model for Example 12.8

The waveforms displayed by the **Scope** blocks in Figure 12.12 are shown in Figures 12.13, 12.14, and 12.15. The amplitude for all three **Sine Wave** blocks is specified as 2.

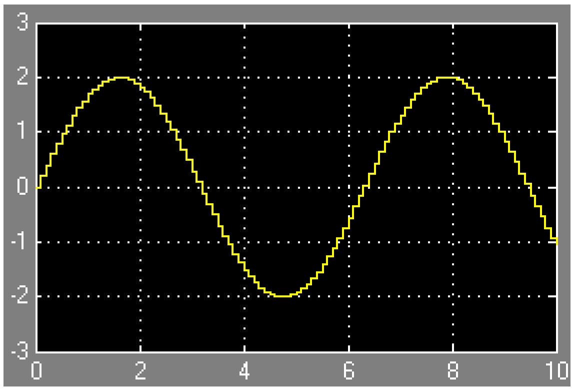


Figure 12.13. Waveform for Scope 1 in Figure 12.12

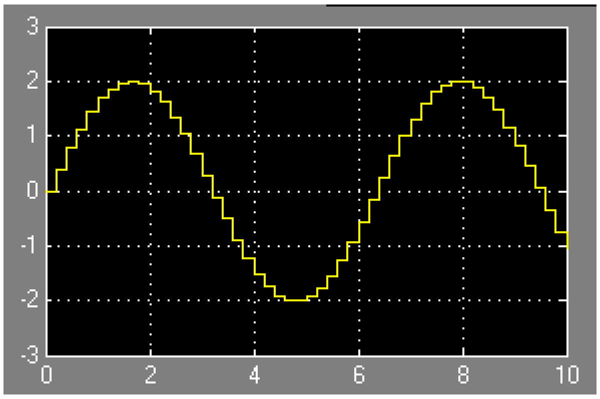


Figure 12.14. Waveform for Scope 2 in Figure 12.12

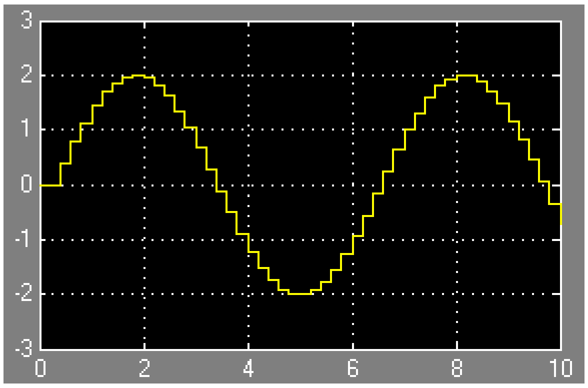


Figure 12.15. Waveform for Scope 3 in Figure 12.12

12.1.9 The Signal Specification Block

The **Signal Specification** block allows us to specify the attributes of the signal connected to its input and output ports. If the specified attributes conflict with the attributes specified by the blocks connected to its ports, Simulink displays an error. If no conflict exists, Simulink eliminates the **Signal Specification** block from the compiled model, that is, the **Signal Specification** block behaves as a virtual block.

Example 12.9

In the model in Figure 12.16, the **Zero–Order Hold** and the **Unit Delay** blocks are both specified for Inherited Sample Time and thus no conflict exists, and the **Signal Specification** block is a virtual block. However, if the Sample Time for the **Unit Delay** block is changed to 0.2 as shown in

Figure 12.17, Simulink displays an error message that an illegal rate transition was found involving the **Unit Delay** block.

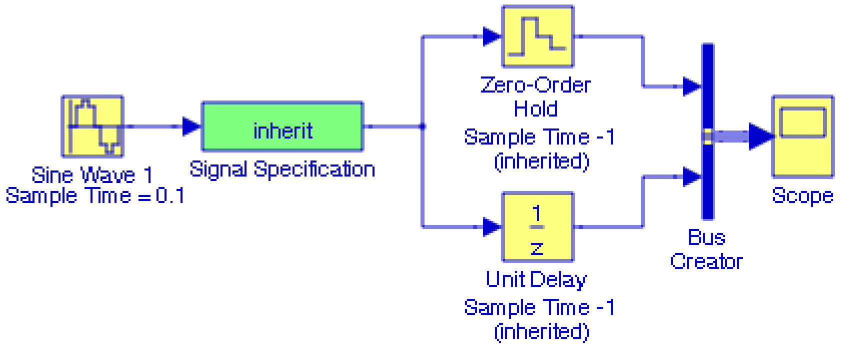


Figure 12.16. Model with the Signal Specification block acting as a virtual block

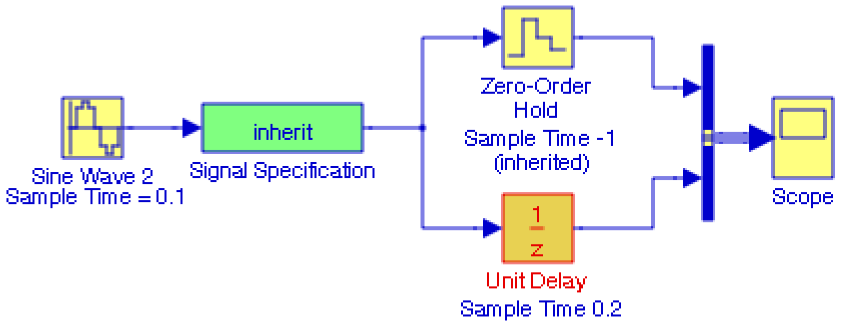
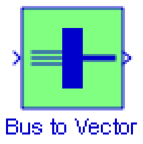


Figure 12.17. Model where the attributes (sample times) of the Signal Specification block do not agree

12.1.10 The Bus to Vector Block



The **Bus to Vector** block converts a virtual bus signal to a vector signal. The input bus signal must consist of scalar, 1–D, or either row or column vectors having the same data type, signal type, and sampling mode. If the input bus contains row or column vectors, this block outputs a row or column vector, respectively; otherwise, it outputs a 1–D array.

Example 12.10

The Model (a) in Figure 12.18 below uses the **Bus Creator 1** block to Display the **Pulse Generator 1** and **Repeating Sequence 1** blocks in **Scope 1** where we observe that the input to that Scope block is a signal bus. In Model (b) the **Bus Creator 1** block is replaced by a **Mux** block and we observe that the input in **Scope 2** block is a vector. In Model (c), instead of replacing the **Bus Creator 3** block with a **Mux** block, we have inserted the **Bus to Vector** block so that the input to the **Scope 3** block is now a vector. The **Pulse Generator** blocks and the **Repeating Sequence** blocks are all in their default parameters and thus all three Scope blocks display the waveforms shown in Figure 12.19.

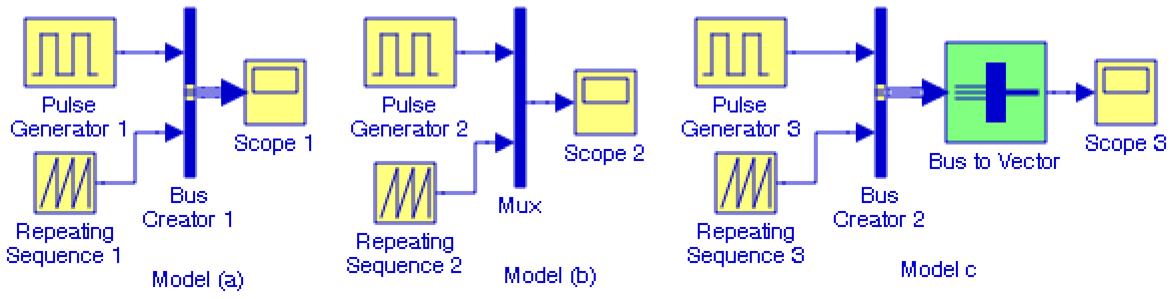


Figure 12.18. Models for Example 12.10

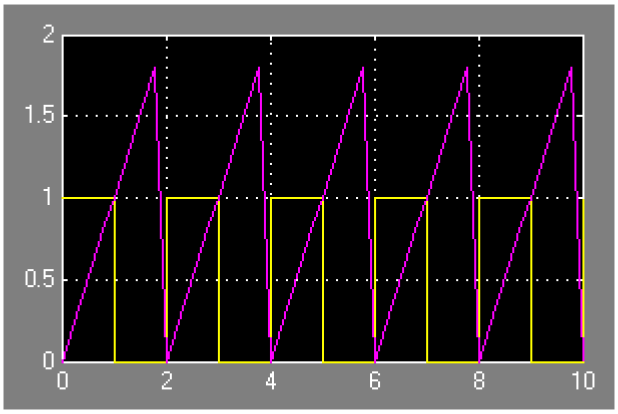
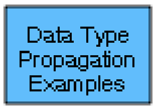


Figure 12.19. Waveforms displayed by Scope 1, Scope 2, and Scope 3 for the model in Figure 12.18

As stated in the Simulink documentation, a **Bus Creator** block creates a bus that contains specified elements whereas a **Mux** block is an indexed vector that implements a composite signal, and we should use a **Bus to Vector** block only to replace an implicit bus–to–vector conversion with an equivalent explicit conversion. For more information, please refer to the Simulink documentation for this block.

12.1.11 The Data Type Propagation Examples Block



Whenever we issue a simulation command, Simulink performs a procedure referred to as **Data Type Propagation** and during this procedure, Simulink determines the types of signals that are not specified to ensure that there is no conflict among those signals. If a conflict occurs, Simulink displays an error dialog that specifies the signal and block whose data causes the conflict.

Example 12.11

Let us consider the models in Figure 12.20 where all five **Constant** blocks have been assigned to unity value with data type uint8 (unsigned 8–bit word).

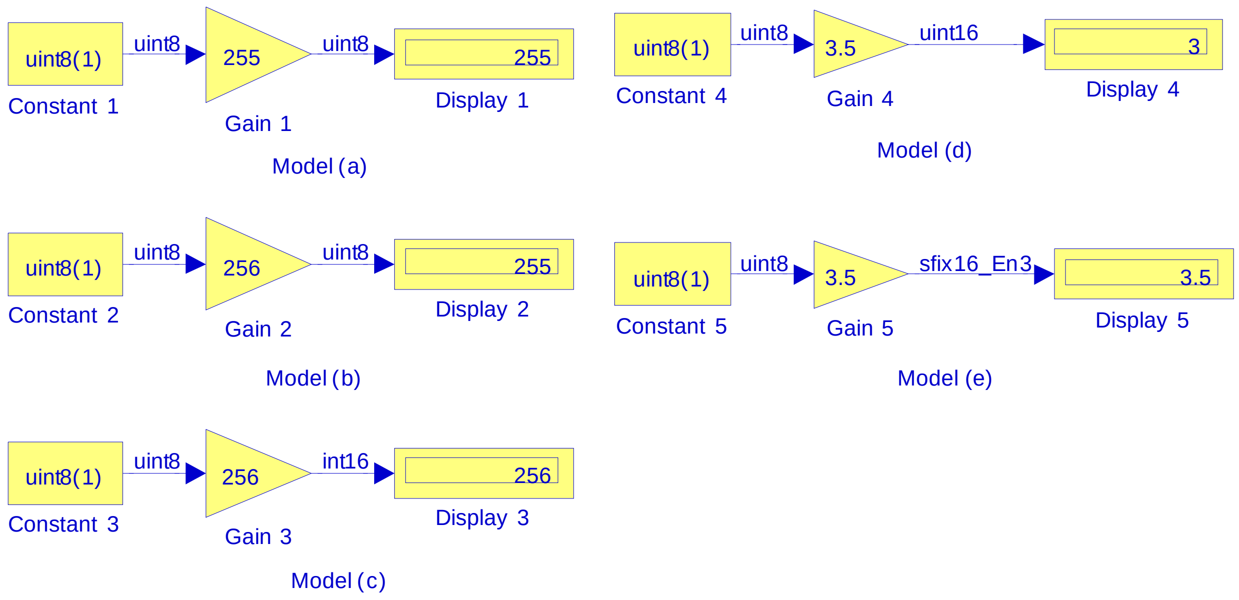
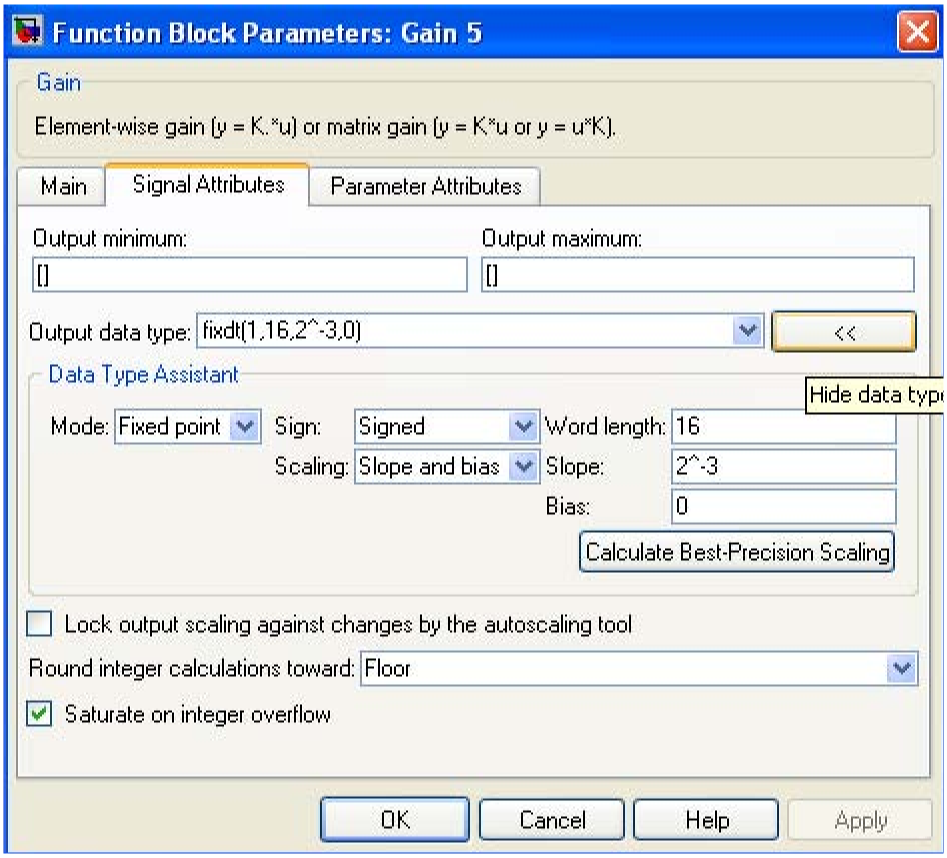


Figure 12.20. Models for Example 12.11

For the Model (a) in Figure 12.20 the **Display 1** block displays the value 255 and this is the true value since it is within the range of the uint8 data type (0 to 255). For the Model (b) the gain is changed to 256 the **Display 2** block displays the value 255 and this is in error because the value 256 is outside the range of the uint8 data type (0 to 255). However, Simulink continues the simulation and issues the following warning message in the MATLAB Command Window:

```
Warning:Saturation occurred.This originated from'Example_12_11/Gain 2'.
```

In Model (c) the **Gain 3** block has been configured for uint16 data type (0 to 65535) and thus the **Display 3** block shows the true value. In Model (d) the gain value is set to 3.5, and since the uint8 data type accommodates only integer values, Simulink truncates 3.5 to the nearest integer value 3 because in the **Function Block Parameters** dialog box for the **Gain 5** block we have specified the field Round integer calculations toward Floor. In Model (e) the **Gain 5** block has been configured as shown in Figure 12.21 and thus the **Display 5** block shows the true value.


Function Block Parameters: Gain 5

Gain

Element-wise gain (y = K.*u) or matrix gain (y = K*u or y = u*K).

Main | Signal Attributes | Parameter Attributes

Output minimum: []

Output maximum: []

Output data type: fixdt(1,16,2^-3,0)

Data Type Assistant

Mode: Fixed point Sign: Signed Word length: 16

Scaling: Slope and bias Slope: 2^-3

Bias: 0

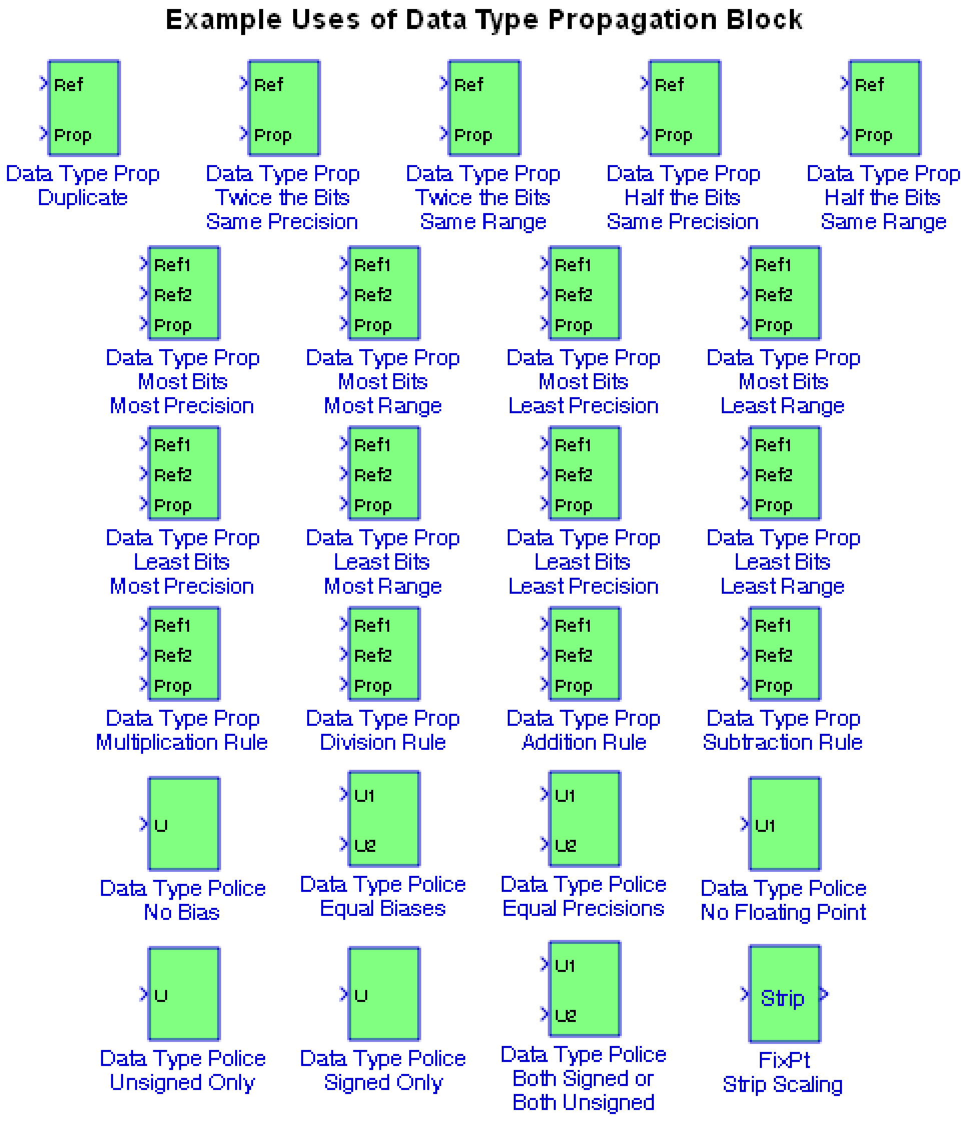
☐ Lock output scaling against changes by the autoscaling tool

Round integer calculations toward: Floor

☑ Saturate on integer overflow

Figure 12.21. Function Block Parameters dialog box for the Gain 5 block in Figure 12.20

The **Data Type Propagation** block is discussed in Subsection 12.1.3 and Example 12.2 illustrates how this block can be used. allows us to control the data type and scaling of signals in our model. Figure 12.22 below shows several **Data Type Propagation** examples.



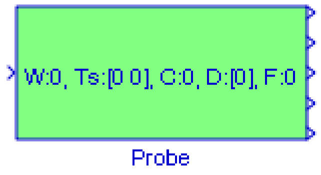
Example Uses of Data Type Propagation Block
Ref
Prop
Data Type Prop Duplicate
Data Type Prop Twice the Bits Same Precision
Data Type Prop Twice the Bits Same Range
Data Type Prop Half the Bits Same Precision
Data Type Prop Half the Bits Same Range
Ref1
Ref2
Data Type Prop Most Bits Most Precision
Data Type Prop Most Bits Most Range
Data Type Prop Most Bits Least Precision
Data Type Prop Most Bits Least Range
Data Type Prop Least Bits Most Precision
Data Type Prop Least Bits Most Range
Data Type Prop Least Bits Least Precision
Data Type Prop Least Bits Least Range
Data Type Prop Multiplication Rule
Data Type Prop Division Rule
Data Type Prop Addition Rule
Data Type Prop Subtraction Rule
U
U1
U2
Data Type Police No Bias
Data Type Police Equal Biases
Data Type Police Equal Precisions
Data Type Police No Floating Point
Data Type Police Unsigned Only
Data Type Police Signed Only
Data Type Police Both Signed or Both Unsigned
Strip
FixPt Strip Scaling

Figure 12.22. Example uses of Data Type Propagation blocks

12.2 The Signal Attribute Detection Sub–Library

The **Signal Attribute Detection Sub–Library** contains the blocks described in Subsections 12.2.1 through 12.2.3 below.

12.2.1 The Probe Block



The **Probe** block provides essential information about the signal on its input. The block can output the input signal's width, dimensionality, sample time, and/or a flag indicating whether the input is a complex–valued signal. The block has one input port. The number of output ports depends on the information that we select for probing. Each probed value is output as a separate signal on a separate output port. During simulation, the block's icon displays the probed data.

Example 12.12

In the model of Figure 12.23, the **Display 1** block indicates the number of the elements of the probed signal, the **Display 2** block is a 2×1 vector that specifies the period and offset of the sample time, respectively, the **Display 3** block shows the value 0 implying that the probed signal is not complex, the **Display 4** block indicates the output the dimensions of the probed signal, and the **Display 5** block shows the value 0 implying that the probed signal is not framed.*

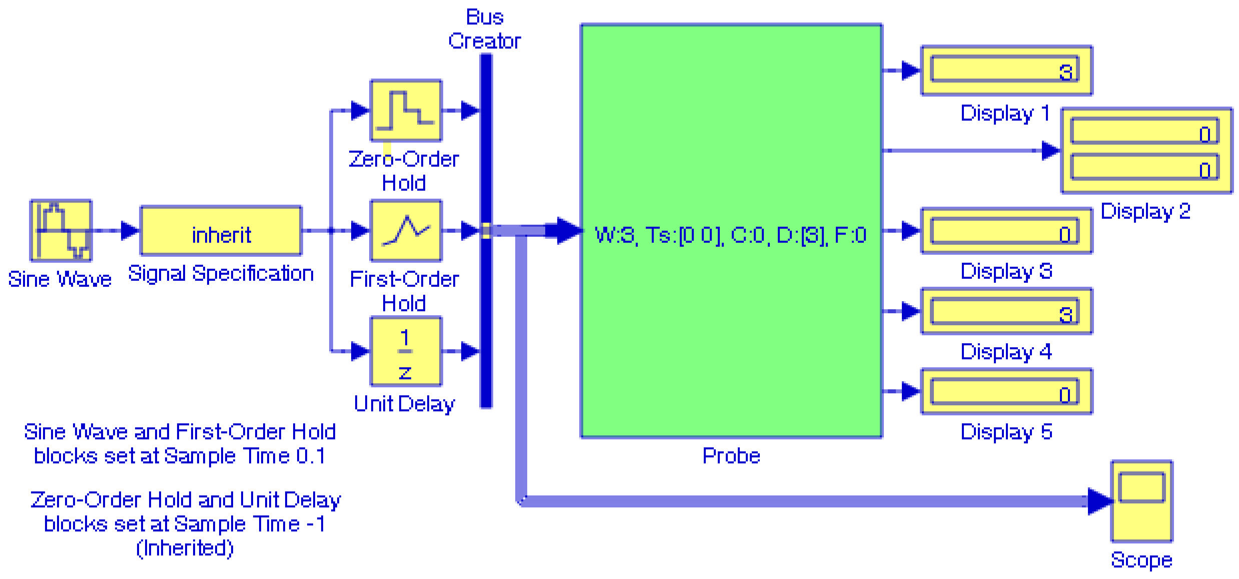
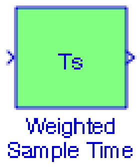

Bus Creator
Zero-Order Hold
First-Order Hold
Unit Delay
1/z
Sine Wave
inherit
Signal Specification
W:3, Ts:[0 0], C:0, D:[3], F:0
Probe
3
Display 1
0
0
Display 2
0
Display 3
3
Display 4
0
Display 5
Scope
Sine Wave and First-Order Hold blocks set at Sample Time 0.1
Zero-Order Hold and Unit Delay blocks set at Sample Time -1 (Inherited)

Figure 12.23. Model for Example 12.12

* *Please logon to http://festvox.org/docs/speech_tools–1.2.0/x15608.htm#SIGPR–EXAMPLE–FRAMES for a description of frame–based signals.*

12.2.2 The Weighted Sample Time Block



The **Weighted Sample Time** block adds, subtracts, multiplies, or divides the input signal, u, by a weighted sample time Ts. The math operation is specified with the Operation parameter. Also, we can specify to use only the weight with either the sample time or its inverse. We enter the weighting factor in the Weight value parameter. If the weight is 1, w is removed from the equation.

Example 12.13

In the model in Figure 12.24, the parameters for all blocks are specified as annotated. Thus, the **Display 1** block shows the values of the **Constant** blocks, the **Display 2** block shows the Weighted Sample Time, the **Display 3** block shows the inverse of the Weighted Sample Time, and the **Display 4** block shows the results of the division $u/Ts/w$, where $w = 2$ for $u = 1, 2,$ and 3.

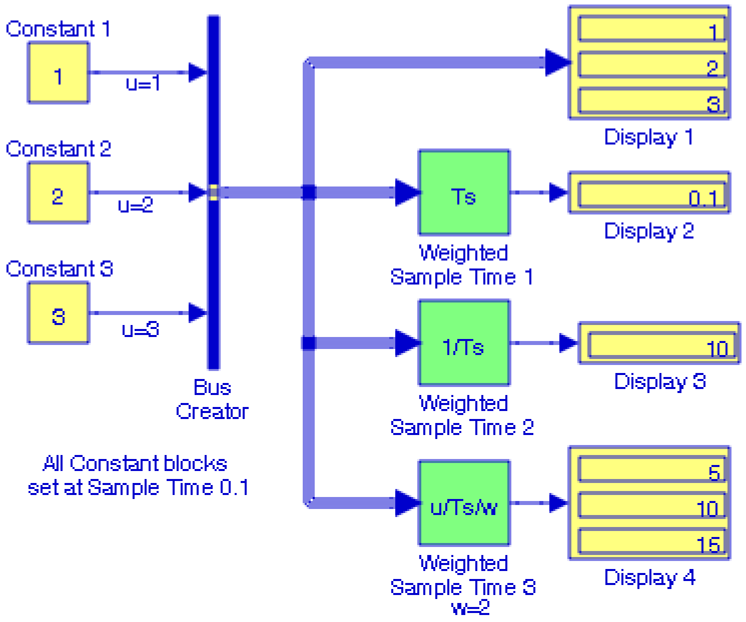
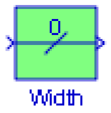


Figure 12.24. Model for Example 12.13

12.2.3 The Width Block



The **Width** block generates an output that displays the width of its input vector, or the sum of the widths of two or more vectors.

Example 12.14

In the model in Figure 12.25, the vectors A and B are specified at the MATLAB command prompt as

```
A=[1  3  5  7  9]; B=[2  4  6  8];
```

The Width block outputs the sum of the widths of the vectors A and B .

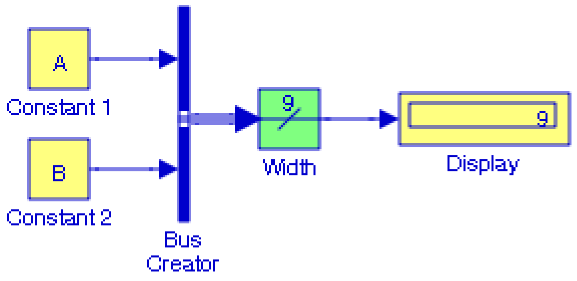


Figure 12.25. Model for Example 12.14

12.3 Summary

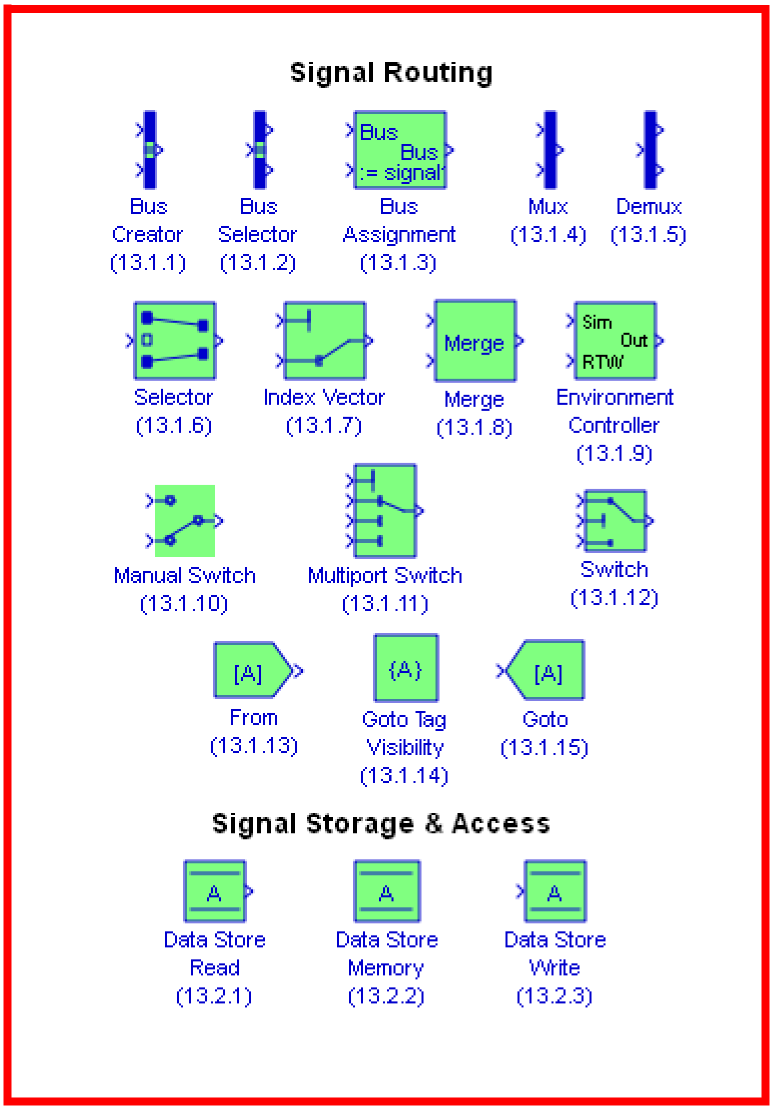
- The **Data Type Conversion block** converts an input signal of any Simulink data type to the data type and scaling specified by the block's Output data type mode, Output data type, and/or Output scaling parameters.
- The **Data Type Duplicate** block is used to ascertain that all inputs have the same data type. We use the Data Type Duplicate block to check for consistency of data types among blocks. If all signals do not have the same data type, the block returns an error message.
- The **Data Type Propagation** block allows us to control the data type and scaling of signals in our model. We can use this block in conjunction with fixed–point blocks that have their Specify data type and scaling parameter configured to Inherit via back propagation.
- The **Data Type Scaling Strip** block removes the scaling off a fixed point signal. It maps the input data type to the smallest built in data type that has enough data bits to hold the input. The stored integer value of the input is the value of the output.
- The **Data Type Conversion Inherited** block converts one data type to another using inherited data types. In other words, this block commands that different types of data be converted to be all the same. The first input is used as the reference signal and the second input is converted to the reference type by inheriting the data type and scaling information.
- The **IC (Initial Condition)** block sets the initial condition of the signal at its input port, i.e., the value of the signal at t=0. The block does this by outputting the specified initial condition at t=0, regardless of the actual value of the input signal. Thereafter, the block outputs the actual value of the input signal.
- The **Signal Conversion** block converts a signal from one type to another. The block's Output parameter lets us select the type of conversion to be performed. We can choose one of four types: Contiguous copy, Bus copy, Virtual bus, or Nonvirtual bus.
- The **Rate Transition** block transfers data from the output of a block operating at one rate to the input of another block operating at a different rate. Systems containing blocks that are sampled at different rates are referred to as **multirate systems**.
- The **Signal Specification** block allows us to specify the attributes of the signal connected to its input and output ports. If the specified attributes conflict with the attributes specified by the blocks connected to its ports, Simulink displays an error at the beginning of a simulation.
- The **Bus to Vector** block converts a virtual bus signal to a vector signal. The input bus signal must consist of scalar, 1–D, or either row or column vectors having the same data type, signal type, and sampling mode. If the input bus contains row or column vectors, this block outputs a row or column vector, respectively; otherwise, it outputs a 1–D array.
- The **Data Type Propagation Examples** block contains example uses of Data Type Propagation blocks.

- The **Probe** block provides essential information about the signal on its input. The block can output the input signal's width, dimensionality, sample time, and/or a flag indicating whether the input is a complex–valued signal.
- The **Weighted Sample Time** block adds, subtracts, multiplies, or divides the input signal, `u`, by a weighted sample time `Ts`. The math operation is specified with the Operation parameter.
- The **Width** block generates an output that displays the width of its input vector, or the sum of the widths of two or more vectors.

Chapter 13

The Signal Routing Library

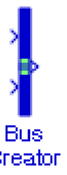
This chapter is an introduction to the **Signal Routing** library**.** This is the twelfth library in the Simulink group of libraries and consists of two sub–libraries, the **Signal Routing Group Sub–Library,** and the **Signal Storage & Access Group Sub–Library** blocks shown below. Their functions are illustrated with examples.



13.1 Signal Routing Group Sub–Library

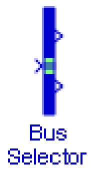
The **Signal Routing Group Sub–Library** contains the fifteen blocks described in Subsections 13.1.1 through 13.1.15 below.

13.1.1 The Bus Creator Block



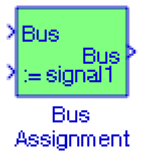
The **Bus Creator** block combines a set of signals into a group of signals represented by a single line. This block is described in Section 2.6, Chapter 2.

13.1.2 The Bus Selector Block



The **Bus Selector** block outputs a specified subset of the elements of the bus at its input. This block is described in Section 2.6, Chapter 2.

13.1.3 The Bus Assignment Block



The **Bus Assignment** block assigns values, specified by signals connected to its assignment (:=) input ports, to specified elements of the bus connected to its Bus input port. We use the block's dialog box to specify the bus elements to be assigned values. The block displays an assignment input port for each bus element to be assigned a signal.

In the **Function Block Parameters** dialog box, the **Signals in the bus** displays the names of the signals contained by the bus at the block's Bus input port. We can click any item in the list to select it. To find the source of the selected signal, we click the adjacent Find button. Simulink opens the subsystem containing the signal source, if necessary, and highlights the source's icon. We use the **Select** button to move the currently selected signal into the adjacent list of signals to be assigned values (see Signals that are being assigned below). To refresh the display (e.g., to reflect modifications to the bus connected to the block), we click the adjacent **Refresh** button.

In the Function Block Parameters dialog box, the **Signals that are being assigned** lists the names of bus elements to be assigned values. This block displays an assignment input port for each bus element in this list. The label of the corresponding input port contains the name of the element. We can re–order the signals by using the **Up**, **Down**, and **Remove** buttons. Port connectivity is maintained when the signal order is changed.

Occasionally, we may see three question marks (???) before the name of a bus element. This indicates that the input bus no longer contains an element of that name, for example, because the bus has changed since the last time we refreshed the Bus Assignment block's input and bus element assignment lists. We can fix the problem either by modifying the bus to include a signal of the specified name, or by removing the name from the list of bus elements to be assigned values.

Example 13.1

We begin with the model 13.1. Initially, the **Bus Assignment 1** block appears with two inputs, one for the block's Bus input port, and the other which serves as the assignment input port for each bus element to be assigned a signal. We double–click this block and we configure the **Function Block Parameters** dialog box as shown in Figure 13.2. The output waveforms are shown in Figure 13.3.

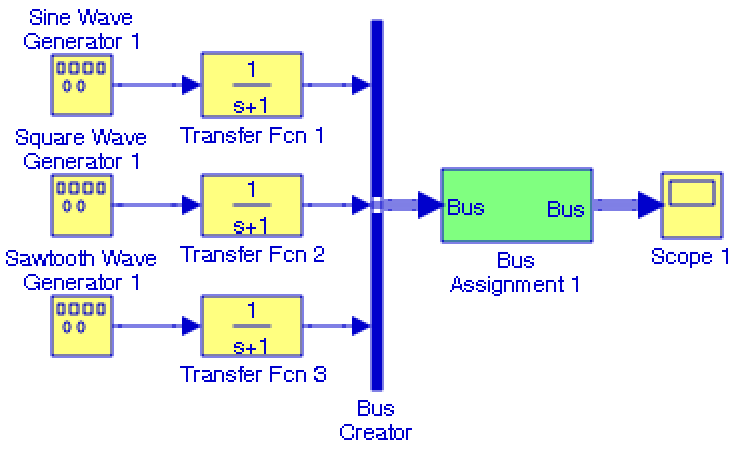
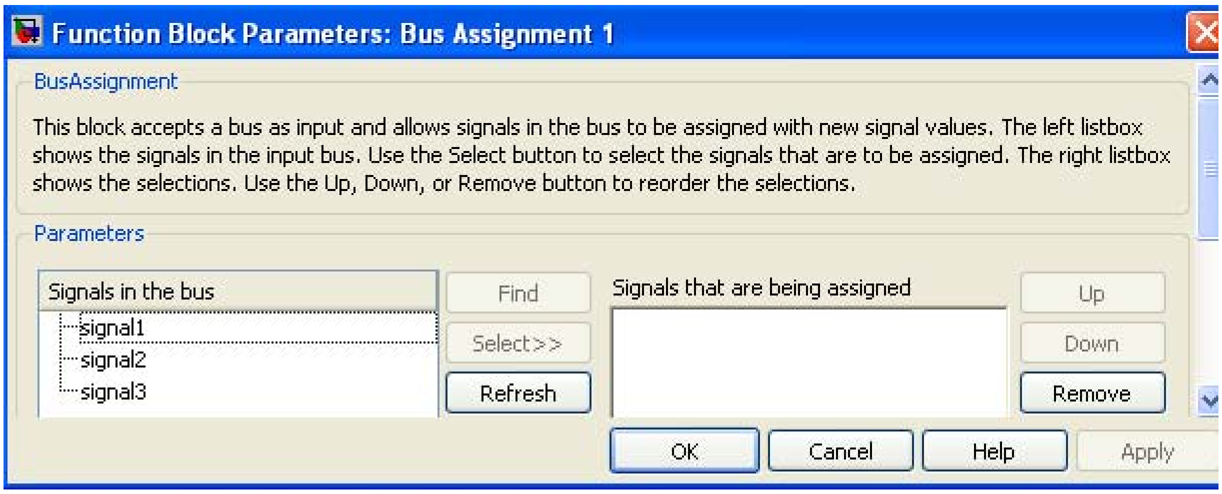


Figure 13.1. Model for Example 13.1

Next, suppose that we wish to replace the **Square Wave Generator 1** block and the **Sawtooth Wave Generator 1** block with a **Random Wave Generator** block and a **Band–Limited White Noise** block. Instead of replacing the blocks, we add the **Random Wave Generator** block and the **Band–Limited White Noise** block as shown in Figure 13.4, we double–click the Bus Assignment block, and we use the **Select** button to move the currently selected signal into the adjacent list of signals to be assigned values. To refresh the display, we click the adjacent **Refresh** button, and the **Function Block Parameters** dialog box now appears as shown in Figure 13.5. When this is done, the output waveforms appear as shown in Figure 13.6.


Function Block Parameters: Bus Assignment 1

BusAssignment

This block accepts a bus as input and allows signals in the bus to be assigned with new signal values. The left listbox shows the signals in the input bus. Use the Select button to select the signals that are to be assigned. The right listbox shows the selections. Use the Up, Down, or Remove button to reorder the selections.

Parameters

Signals in the bus
- signal1
- signal2
- signal3

Signals that are being assigned

Figure 13.2. Configuration of the Function Block Parameters for the Bus Assignment Block in Figure 13.1

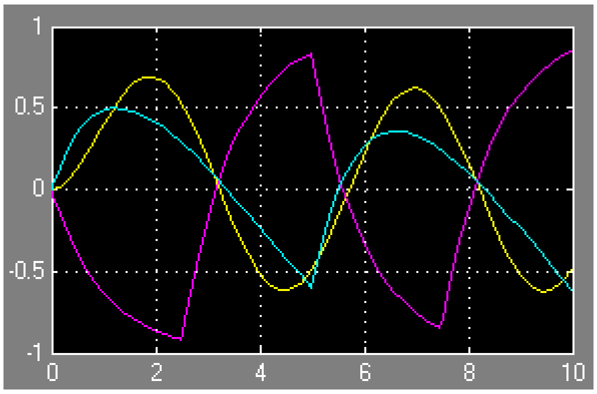


Figure 13.3. Output waveforms for the model in Figure 13.1

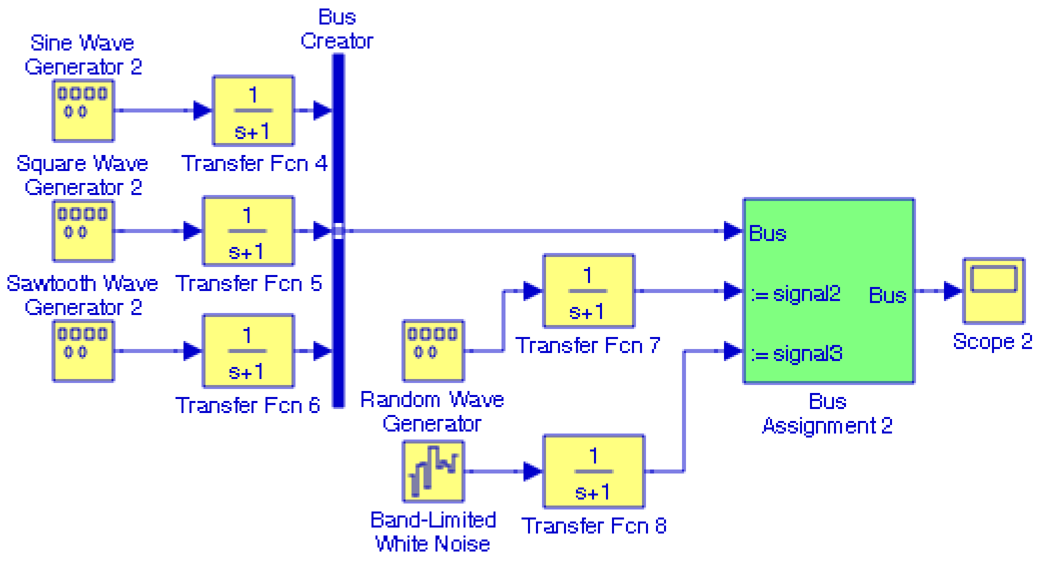
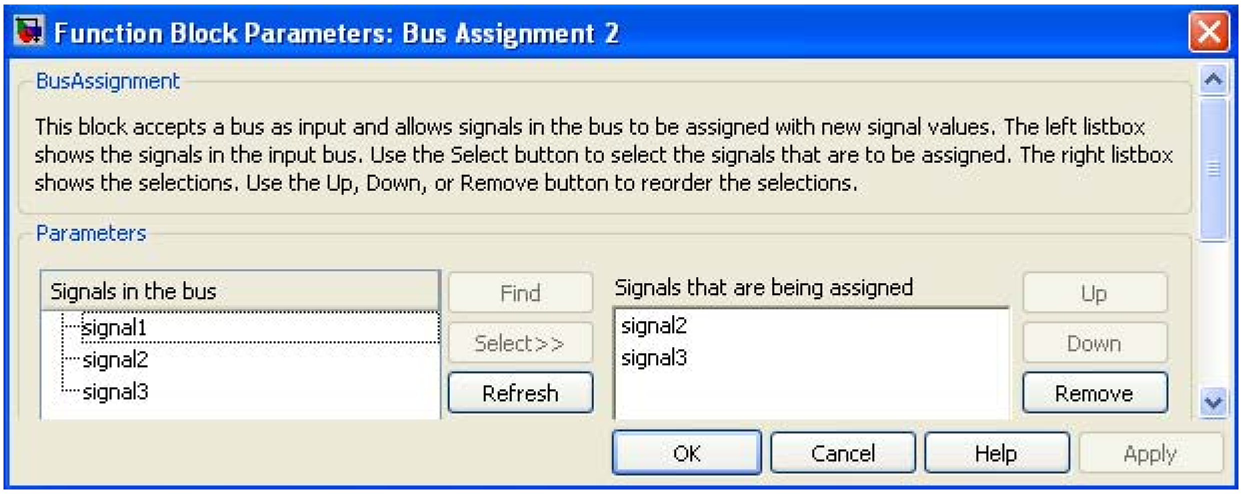


Figure 13.4. Modified model for Example 13.1



BusAssignment

This block accepts a bus as input and allows signals in the bus to be assigned with new signal values. The left listbox shows the signals in the input bus. Use the Select button to select the signals that are to be assigned. The right listbox shows the selections. Use the Up, Down, or Remove button to reorder the selections.

Parameters

Signals in the bus
- signal1
- signal2
- signal3

Signals that are being assigned
- signal2
- signal3

Figure 13.5. Configuration of the Function Block Parameters for the Bus Assignment Block in Figure 13.4

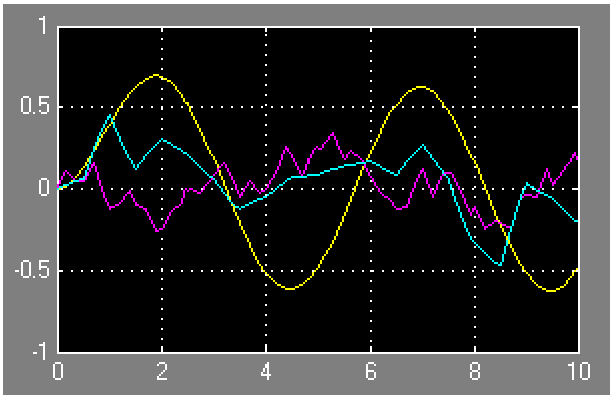
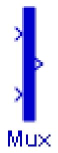


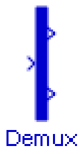
Figure 13.6. Output waveforms for the model in Figure 13.4

13.1.4 The Mux Block



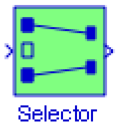
The **Mux** block combines its inputs into a single output. An input can be a scalar, vector, or matrix signal. This block is described in Section 2.7, Chapter 2.

13.1.5 The Demux Block



The **Demux** block extracts the components of an input signal and outputs the components as separate signals. This block is described in Section 2.7, Chapter 2.

13.1.6 The Selector Block



The **Selector** block generates as output selected elements of an input vector or matrix. If the input type is vector, the block outputs a vector of selected elements specified by element indices. The meaning of the indices depends on the setting of the Index mode parameter. If the setting is One–based (the default), the index of the first input element is 1, the second 2, and so on. If the setting is Zero–based, the index of the first element is 0, the second element 1, and so on.

Example 13.2

For the model of Figure 13.7, the elements a11, a12, …a44 of the 4×4 matrix in the Constant block are specified at the MATLAB command prompt as:

```
a11=2; a12=–1; a13=0; a14=–3;...
a21=–1; a22=1; a23=0; a24=–1;...
a31=4; a32=0; a33=3; a34=–2;...
a41=–3; a42=0; a43=0; a44=1;
```

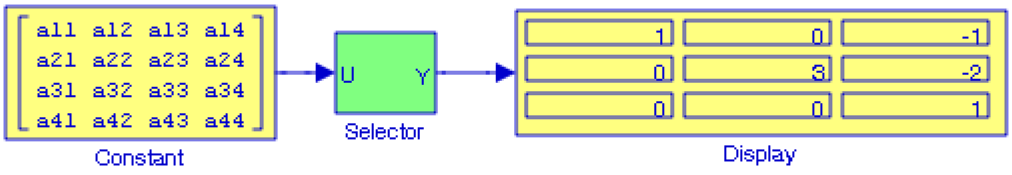
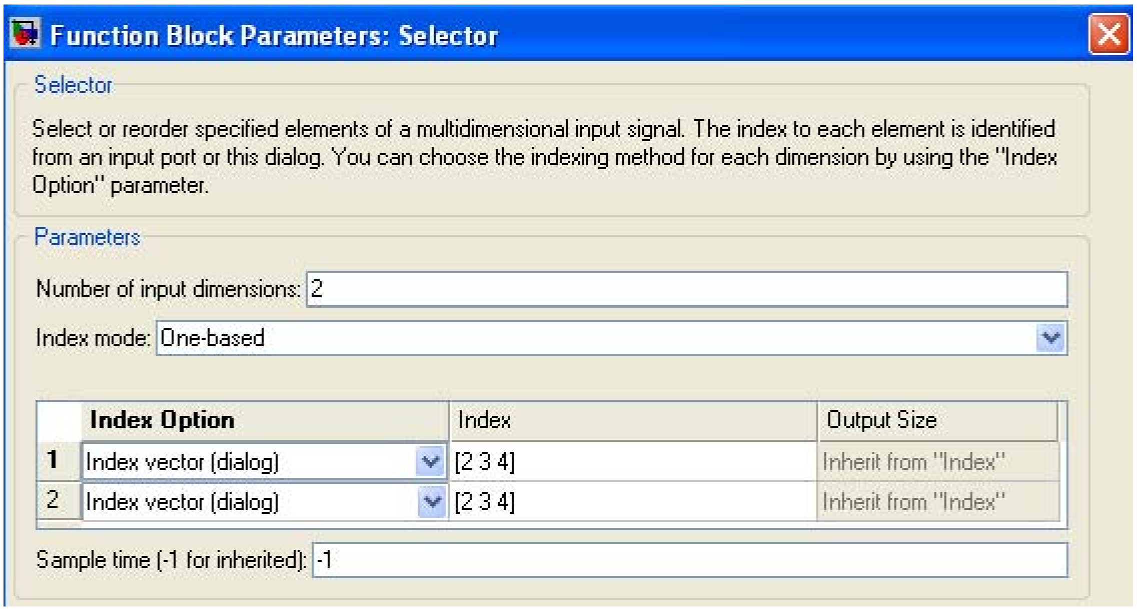


Figure 13.7. Model for Example 13.2

The **Display** block shows the cofactor of a_{11} defined as $(-1)^{i+j}[M_{ij}]$, where the index i denotes the ith row, the index j denotes the jth column, and M is the minor of the element a_{ij}.

For the **Selector** block Function Block Parameters dialog box we specified the parameters as shown in Figure 13.8.



Function Block Parameters: Selector

Selector

Select or reorder specified elements of a multidimensional input signal. The index to each element is identified from an input port or this dialog. You can choose the indexing method for each dimension by using the "Index Option" parameter.

Parameters

Number of input dimensions: 2

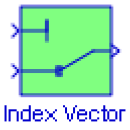
Index mode: One-based

	Index Option	Index	Output Size
1	Index vector (dialog)	[2 3 4]	Inherit from "Index"
2	Index vector (dialog)	[2 3 4]	Inherit from "Index"

Sample time (-1 for inherited): -1

Figure 13.8. Function Block Parameters for the model in Figure 13.7

13.1.7 The Index Vector Block



The **Index Vector** block switches the output between different inputs based on the value of the first input, referred to as the **Control Input**. This block is an implementation of the **Multiport Switch** block which is described in Subsection 13.1.11, this chapter.

Example 13.3

For the **Index Vector** block in Figure 13.9, the parameters are specified as Number of inputs 2, and the Use zero–based indexing box is unchecked. All other parameters are left in their default state. Since the Control Input is specified as 2, the **Index Vector** block outputs the value of Data Input 2.

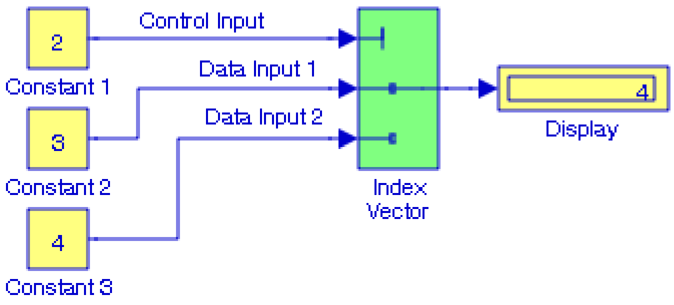
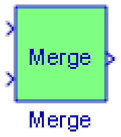


Figure 13.9. Model for Example 13.3

13.1.8 The Merge Block



The **Merge** block combines its inputs into a single output line whose value at any time is equal to the most recently computed output of its driving blocks. We can specify any number of inputs by setting the block's Number of inputs parameter. This block is useful in creating alternately executing subsystems as illustrated by the example below.

Example 13.4

The **Enable Subsystem 1** and **Enable Subsystem 2** blocks in the model of Figure 13.10 are specified as shown in Figure 13.11. This model outputs the half–wave rectification* waveform shown in Figure 13.12.

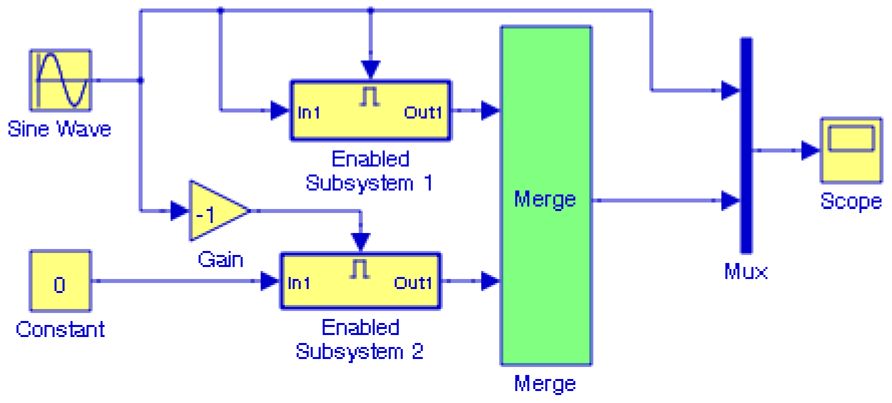


Figure 13.10. Model for Example 13.4

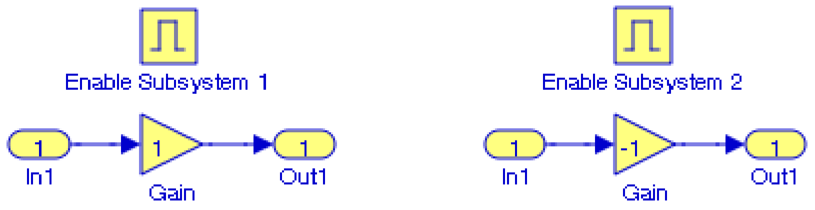


Figure 13.11. Configuration of the Enabled Subsystem 1 and 2 blocks in Figure 13.10

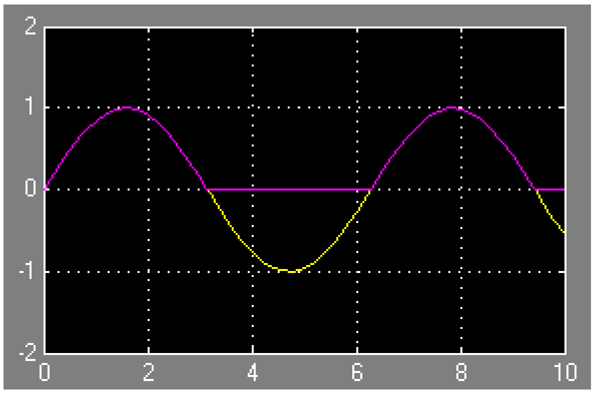
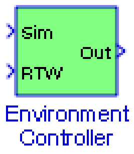


Figure 13.12. Waveforms for the model of Figure 13.10

* *For the creation of a full–wave rectification waveform, please refer to the Help menus for the Merge block and click on the "Creating Alternately Executing Subsystems" link. Full–wave rectifiers are used in the conversion from AC to DC signals. For a detailed discussion, please refer to Signals & Systems with MATLAB Computing and Simulink Modeling, ISBN 978–0–934408–9–9.*

The Simulink documentation includes the **Merge Block Demonstration** demo. It can be accessed by typing mergedemo at the MATLAB command prompt.

13.1.9 The Environmental Controller Block



The **Environmental Controller** block outputs the signal at its Sim port only if the model that contains it is being simulated. It outputs the signal at its Real–Time Workshop[*] (RTW) port only if code is being generated from the model.

Example 13.5

The **Environmental Controller** block in Figure 13.13 outputs the signal from the Sim port only. It does not output the signal from the RTW port because no code is generated for that port. Accordingly, after simulation the **Scope** block displays the pulse waveform shown in Figure 13.14.

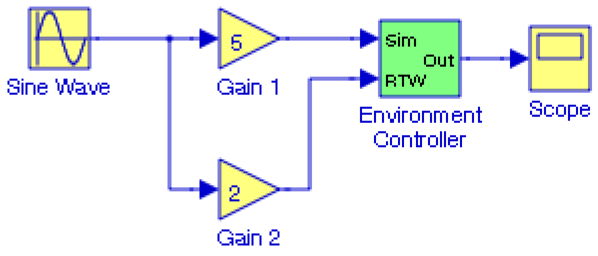


Figure 13.13. Model for Example 13.5

* *Real–Time Workshop is an extension of MATLAB and Simulink capabilities that generates source code from Simulink models to create real–time software applications. We will not discuss source code generation in this text. Tutorials are provided in the "Real–Time Workshop For Use with Simulink" documentation. A good example to begin with is the Grumman Aerospace F–14 aircraft and it can be accessed by typing f14 at the MATLAB command prompt. These tutorials require that a MATLAB compatible C compiler is installed in the system.*

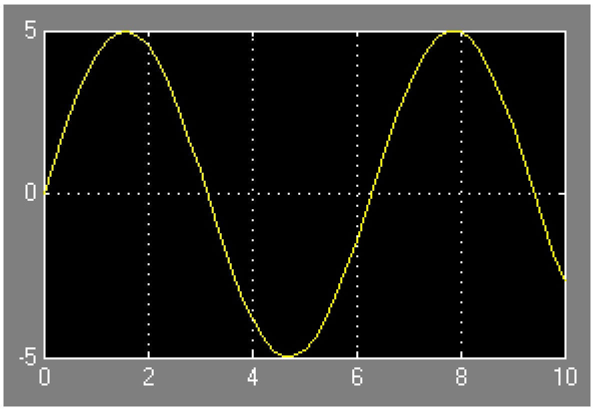


Figure 13.14. Waveform displayed by the Scope block in Figure 13.13

Next, we generate code for the RTW port as follows:

1. We create the directory Example_13_5_codegen and we make it our working directory by typing at the MATLAB command prompt the following:

```
!mkdir  Example_13_5_codegen
cd  Example_13_5_codegen
```

2. We create a new model and we save it as Example_13_5. Simulink adds the extension .mdl

3. In the new model we drag and interconnect the blocks shown in Figure 13.13, and this model is shown as in Figure 13.15.

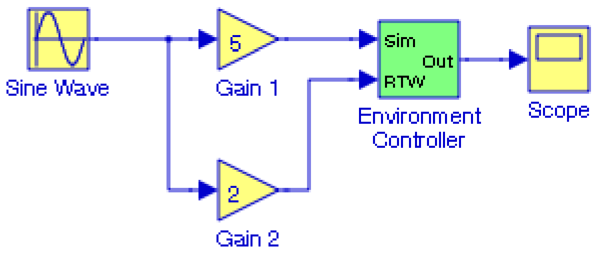


Figure 13.15. Model for Example 13.5 to generate RTW code

4. In the model in Figure 13.15 from the **Simulation** drop menu we choose **Configuration Parameters**, in the dialog box on the left pane we click the **Solver** tab, and in the **Solver Options** we choose Fixed−Step, ode5(Dormand−Prince). We leave all other parameters in their default state and we click **Apply**.

5. With the **Configuration Parameters** dialog box still open, on the left pane we click the **Data Import/Export** tab, we clear all check boxes, and we click **Apply**.

6. With the **Configuration Parameters** dialog box still open, on the left pane we click the **Real–Time Workshop** tab, and we select **Generate code only** option at the bottom of the right pane. We observe that the caption on the **Build** button on the right side changes to **Generate code**, and the **System target file** on the top of the right pane is shown as grt.tlc. We click **Apply** to accept these settings.

7. In the model in Figure 13.15 from the **Simulation** drop menu we click the **Start** option and the **Scope** block now displays the signal at its **Real–Time Workshop** (RTW) port as shown in Figure 13.16.

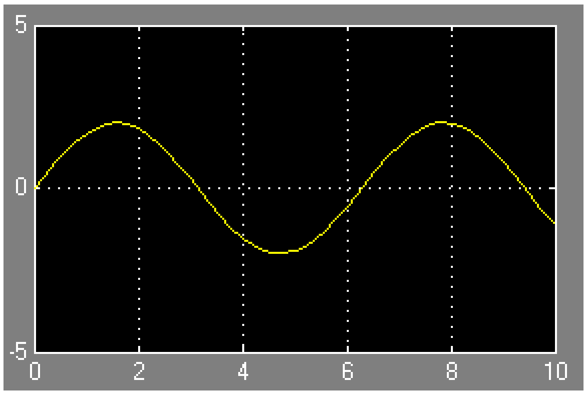


Figure 13.16. Waveform displayed by the Scope block in Figure 13.15

13.1.10 The Manual Switch Block

Manual Switch

The **Manual Switch** block is a toggle switch that selects one of its two inputs to pass through to the output. There is no dialog box for this block; to toggle between inputs, we double–click the block. The block retains its current state when the model is saved.

Example 13.6

In Figure 13.17, the matrix A is defined at the MATLAB command prompt as

```
A=[1  2 –3; 2 –4  2; –1  2 –6];
```

The **MATLAB Function** block in the **Function Block Parameters** dialog box for the models in Figures 13.17 and 13.8 is specified as inv (for matrix inversion), and when the **Switch** block is in the upper position as shown in Figure 13.17, the **Display** block shows the elements of the matrix.

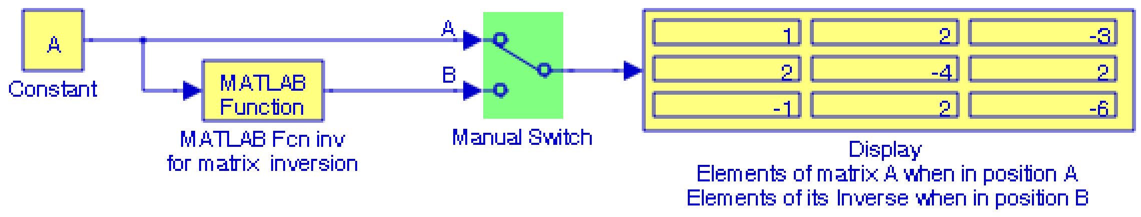

A
Constant
MATLAB Function
MATLAB Fcn inv for matrix inversion
A
B
Manual Switch
1 2 -3
2 -4 2
-1 2 -6
Display
Elements of matrix A when in position A
Elements of its Inverse when in position B

Figure 13.17. Model for Example 13.6 displaying the elements of Matrix A

When we double–click the **Switch** block, it changes to the lower position as shown in Figure 13.18, the **Display** block shows the elements of the inverted matrix A.

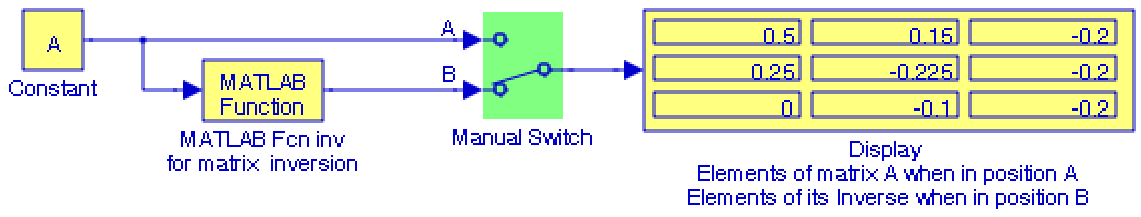
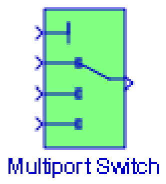

A
Constant
MATLAB Function
MATLAB Fcn inv for matrix inversion
A
B
Manual Switch
0.5 0.15 -0.2
0.25 -0.225 -0.2
0 -0.1 -0.2
Display
Elements of matrix A when in position A
Elements of its Inverse when in position B

Figure 13.18. Model for Example 13.6 displaying the elements of the Inverse of Matrix A

The Simulink documentation includes the **Modeling a Fault–Tolerant Fuel Control System** demo. It can be accessed by typing sldemo_fuelsys at the MATLAB command prompt.

13.1.11 The Multiport Switch Block



The **Multiport Switch** block chooses between a number of inputs. The first (top) input is called the **control input**, while the rest of the inputs are called **data inputs**. The value of the control input determines which data input is passed through to the output port. If the control input is an integer value, the specified data input is passed through to the output. For example, if the one–based indexing parameter is selected and the control input is 1, the first data input is passed through to the output. If the control input is 2, the second data input is passed through to the output, and so on.

Example 13.7

The model of Figure 13.19 outputs the value 64 corresponding to the control input value 4.

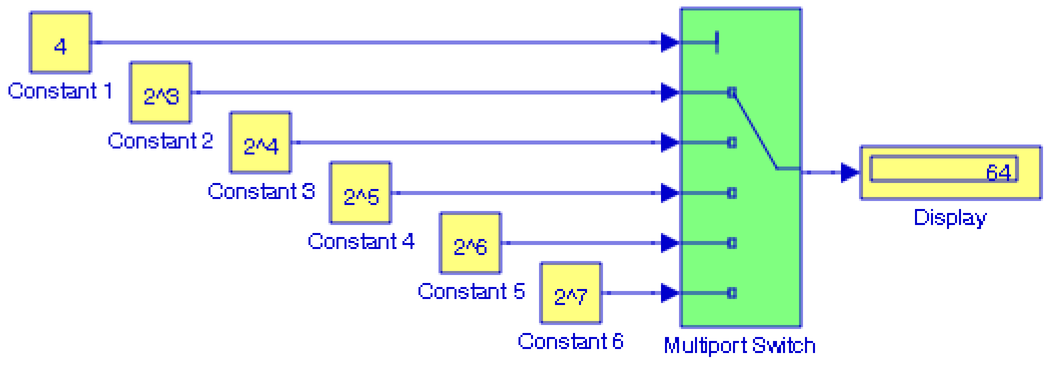
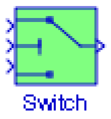


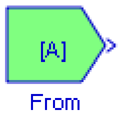
Figure 13.19. Model for Example 13.7

13.1.12 The Switch Block



The **Switch** block outputs the first (top) input or the third (bottom) input depending on the value of the second (middle) input. The first and third inputs are the **data inputs**. The second input is the **control input**. This block is described in Section 2.8, Chapter 2.

13.1.13 The From Block



The **From** block accepts a signal from a corresponding **Goto** block which is described in Subsection 13.1.15, this chapter, and passes it as output. The visibility of a **Goto** block tag determines the **From** blocks that can receive its signal.

Example 13.8

In Figure 13.14, the matrix A is defined at the MATLAB command prompt as

```
A=[1  2 –3; 2 –4  2; –1  2 –6];
```

In the upper model of Figure 13.20, the **Display 1** block shows the elements of matrix A. In the lower model of Figure 13.14, the **Constant 2** block sends the elements of matrix A to the **Goto** block, it is accepted by the **From** block, and outputs it to the **Display 2** block.

The upper and lower models in Figure 13.20 are equivalent. As we can see, the **From** and **Goto** blocks allow us to pass a signal from one block to another without a physical connection.

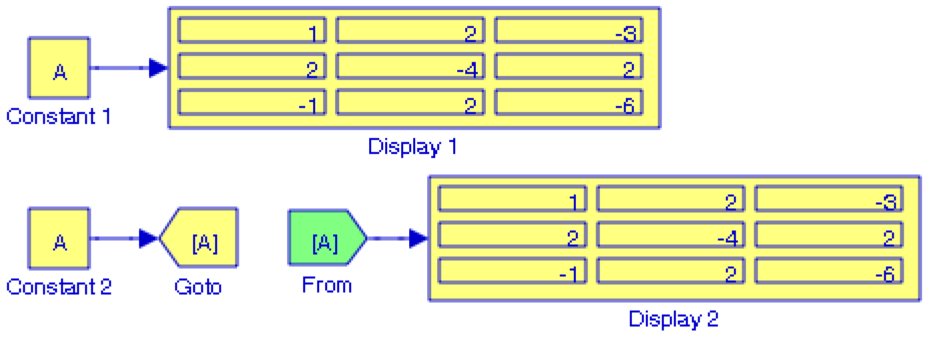


Figure 13.20. Models for Example 13.8

To associate a **Goto** block with a **From** block, we enter the **Goto** block's tag in the **Goto** Tag parameter. A **From** block can receive its signal from only one **Goto** block, although a **Goto** block can pass its signal to more than one **From** block.

The Simulink documentation includes the **Simulating Automatic Climate Control Systems** demo and the **Bus Signal Demonstration** demo. They can be accessed by typing sldemo_auto_climatecontrol and busdemo at the MATLAB command prompt respectively.

13.1.14 The Goto Tag Visibility Block

The **Goto Tag Visibility** block defines the accessibility of Goto block tags that have scoped visibility. The tag specified as the **Goto** tag parameter is accessible by **From** blocks in the same subsystem that contains the **Goto Tag Visibility** block and in subsystems below it in the model hierarchy. A **Goto Tag Visibility** block is required for **Goto** blocks whose Tag visibility parameter value is specified as scoped. No **Goto Tag Visibility** block is required if the tag visibility is either local or global. When scoped, the block shows the tag name enclosed in braces ({}).

Example 13.9

The model in Figure 13.21, is the same as that of in Figure 13.20, except that it includes the **Goto Tag Visibility Tag** block.

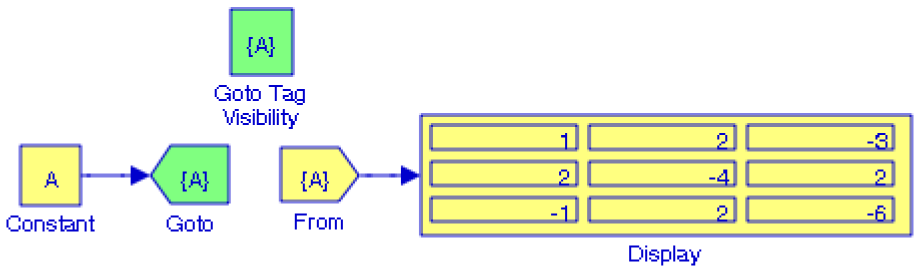
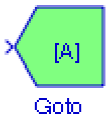


Figure 13.21. Model for Example 13.9

As indicated, in Figure 13.21, the **Goto Tag Visibility** block has no input and no output but it must be included whenever the visibility is specified as scoped. Since the tag visibility in the **Goto** block is specified as scoped, the **Goto Tag Visibility** block is shown in the model with the tag name enclosed in braces ({}).

13.1.15 The Goto Block



The **Goto** block passes its input to its corresponding **From** blocks. **From** and **Goto** blocks allow us to pass a signal from one block to another without actually connecting them. A **Goto** block can pass its input signal to more than one **From** block, although a **From** block can receive a signal from only one **Goto** block. The input to that **Goto** block is passed to the **From** blocks associated with it as though the blocks were physically connected. **Goto** blocks and **From** blocks are matched by the use of **Goto** tags, defined in the Tag parameter. The Tag visibility parameter determines whether the location of **From** blocks that access the signal is limited. The three options are:

1. Local, the default, means that **From** and **Goto** blocks using the same tag must be in the same subsystem. A local tag name is enclosed in brackets ([]).
2. Global means that **From** and **Goto** blocks using the same tag can be anywhere in the model except in locations that span nonvirtual subsystem boundaries. The rule that **From–Goto** block connections cannot cross nonvirtual subsystem boundaries has the following exception: A **Goto** block connected to a state port in one conditionally executed subsystem is visible to a

From block inside another conditionally executed subsystem. A global tag name is not enclosed.

3. Scoped means that **From** and **Goto** blocks using the same tag must be in the same subsystem or at any level in the model hierarchy below the **Goto Tag Visibility** block that does not entail crossing a nonvirtual subsystem boundary, i.e., the boundary of an atomic, conditionally executed, or function–call subsystem or a model reference. A scoped tag name is enclosed in braces ({}).

Example 13.10

The upper and lower models in Figure 13.22, are equivalent and thus both **Scope 1** and **Scope 2** blocks display the same waveform shown in Figure 13.23.

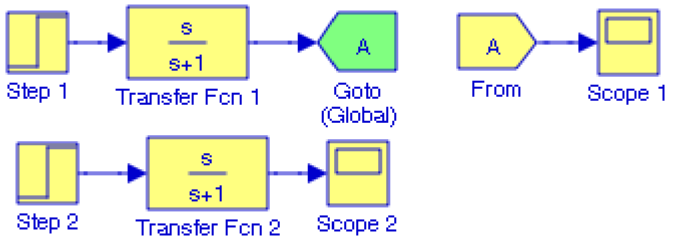


Figure 13.22. Model for Example 13.10

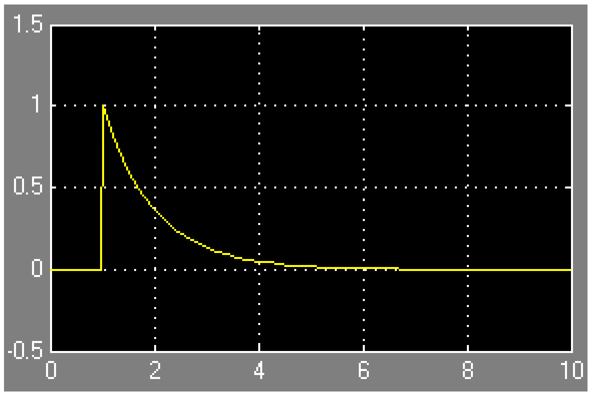


Figure 13.23. Waveform displayed in Scope 1 and Scope 2 blocks in Figure 13.22

The Simulink documentation includes the **Power Window Controller Hybrid System** demo and the **Bus Signal Demonstration** demo. They can be accessed by typing powerwindow01 & powerwindow02 and busdemo at the MATLAB command prompt.

13.2 The Signal Storage and Access Group Sub–Library

Data stores are signals that are accessible at any point in a model hierarchy at or below the level in which they are defined. Because they are accessible across model levels, data stores allow subsystems and model references to share data without having to use I/O ports to pass the data from level to level. The **Signal Storage and Access Group Sub–Library** contains the three blocks described in Subsections 13.2.1 through 13.2.3 below.

13.2.1 The Data Store Read Block

The **Data Store Read** block copies data from the named data store to its output. The data store from which the data is read is determined by the location of the **Data Store Memory** block or signal object that defines the data store. More than one **Data Store Read** block can read from the same data store. For more information, please refer to **Working with Data Stores and Data Store Memory** in Help menu for this block. An example is presented in Subsection 13.2.3 below.

13.2.2 The Data Store Memory Block

The **Data Store Memory** block defines and initializes a named shared data store, which is a memory region usable by **Data Store Read** and **Data Store Write** blocks with the same data store name. The location of the **Data Store Memory** block that defines a data store determines the **Data Store Read** and **Data Store Write** blocks that can access the data store:

1. If the **Data Store Memory** block is in the top–level system, the data store can be accessed by **Data Store Read** and **Data Store Write** blocks located anywhere in the model.

2. If the **Data Store Memory** block is in a subsystem, the data store can be accessed by **Data Store Read** and **Data Store Write** blocks located in the same subsystem or in any subsystem below it in the model hierarchy.

An example is presented in Subsection 13.2.3 below.

13.2.3 The Data Store Write Block

The **Data Store Write** block copies the value at its input to the named data store. Each write operation performed by a Data Store Write block writes over the data store, replacing the previous contents. The data store to which this block writes is determined by the location of the Data Store Memory or signal object that defines the data store. More than one Data Store Write block can write to the same data store.

Example 13.11

In this example, we will create a model that will alternately will display the outputs of a low–pass filter and a high–pass filter whose transfer functions are $1/(s+1)$, and $s/(s+1)$ respectively, when the input is the step function.

We begin with a new model, we drag two **Data Store Memory** blocks into it, for the first we define the name lpfilter, and for the second the name hpfilter as shown in Figure 13.24. Then, we drag two **Step** blocks, two **Transfer Fcn** blocks, two **Gain** blocks, two **Data Store Write** blocks, and two **Scope** blocks into the same model. We connect them as shown, to the first **Data Store Write** block we assign the name lpfilter, and to the second the name hpfilter as shown in Figure 13.24.

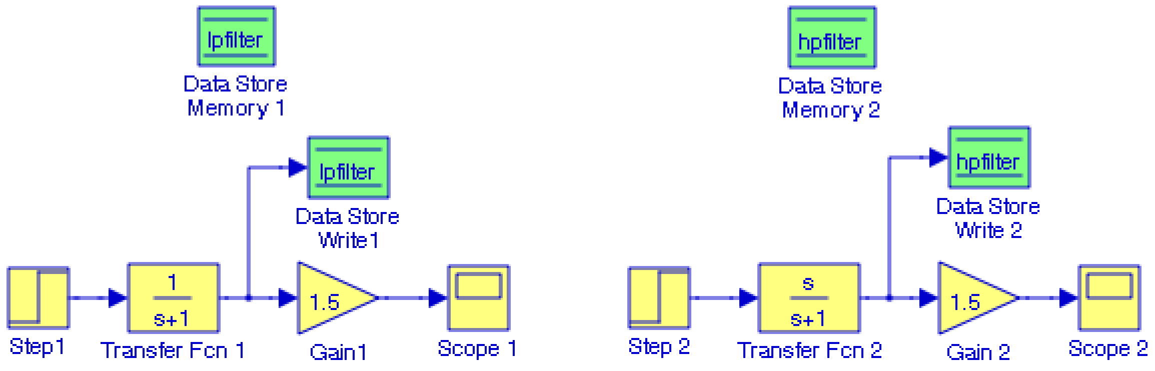


Figure 13.24. Initial model for Example 13.11

Next, we select the **Transfer Fcn 1**, **Gain 1**, and **Data Store Write 1** blocks, we enclose them in a bounding box, and from the **Edit** drop menu we choose **Create Subsystem**. We label this subsystem as **Subsystem 1**. We repeat for the **Transfer Fcn 2**, **Gain 2**, and **Data Store Write 2** blocks, and we label this subsystem as **Subsystem 2**. The model is now as shown in Figure 13.25, after reshaping and renaming the subsystem blocks.

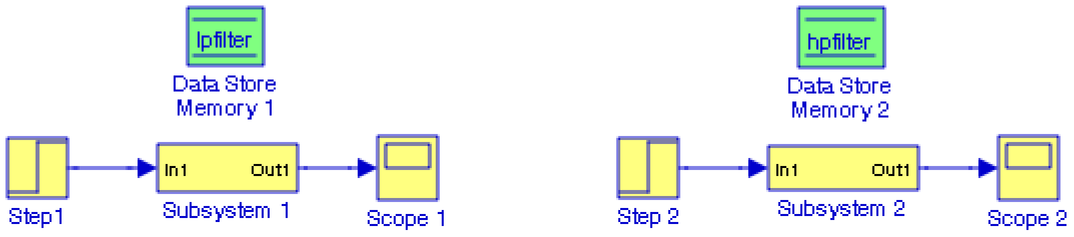


Figure 13.25. Modified model for Example 13.11

Now, we revise the model of Figure 13.25 by adding the **Manual Switch** block as shown in Figure 13.26 so that we can switch between **Subsystem 1** for the low–pass filter, and **Subsystem 2** for the high–pass filter to observe their waveforms shown in Figures 13.27 and 13.28 respectively.

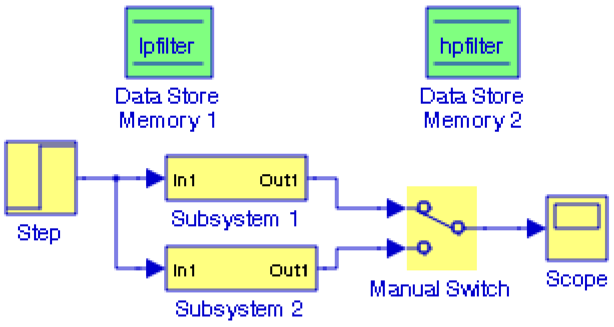


Figure 13.26. The model of Example 13.11 in its final form

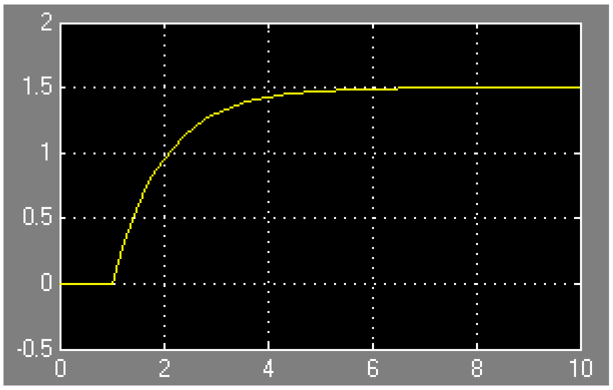


Figure 13.27. Waveform of the output of Subsystem 1 (Low–pass filter with Gain = 1.5)

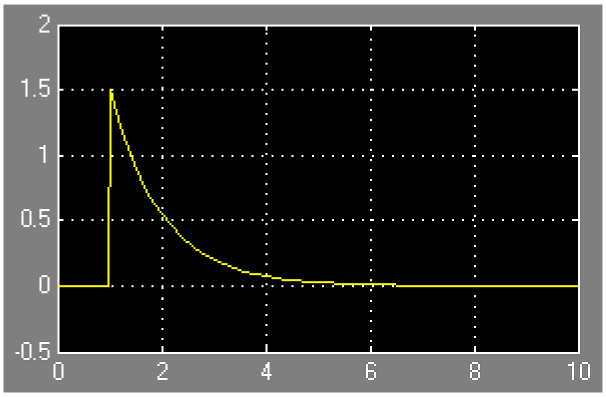


Figure 13.28. The output waveform of Subsystem 2 (High−pass filter with Gain = 1.5) in Figure 13.26

In Example 13.11 we illustrated the use of the **Data Store Memory** block and the **Data Store Write** block. The use of the **Data Store Read** block is illustrated in Figure 13.29.

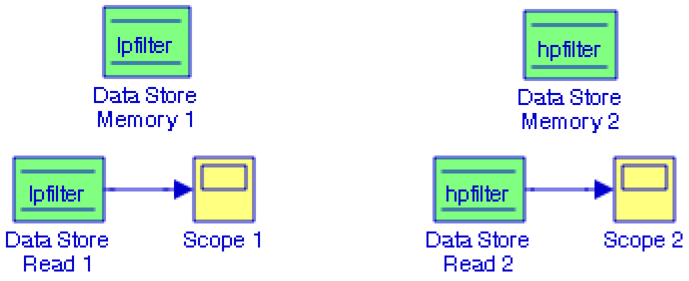


Figure 13.29. Models to illustrate the use of the Data Store Read block

The **Scope 1** and **Scope 2** blocks in Figure 13.29 display the same waveforms as those in Figure 13.27 and Figure 13.28.

13.3 Summary

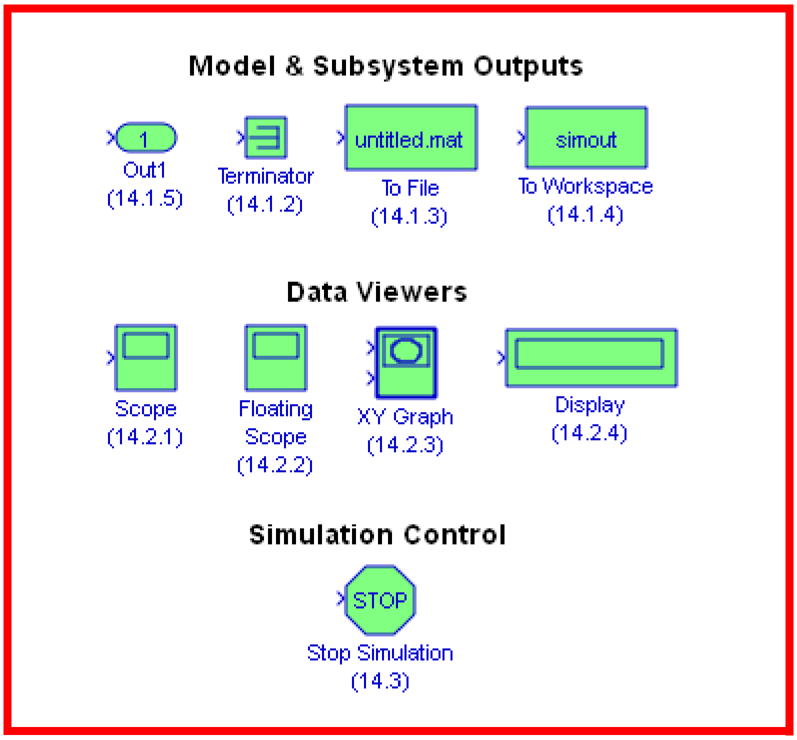
- The **Bus Creator** block combines a set of signals into a group of signals represented by a single line.
- The **Bus Selector** block outputs a specified subset of the elements of the bus at its input.
- The **Bus Assignment** block assigns values, specified by signals connected to its assignment (:=) input ports, to specified elements of the bus connected to its Bus input port.
- The **Mux block** combines its inputs into a single output. An input can be a scalar, vector, or matrix signal.
- The **Demux block** extracts the components of an input signal and outputs the components as separate signals.
- The **Selector** block generates as output selected elements of an input vector or matrix. If the input type is vector, the block outputs a vector of selected elements specified by element indices. If the input type is matrix, the Selector block outputs a matrix of elements selected from the input matrix.
- The **Index Vector** block switches the output between different inputs based on the value of the first input, referred to as the Control Input. This block is an implementation of the Multiport Switch block.
- The **Merge** block combines its inputs into a single output line whose value at any time is equal to the most recently computed output of its driving blocks. We can specify any number of inputs by setting the block's Number of inputs parameter.
- The **Environmental Controller** block outputs the signal at its Sim port only if the model that contains it is being simulated. It outputs the signal at its Real–Time Workshop (RTW) port only if code is being generated from the model.
- The **Manual Switch** block is a toggle switch that selects one of its two inputs to pass through to the output. There is no dialog box for this block; to toggle between inputs, we double–click the block. The block retains its current state when the model is saved.
- The **Multiport Switch** block chooses between a number of inputs. The first (top) input is called the **control input**, while the rest of the inputs are called **data inputs**. The value of the control input determines which data input is passed through to the output port.
- The **Switch** block outputs the first (top) input or the third (bottom) input depending on the value of the second (middle) input. The first and third inputs are the **data inputs**. The second input is the **control input**.
- The **From** block accepts a signal from a corresponding Goto block, then passes it as output.

- The **Goto Tag Visibility** block defines the accessibility of Goto block tags that have scoped visibility.
- The **Goto** block passes its input to its corresponding From blocks.
- The **Data Store Read** block copies data from the named data store to its output. The data store from which the data is read is determined by the location of the Data Store Memory block or signal object that defines the data store.
- The **Data Store Memory** block defines and initializes a named shared data store, which is a memory region usable by Data Store Read and Data Store Write blocks with the same data store name.
- The **Data Store Write** block copies the value at its input to the named data store. Each write operation performed by a Data Store Write block writes over the data store, replacing the previous contents.

Chapter 14

The Sinks Library

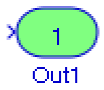
This chapter is an introduction to the **Sinks** library**.** This is the thirteenth library in the Simulink group of libraries and consists of three sub–libraries, the **Model & Subsystem Outputs Sub–Library**, the **Data Viewers Sub–Library**, and the **Simulation Control Sub–Library** blocks shown below. Their functions are illustrated with examples.



14.1 Models and Subsystems Outputs Sub–Library

The **Models and Subsystems Outputs Sub–Library** contains the blocks described in Subsections 14.1.1 through 14.1.4 below.

14.1.1 The Outport Block



The **Outport** block creates an external output or an output port for a subsystem. This block is described in Section 2.1, Chapter 2.

14.1.2 The Terminator Block

Terminator

The **Terminator** block can be used to cap blocks whose output ports are not connected to other blocks. If we run a simulation with blocks having unconnected output ports, Simulink issues warning messages. We use **Terminator** blocks to cap those blocks to avoid warning messages. This block is described in Section 2.3, Chapter 2.

14.1.3 The To File Block

untitled.mat
To File

The **To File** block writes its input to a matrix in a MAT–file. The block writes one column for each time step: the first row is the simulation time; the remainder of the column is the input data, one data point for each element in the input vector.

Example 14.1

Let us consider the matrix C defined as

$$C = \begin{bmatrix} 1 & 2 & 3 & 4 \\ -1 & 1 & 0 & -1 \\ 4 & 0 & 3 & -2 \\ -3 & -1 & 2 & -4 \end{bmatrix}$$

where the elements of the first row are time points,[*] and the remaining rows contain data points that correspond to the time point in that column. Thus at time 3, the outputs are 0, 3, and 2,

[*] *The time points must always be monotonically increasing.*

which are the data points for the third column encountered at time 3. We enter the elements of matrix C at the MATLAB command prompt as

```
matrixC=[1 2 3 4; −1 1 0 −1; 4 0 3 −2; −3 −1 2 −4];
```

and we save it as matrixC.mat by selecting **Save Workspace As** from MATLAB's **File** menu.

Next, we drag the **From File** block* found in the **Sources** library and the **To File** block from the **Sinks** library into a new model as shown in Figure 14.1 where to the **From File** block we have assigned the name matrixC, and to the **To File** block we have assigned the name matrixCToFile.mat.

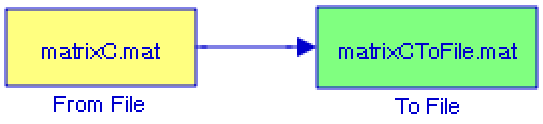


Figure 14.1. Example of copying the contents of a From File block to a To File block

Upon execution of the simulation command the contents of the matrixC file are copied into the matrixCToFile.mat file and saved by that name. We can verify this as follows:

At the MATLAB command prompt we type

```
open matrixCToFile.mat
```

```
  ans =

      ans: [4x51 double]
```

Next, at the MATLAB command prompt we type

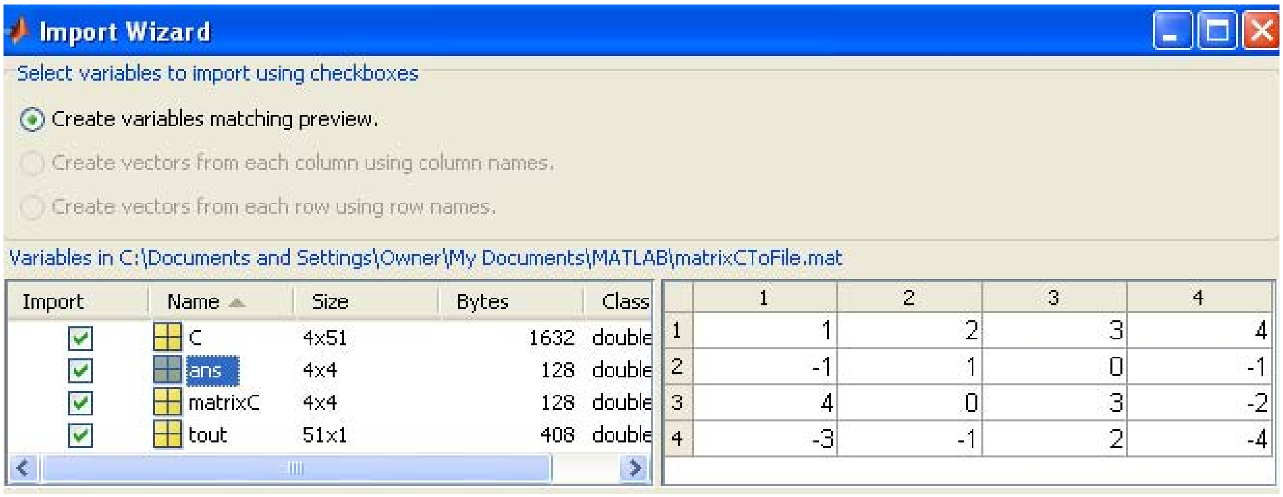
```
whos
```

and MATLAB outputs

```
  Name          Size            Bytes  Class     Attributes

  C             4x4               128  double
  ans           1x1              1756  struct
  matrixC       4x4               128  double
  tout         51x1               408  double
```

From the MATLAB Command Window we select **Import Data** from the **File** drop menu and we choose the file matrixCToFile.mat. The **Import Wizard** window displays the data shown in Figure 14.2.

* *The From File block belongs to the Model and Subsystem Input sub–library described in the Sources Library, Section 15.1.3, Chapter 15.*


Import Wizard
Select variables to import using checkboxes
Create variables matching preview.
Create vectors from each column using column names.
Create vectors from each row using row names.
Variables in C:\Documents and Settings\Owner\My Documents\MATLAB\matrixCToFile.mat

Import	Name	Size	Bytes	Class
✓	C	4x51	1632	double
✓	ans	4x4	128	double
✓	matrixC	4x4	128	double
✓	tout	51x1	408	double

	1	2	3	4
1	1	2	3	4
2	-1	1	0	-1
3	4	0	3	-2
4	-3	-1	2	-4

Figure 14.2. Displaying the contents of matrix C of Example 14.1 in Import Wizard

14.1.4 The To Workspace Block

The **To Workspace** block writes its input to the workspace. This block writes its output to an array or structure that has the name specified by the block's Variable name parameter. The Save format parameter determines the output format.

The MATLAB Workspace consists of the set of variables generated by the execution of a program and these are stored in memory.

Example 14.2

Let us consider the matrix multiplication $A \cdot B$ where $A = [1 \ \ -1 \ \ 2]'$ and $B = [2 \ \ 3 \ \ 4]$, and create a model to include a **To Workspace** block at the output.

Matrix A is a 3×1 size and matrix B is a 1×3 size and matrix so these matrices are conformable for multiplication. The model is shown in Figure 14.3 where to the **To Workspace** block we assigned the name matrixmult.

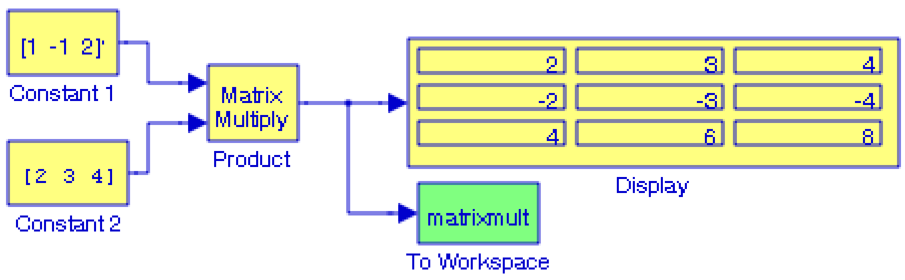


Figure 14.3. Model for Example 14.2

Next, at the MATLAB command prompt we type

```
who
```

and MATLAB lists the current workspace variables as

```
Your variables are:
 matrixmult  simout  tout
```

Also, at the MATLAB command prompt we type

```
whos
```

and MATLAB lists the current workspace variables and information about their size and class as

```
Name                Size     Bytes  Class
matrixmult          1x1       4482  struct array
simout              1x1       4482  struct array
tout               51x1        408  double array
Grand total is 1035 elements using 9372 bytes
```

If we exit MATLAB, the workspace is cleared. But we can save any or all of the variables to a **MAT–file.**[*] MAT–files use the .mat extension. We can then invoke this MAT–file at a later time.

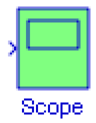
To save the workspace variables for this file, we select **Save Workspace As** from the MATLAB **File** menu.

* *A MAT–file stores data in binary (not human–readable) form. We need not know the internal format of a MAT–file. This file writes the arrays currently in memory to a file as a continuous byte stream. For a detailed discussion please log on to www.csb.yale.edu/userguides/ datamanip/matlab/pdf/**matfile**_format.pdf.*

14.2 The Data Viewers Sub–Library

The **Data Viewers Sub–Library** contains the four blocks described in Subsections 14.2.1 through 14.2.4 below.below.

14.2.1 The Scope Block



The **Scope** block displays its input with respect to simulation time. The **Scope** block can have multiple axes (one per port), but all axes have a common time range with independent y–axes. This block allows us to adjust the amount of time and the range of input values displayed. We can move and resize the **Scope** window and we can modify the Scope's parameter values during the simulation. At the end of the simulation, Simulink transmits data to the connected Scopes but does not automatically open the Scope windows. The signal(s) will be displayed when we double–click on the **Scope** block after simulation termination.

If the signal is continuous, the **Scope** block produces a point–to–point plot. If the signal is discrete, the Scope produces a stair–step plot. When displaying a vector or matrix signal, the **Scope** block assigns colors to each signal element in this order: yellow, magenta, cyan, red, green, and dark blue. When more than six signals are displayed, the **Scope** block cycles through the colors in the order listed. We set y–limits by right–clicking an axis and choosing **Axes Properties**.

When we open the **Scope** block we observe several toolbar icons that enable us to zoom in on displayed data, preserve axis settings from one simulation to the next, limit data displayed, and save data to the workspace. The toolbar icons are labeled in the Help menu for this block. The Help menu provides more information than what is provided in this subsection.

Example 14.3

The model shown in Figure 14.4 displays a sine waveform, a square waveform, a sawtooth waveform, and a random signal waveform on a single Scope block with one input. All four generators are **Signal Generator** blocks configured to produce and display the four different waveforms. Each was specified at 0.2 Hz frequency, and all other parameters are left in their default states. The waveforms are shown in Figure 14.5.

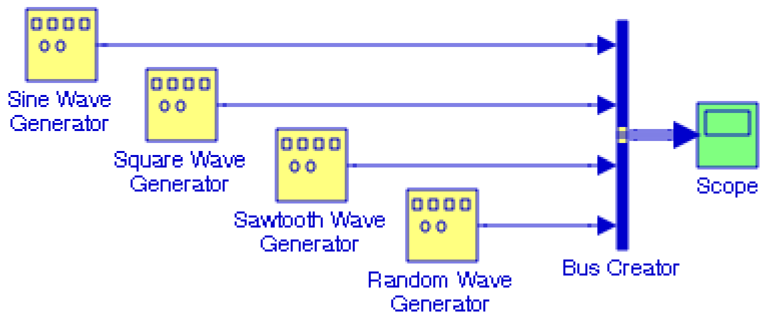


Figure 14.4. Model for Example 14.3

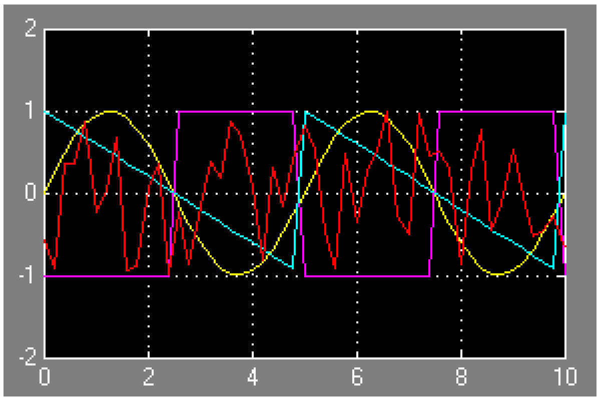


Figure 14.5. Waveforms for sine wave, square wave, sawtooth wave and random wave signal generators

In all of the previous examples we have shown the **Scope** block with only one input where the signals from the previous blocks have been combined via a **Bus Creator** block. However, we can display the **Scope** block with two or more inputs as illustrated with the following example.

Example 14.4

The model shown in Figure 14.6 displays a sine waveform, a square waveform, a sawtooth waveform, and a random signal waveform on a single **Scope** block with four inputs. All four generators are **Signal Generator** blocks configured to produce and display the four different waveforms. Each is specified at 0.2 Hz frequency, and all other parameters were left in their default states.

On the **Scope** block we click the Parameters icon (second from left), and we specify Number of Axes: 4. The waveforms are shown in Figure 14.7.

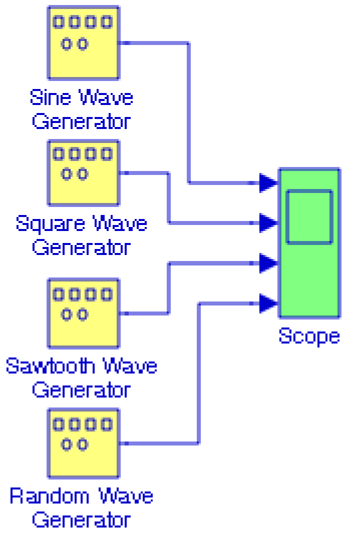


Figure 14.6. Model for Example 14.4

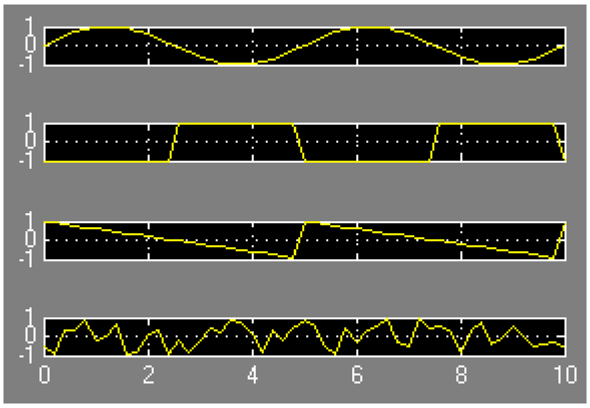
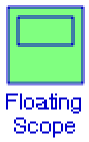


Figure 14.7. Waveforms for the model in Figure 14.6

14.2.2 The Floating Scope Block



One of the options appearing on the General parameters pane for the **Scope** block described in the previous subsection, is the **Floating Scope**. A **Floating Scope** is a **Scope** block that can display the signals carried on one or more lines. We can create a **Floating Scope** block in a model either by copying a **Scope** block from the **Sinks** library into a model and selecting this option or, more simply, by copying the **Floating Scope** block from the **Sinks** library into the model window.

The **Floating Scope** block has the Floating scope parameter selected by default. The procedure for using and displaying one or more signals on a **Floating Scope** is illustrated with the example below.

Example 14.5

The model shown in Figure 14.8 displays a sine waveform, a square waveform, a sawtooth waveform, and a random signal waveform on a single Floating Scope block with four inputs. All four generators are **Signal Generator** blocks configured to produce and display the four different waveforms. Each specified set at 0.2 Hz frequency, and all other parameters were left in their default states.

Before executing the simulation command, we click the **Floating Scope** block whose display is as shown in Figure 14.9. On the **Floating Scope** block, we click on the Parameters icon (second from left, to the right of the print icon), and we specify Number of Axes: 4. The **Floating Scope** block now becomes a a multi–axis floating scope as shown in Figure 14.10.

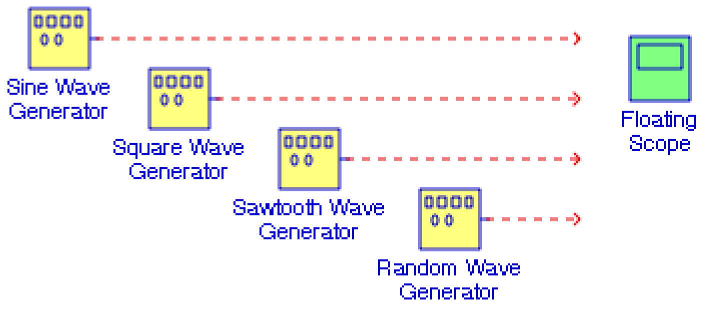


Figure 14.8. Model for Example 14.5

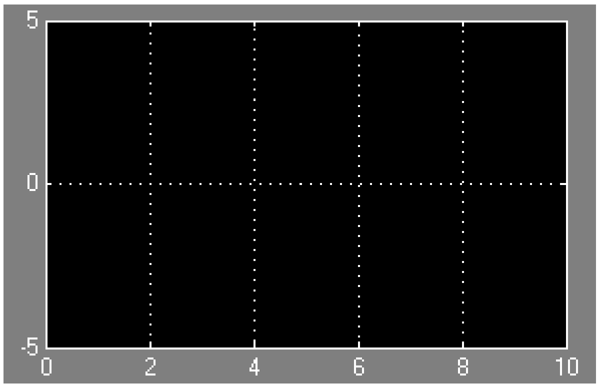


Figure 14.9. Floating Scope for the model of Figure 14.8

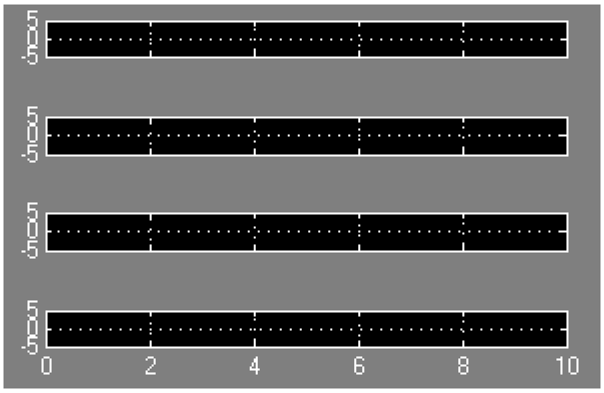


Figure 14.10. The Floating Scope of Figure 14.9 with 4 axes

1. To specify the display of the sine waveform on the first (top) axis, we click on that axis. Simulink draws a blue border around that axis as shown in Figure 14.11.

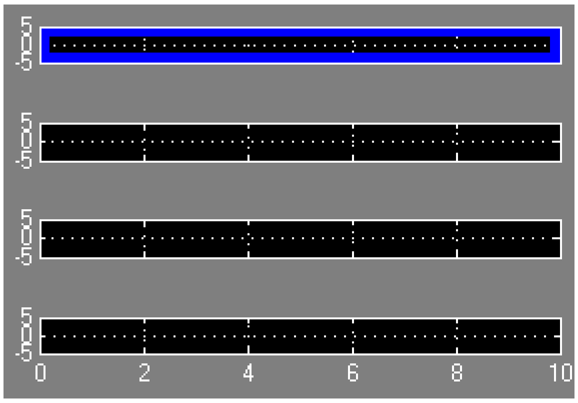
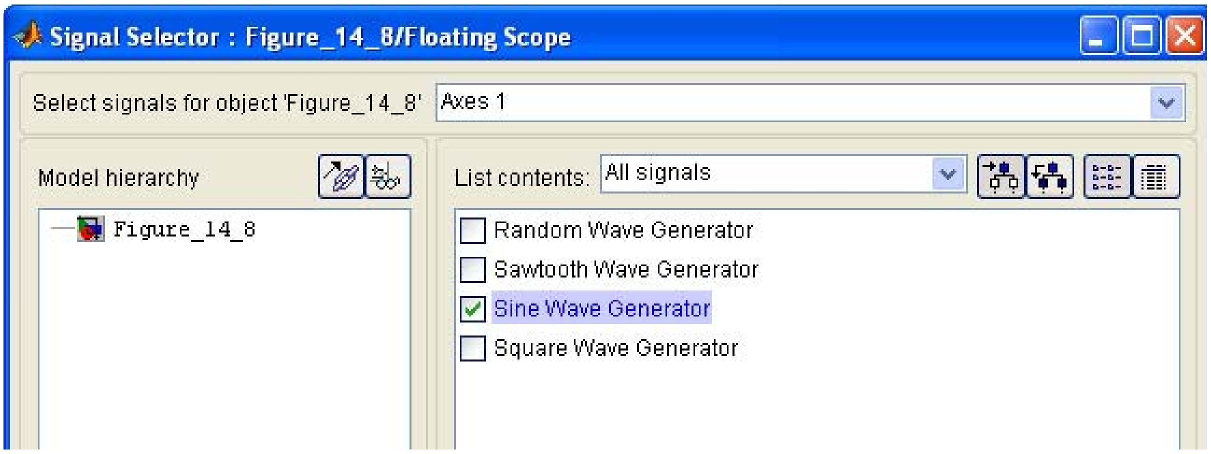


Figure 14.11. Specifying display of a signal on the Floating Scope

2. We return to the model of Figure 14.8 and we select one or more signal (broken) line(s). To select multiple lines, we hold down the **Shift** key while clicking another line.

3. To use a **Floating Scope** during a simulation, we must disable the Signal storage reuse and block reduction optimization options. To disable them, we click **Simulation** on the model in Figure 14.8, we click on the **Configuration Parameters**, we click the **Optimization** field (left pane), and we deselect the **Signal storage reuse** and **Block reduction optimization** parameters.

4. We right–click the axis with the blue border around it, we click on **Axis properties** we set the y–axis at –1 (min) and +1 (max), we right–click again, and we click on **Signal selection**. On the **Signal Selector** dialog box shown in Figure 14.12 we choose the **Sine Wave Generator**.


Signal Selector : Figure_14_8/Floating Scope
Select signals for object 'Figure_14_8'
Axes 1
Model hierarchy
Figure_14_8
List contents:
All signals

- [ ] Random Wave Generator
- [ ] Sawtooth Wave Generator
- [x] Sine Wave Generator
- [ ] Square Wave Generator

Figure 14.12. The Signal Selector window for the model of Figure 14.8

5. We issue the Simulation command and the displays on the Floating Scope are as shown in Figure 14.13.

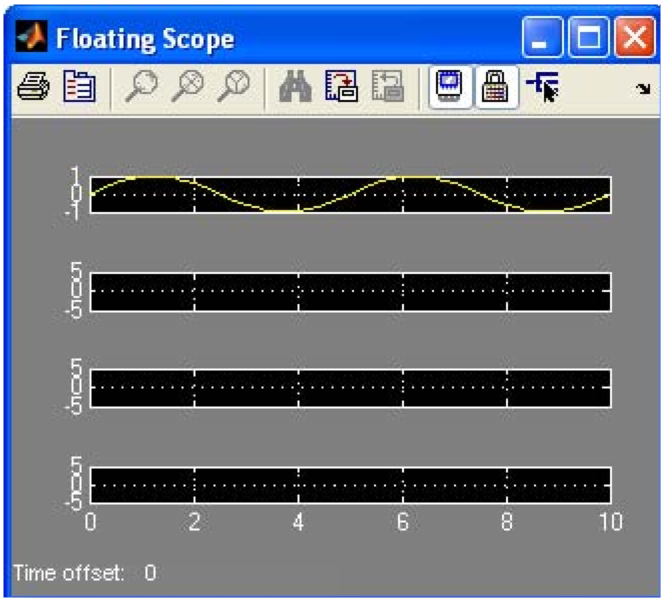


Figure 14.13. The display of the sine waveform on the Floating Scope

We repeat steps 1 through 5 for the remaining axes. The **Floating Scope** displays are now as shown in Figure 14.14.

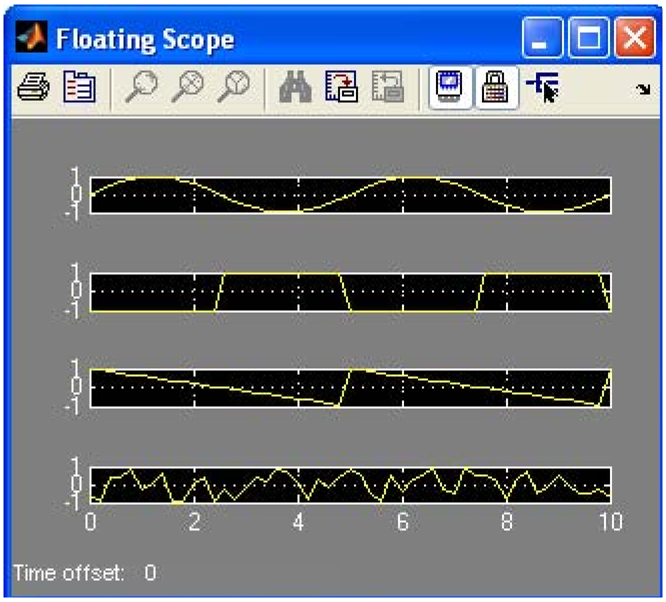
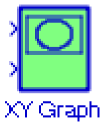


Figure 14.14. Floating Scope for the model in Figure 14.8 with all signals displayed

We can choose to have more than one **Floating Scope** in a model, but only one set of axes in one scope can be active at a given time. Active floating scopes show the active axes with a blue border.

14.2.3 The XY Graph Block



The **XY Graph** block displays an X–Y plot of its inputs in a MATLAB figure window. This block plots data in the first input (the x–direction) against data in the second input (the y–direction).

Example 14.6

Suppose that we want to plot the sine squared function in the interval $0 \le t \le 2\pi$. Using MATLAB this can be achieved with the following script typed at the MATLAB command prompt:

```
t=0:pi/32:2*pi; y=(sin(t)).^2; plot(t,y)
```

This task can also be accomplished with the model in Figure 14.15.

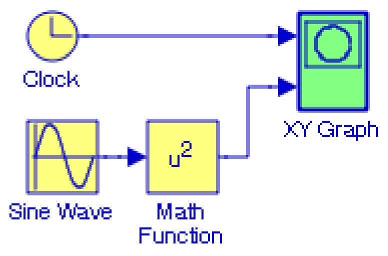


Figure 14.15. Model for Example 14.6

When the simulation command is executed for the first time, the **XY Graph** block pops–up and displays the waveform shown in Figure 14.16.

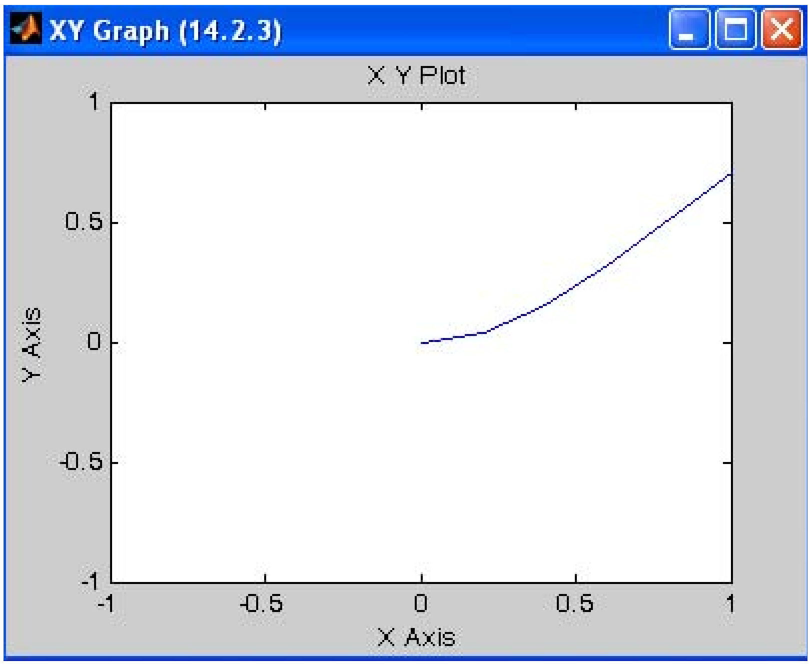


Figure 14.16. Pop–up graph when the simulation command in the model in Figure 14.15 is executed

Of course, this is not what we expected. To edit it, we double click the **XY Graph** block in the model in Figure 14.15 and in the **Block Parameters** dialog box we choose x–min = 0, x–max = 2*pi, y–min = – 0.5, y–max = 1.5, and we click **OK**. The **XY Graph** block now displays the waveform shown in Figure 14.17.

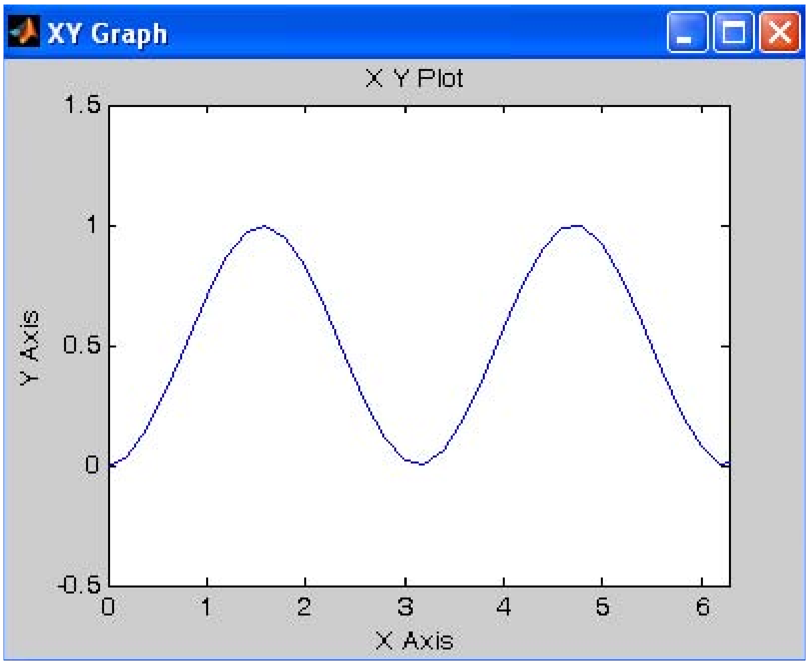


Figure 14.17. Updated waveform for the model in Figure 14.15

Example 14.7

The model in Figure 14.18 is produces the curve in Figure 14.19 and it is known as *nephroid.* It is described by the equations

$$x = 0.5a(3\cos\phi - \cos 3\phi)$$
$$y = 0.5a(3\sin\phi - \sin 3\phi)$$

For this model, the value of a is entered at the MATLAB command prompt as

```
a=2;
```

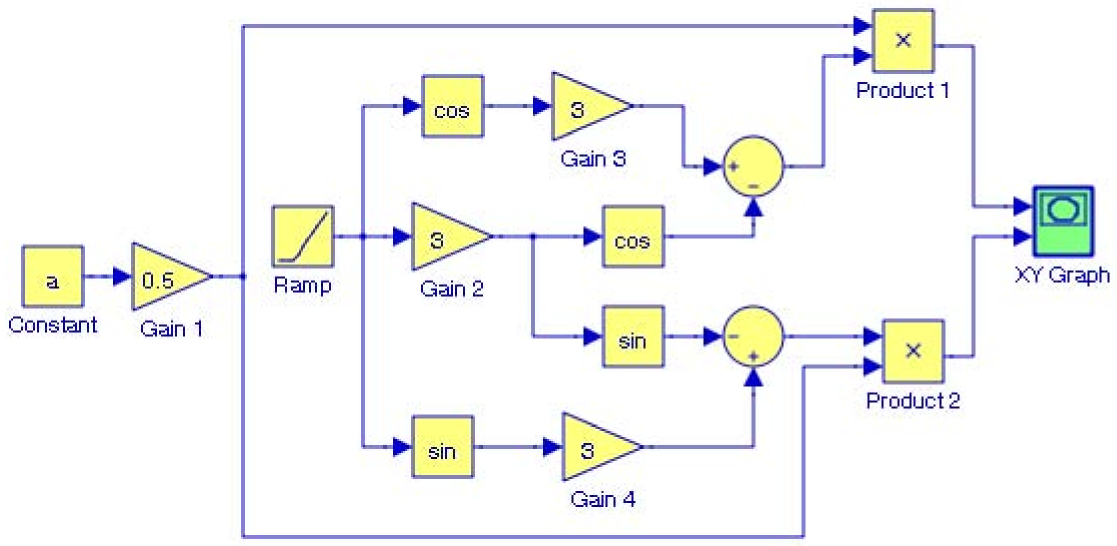


Figure 14.18. Model for Example 14.7

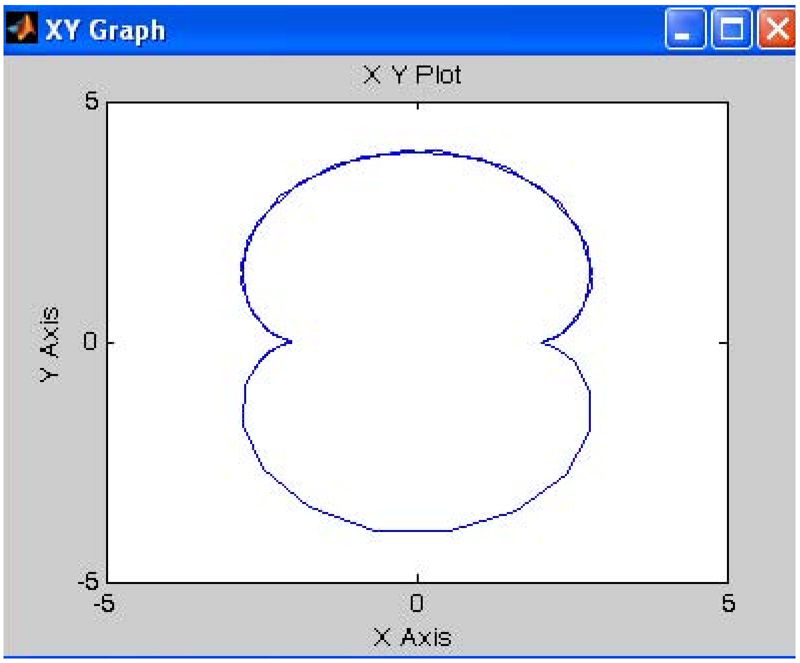
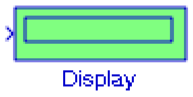


Figure 14.19. The XY Plot displayed by the XY Graph block in Figure 14.18

Another example with the **XY Graph** block is presented in Chapter 20, Subsection 20.1.9.

14.2.4 The Display Block



The **Display** block shows the value of its input on its icon. The display formats are the same as those of MATLAB. They are also specified in the Help menu for this block. The Decimation parameter enables us to display data at every *nth* sample, where *n* is the decimation factor. Thus, the default decimation 1 displays data at every time step. We use the Sample time parameter to specify a sampling interval at which to display points. This parameter is useful when we are using a variable–step solver where the interval between time steps might not be the same. The default value of –1 causes the block to ignore the sampling interval when determining the points to display.

If the block input is an array, we must resize the block to see more than just the first element. The **Display** block can be resized vertically and/or horizontally. The presence of a small black triangle indicates that the block is not displaying all input array elements.

Example 14.8

The model in Figure 14.20 displays the trigonometric functions $\sin x$, $\cos x$, $\tan x$, $\sinh x$, $\cosh x$, and $\tanh x$ evaluated at $\pi/6$ and $\pi/3$. It is necessary to resize the **Display** block to display all values.

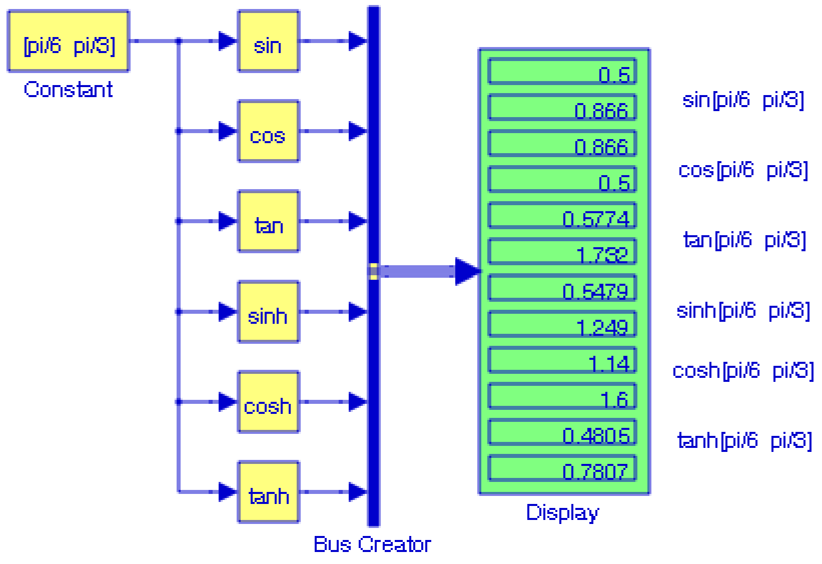


Figure 14.20. Model for Example 14.8

14.3 The Simulation Control Sub–Library

The **Simulation Control Sub–Library** contains only one block, the **Stop Simulation** block described below.

The **Stop Simulation** block stops the simulation when the input is nonzero. A common use of this block is when used in conjunction with a relational operator. The simulation completes the current time step before terminating. If the block input is a vector, any nonzero vector element causes the simulation to stop. For a Simulink demo using this block, we type sldemo_absbrake at the MATLAB command prompt.

Example 14.9

The model shown in Figure 14.21 uses a **Stop Simulation** block and a **Relational Operator** block to terminate simulation when the first input is equal to the second input. We observe that the simulation stops when the digital clock attains the value 10. The waveforms are shown in Figure 14.22.

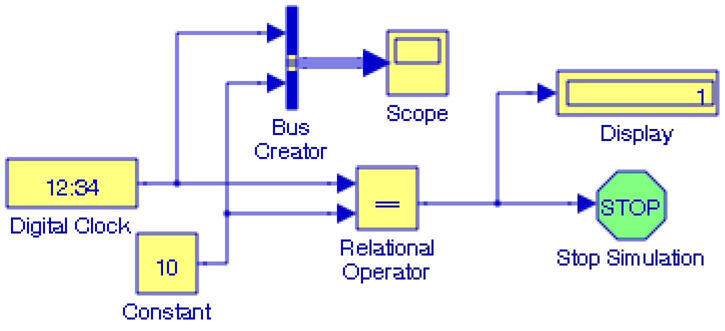


Figure 14.21. Model for Example 14.9

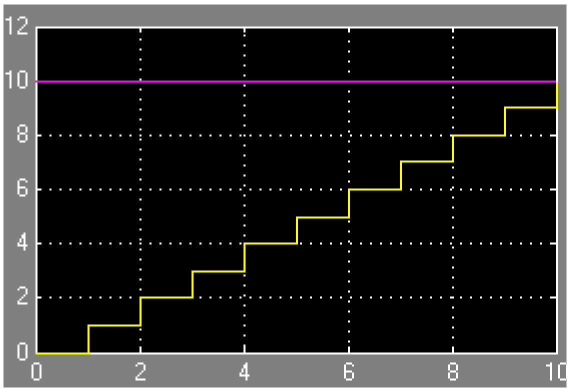


Figure 14.22. Waveforms for the model in Figure 14.21

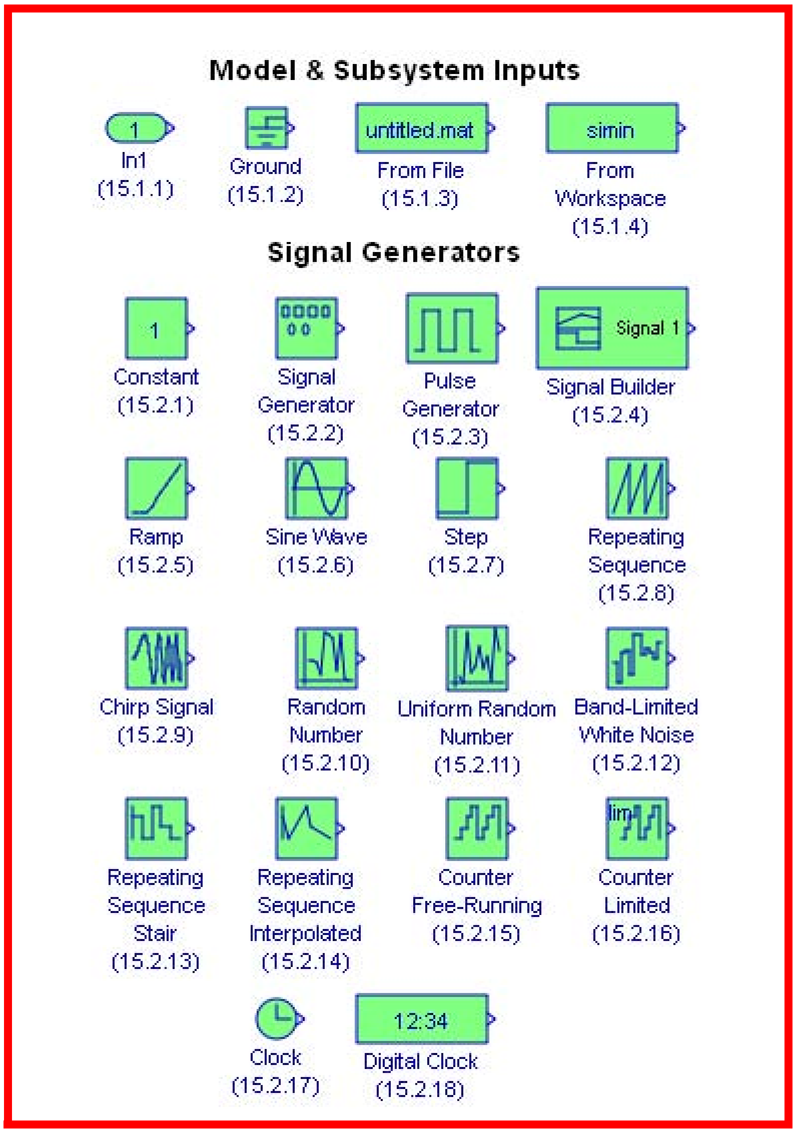
14.4 Summary

- The **Outport** block creates an external output or an output port for a subsystem.
- The **Terminator** block is used to cap blocks whose output ports are not connected to other blocks. We use Terminator blocks to cap those blocks to avoid warning messages.
- The **To File** block writes its input to a matrix in a MAT–file. The block writes one column for each time step: the first row is the simulation time; the remainder of the column is the input data, one data point for each element in the input vector.
- The **To Workspace** block writes its input to the workspace. The block writes its output to an array or structure that has the name specified by the block's Variable name parameter. The Save format parameter determines the output format.
- The **Scope** block displays its input with respect to simulation time. The Scope block can have multiple axes (one per port); all axes have a common time range with independent y–axes. We can use a Bus Creator block to combine two or more signals to a Scope block with only one input. We can also display the input signals to a Scope block with two or more inputs.
- The **Floating scope** is a Scope block that can display the signals carried on one or more lines.
- The **XY Graph** block displays an X–Y plot of its inputs in a MATLAB figure window. This block plots data in the first input (the x direction) against data in the second input (the y direction).
- The **Display** block shows the value of its input on its icon. The display formats are the same as those of MATLAB. They are also specified in the Help menu for this block. If the block input is an array, we must resize the block to see more than just the first element. The Display block can be resized vertically or horizontally. The presence of a small black triangle indicates that the block is not displaying all input array elements.
- The **Stop Simulation** block stops the simulation when the input is nonzero. A common use of this block is when used in conjunction with a relational operator. The simulation completes the current time step before terminating. If the block input is a vector, any nonzero vector element causes the simulation to stop.

Chapter 15

The Sources Library

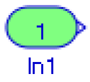
This chapter is an introduction to the **Sources** library**.** This is the fourteenth library in the Simulink group of libraries and consists of two sub–libraries, the **Model & Subsystem Inputs Sub–Library**, and the **Signal Generators Sub–Library** blocks shown below. Their functions are illustrated with examples.



15.1 Models and Subsystems Inputs Sub–Library

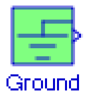
The **Models and Subsystems Inputs Sub–Library** contains the blocks described in Subsections 15.1.1 through 15.1.4 below.

15.1.1 The Inport Block



The **Inport** block creates an input port for a subsystem or an external input. This block is described in Section 2.1, Chapter 2.

15.1.2 The Ground Block



The **Ground** block grounds an unconnected input port. This block is described in Section 2.2, Chapter 2.

15.1.3 The From File Block

The **From File** block outputs data read from a MAT file. The name of the file is displayed inside the block. An example using the **From File** block and the **To File** block is presented in Subsection 14.1.3, Chapter 14.

15.1.4 The From Workspace Block

The **From Workspace** block reads data from the MATLAB workspace. The workspace data are specified in the block's Data parameter via a MATLAB expression that evaluates to a 2–D array.

Example 15.1

For the model in Figure 15.1, the MATLAB workspace contains the statement

```
t=1:10; u=log10(t);
```

In the Display block, the first 10 values are those specified by t, and the last ten values are those specified by u.

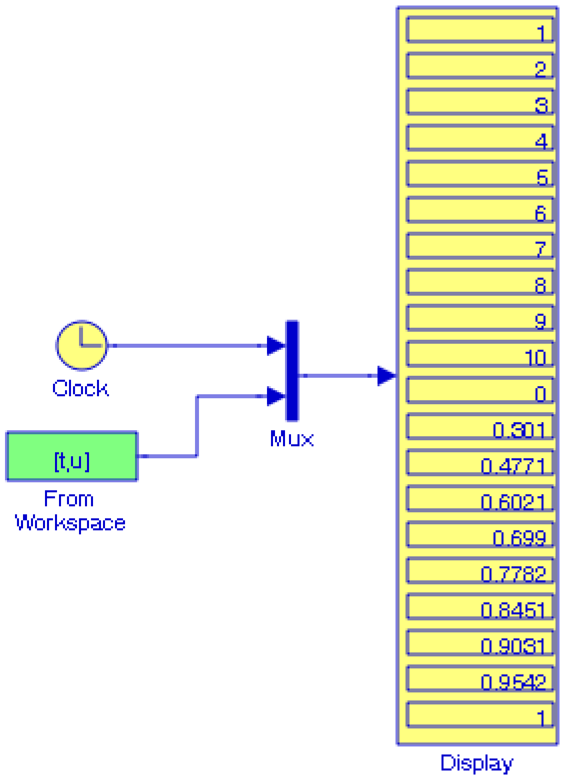


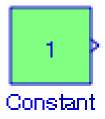
Figure 15.1. Model for Example 15.1

The Simulink documentation includes the **Six Degrees of Freedom Motion Platform** demo. It can be accessed by typing aero_six_dof at the MATLAB command prompt, and clicking the **Roll**, **Pitch**, and **Yaw** moment blocks.

15.2 The Signal Generators Sub–Library

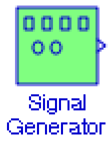
The **Signal Generators Sub–Library** contains the eighteen blocks described in Subsections 15.2.1 through 15.2.18 below.

15.2.1 The Constant Block



The **Constant** block generates a real or complex constant value. This block is described in Section 2.4, Chapter 2.

15.2.2 The Signal Generator Block



The **Signal Generator** block can produce one of four different waveforms: sine wave, square wave, sawtooth wave, and random wave. The signal parameters can be expressed in Hertz (the default) or radians per second. We can invert the waveform by specifying a negative amplitude in the block's parameters window.

Example 15.2

The model in Figure 15.2 shows all four possible configurations of the **Signal Generator** block to produce and display the four different waveforms. Each is specified at 0.2 Hz frequency with the unlisted parameters in their default state. The waveforms are shown in Figure 15.3.

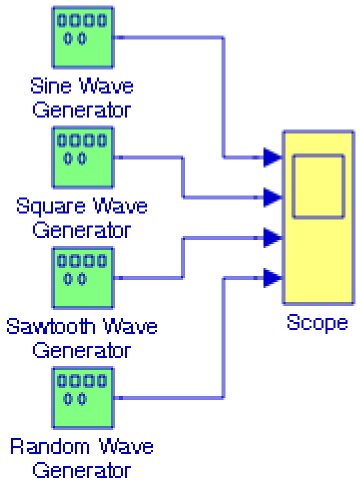


Figure 15.2. Model for Example 15.2

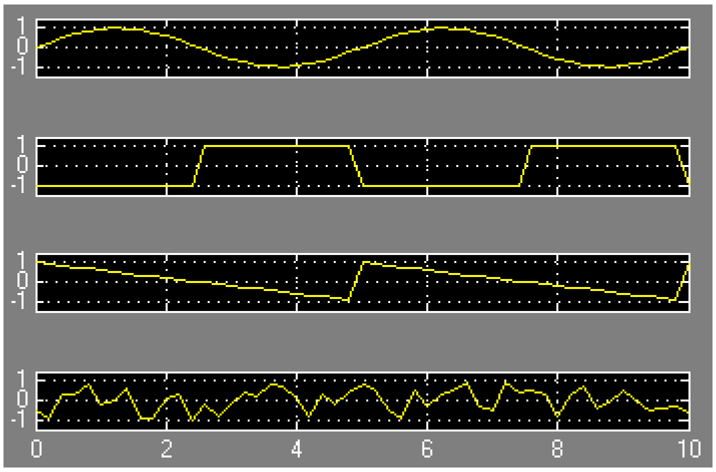
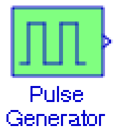


Figure 15.3. Waveforms for sine wave, square wave, sawtooth wave and random wave signal generators

The Simulink documentation includes the **Data Typing Demonstration** demo. It can be accessed by typing combfilter at the MATLAB command prompt.

15.2.3 The Pulse Generator Block



The **Pulse Generator** block generates square wave pulses at regular intervals. The shape of the generated waveform depends on the parameters, Amplitude, Pulse Width, Period, and Phase Delay as shown in Figure 15.4.

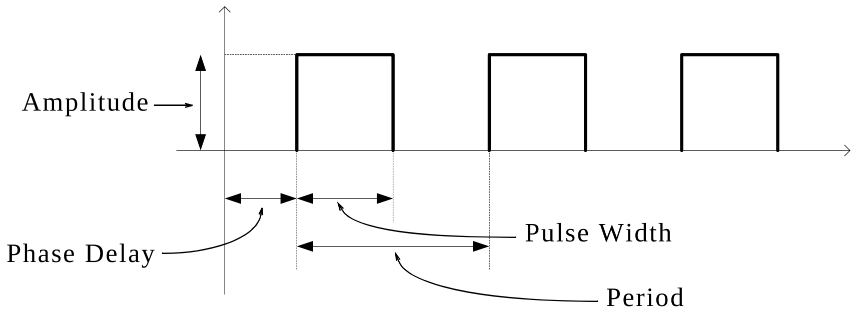


Figure 15.4. Definition of the Pulse Generator block parameters

Example 15.3

In the model in Figure 15.5, the Pulse Generator block parameters are specified as:

Amplitude: 1, Period: 3, Pulse Width: 50, Phase Delay: 1

The unlisted parameters are left in their default states.

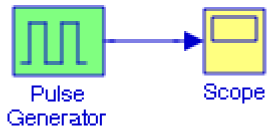


Figure 15.5. Model for Example 15.3

The Scope block displays the waveform shown in Figure 15.6 and thus it can be used as a timer block.

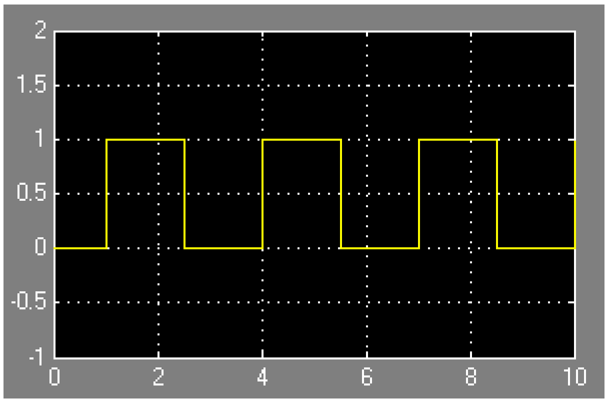
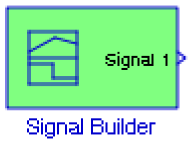


Figure 15.6. Waveform for the model in Figure 15.5

The Simulink documentation includes the **Bus Signal Demonstration** demo and the **Merge Block Demonstration** demo. They can be accessed by typing busdemo and mergedemo at the MATLAB command prompt respectively. Also, the Stateflow documentation includes the **Bang–Bang** demo and it can be accessed by typing sf_boiler at the MATLAB command prompt.

15.2.4 The Signal Builder Block



The **Signal Builder** block allows us to create interchangeable groups of piece–wise linear signal sources and use them in a model. The procedure for building a piece–wise linear signal is as follows:

1. We first double–click on the **Signal Builder** block, and a waveform similar to that shown in Figure 15.7 is displayed. The points at the ends of each line segment indicate that this waveform is selected. To deselect it, we press the **Esc** key.
2. To select a particular point, we position the mouse cursor over that point and we left–click. A circle is drawn around that point to indicate that it is selected.
3. To select a line segment, we left–click on that segment. That line segment is now shown as a thick line indicating that it is selected. To deselect it, we press the **Esc** key.

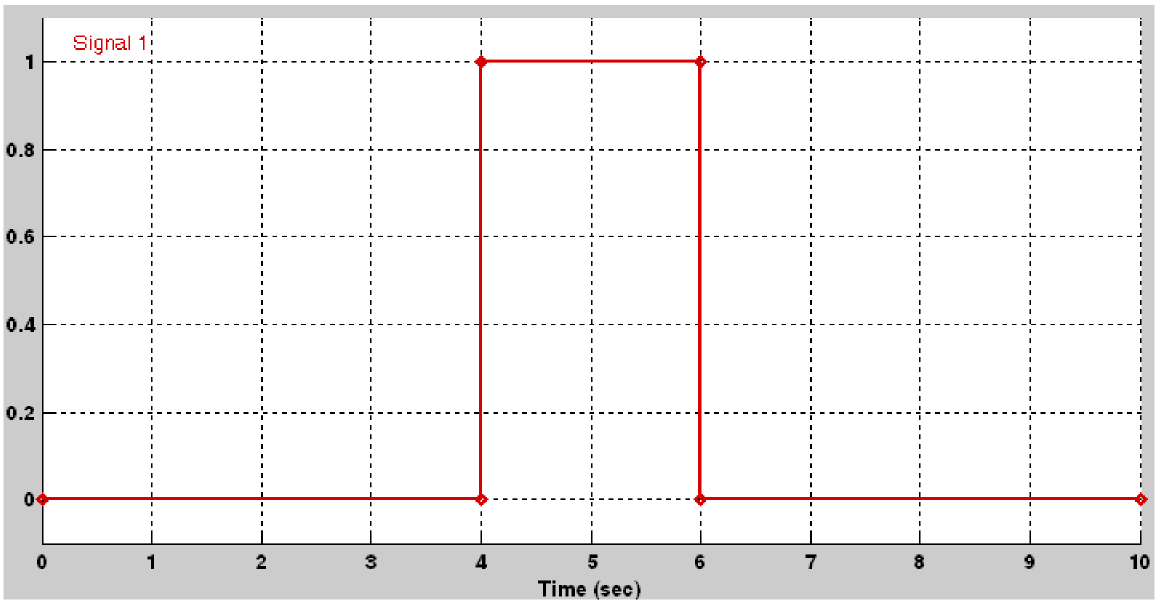


Figure 15.7. Waveform displayed when the Signal Builder block is double–clicked the first time

4. To drag a line segment to a new position, we place the mouse cursor over that line segment and the cursor shape shows the position in which we can drag the segment.
5. To drag a point along the y–axis, we move the mouse cursor over that point, and the cursor changes to a circle indicating that we can drag that point. We can then move that point in a direction parallel to the x–axis.
6. To drag a point along the x–axis, we select that point, and we hold down the Shift key while dragging that point.
7. When we select a line segment on the time axis (x–axis) we observe that at the lower end of the waveform display window the **Left Point** and **Right Point** fields become visible. We can then reshape the given waveform by specifying the Time (**T**) and Amplitude (**Y**) points.
8. We can choose one of several waveforms listed in **New** under the **Signal** drop menu.

Example 15.4

For the triangular waveform of Figure 15.8 it is specified that the Time (**T**) and Amplitude (**Y**) points are (0,0), (1,1), (2,0), (3,1), (4,0), (5,1), (6,0), (7,1), (8,0), (9,1), and (10,0).

The menu bar at the top contains several icons that we could use to modify our waveform.

After the simulation command is executed, the model of Figure 15.9 displays the triangular waveform and its integrated waveform in Figure 15.10.

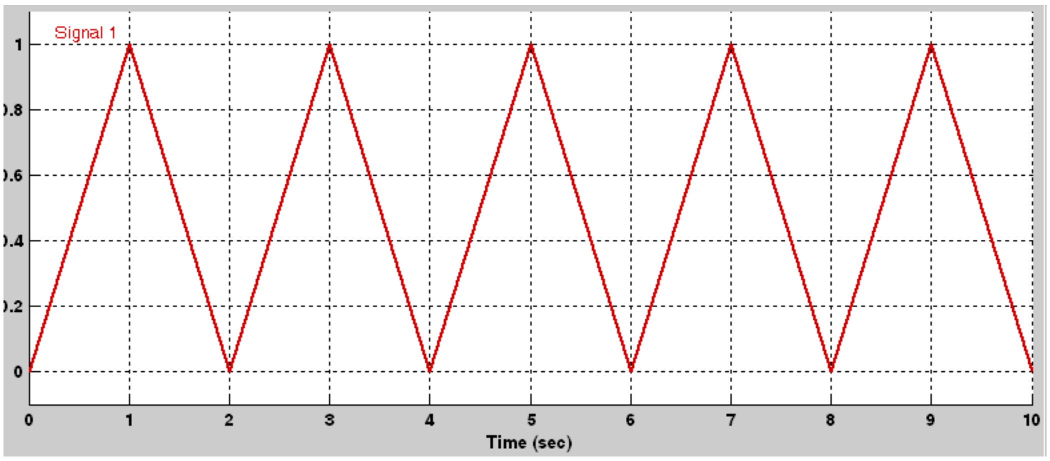


Figure 15.8. Triangular waveform for Example 15.4

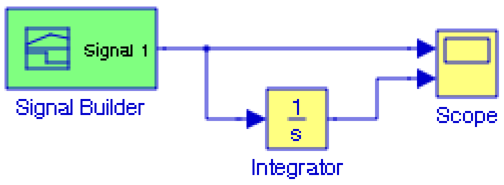


Figure 15.9. Model for Example 15.4

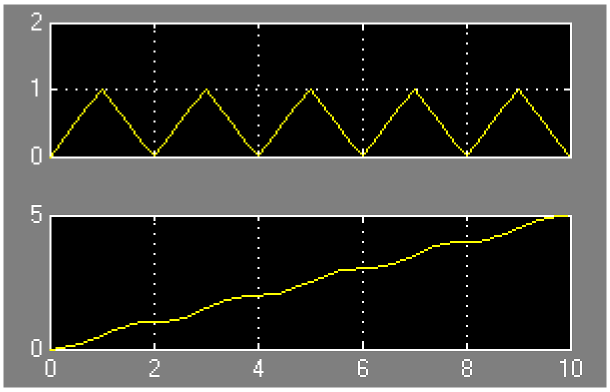
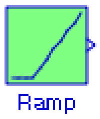


Figure 15.10. Waveforms for the model in Figure 15.9

15.2.5 The Ramp Block



The **Ramp** block generates a signal that starts at a specified time and value and changes by a specified rate. The characteristics of the generated signal are determined by the specified Slope, Start time, Duty Cycle, and Initial output parameters.

Example 15.5

With the Ramp block parameters at their default states, the Scope block in Figure 15.11 displays the waveform shown in Figure 15.12.

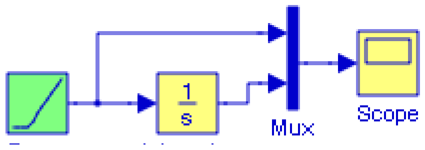


Figure 15.11. Model for Example 15.5

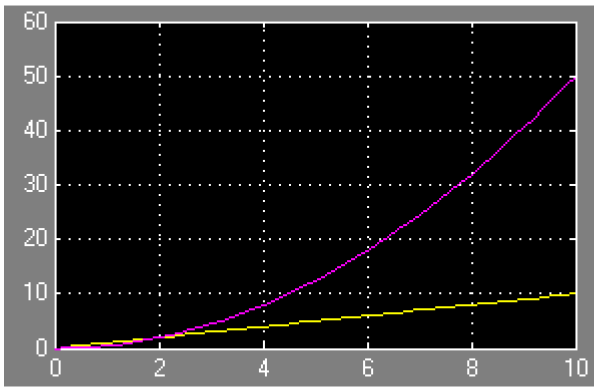
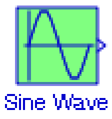


Figure 15.12. Waveform for the model in Figure 15.11

15.2.6 The Sine Wave Block



The **Sine Wave** block generates a sine wave. To generate a cosine wave, we specify the Phase parameter as $\pi/2$.The Sine type can be either **time–based mode** or **sample–based mode** sine wave block.

1. The **time–based** mode has two submodes: **continuous submode** or **discrete submode**. We use the Sample time parameter to specify that the block will operate in the continuous submode or discrete submode. For the continuous submode we specify the 0 value (the default), and for the discrete submode we specify a value greater than zero.
2. The **sample–based** mode requires a finite discrete time. A Sample time parameter value greater than zero causes the block to behave as if it were driving a **Zero–Order Hold** block whose sample time is set to that value. The formulas used are given in the Help menu for this block.

The following parameters appear in the Sine Wave dialog box:

Sine type – Type of sine wave generated by this block, either time– or sample–based. Some of the other options presented by the Sine Wave dialog box depend on whether we select time–based or sample–based as the value of Sine type parameter.

Time – Specifies whether to use simulation time as the source of values for the sine wave's time variable or an external source. If we specify an external time source, the block displays an input port for the time source.

Amplitude – The amplitude of the signal. The default is 1.

Bias – Constant (DC) value added to the sine to produce the output of this block.

Frequency – The frequency, in radians/second. The default is 1 rad/s. This parameter appears only if we specify time–based as the Sine type of the block.

Samples per period – Number of samples per period. This parameter appears only if we specify sample–based as the Sine type of the block.

Phase – The phase shift, in radians. The default is 0 radians. This parameter appears only if we specify time–based as the Sine type of the block.

Number of offset samples – The offset (discrete phase shift) in number of sample times. This parameter appears only if we specify sample–based as the Sine type of the block.

Sample time – The sample period. The default is 0. If the sine type is sample–based, the sample time must be greater than 0. We can refer to Specifying Sample Time in the online documentation for more information.

Interpret vector parameters as 1–D – If checked, column or row matrix values for the Sine Wave block's numeric parameters result in a vector output signal; otherwise, the block outputs a signal of the same dimensionality as the parameters. If this option is not selected, the block always outputs a signal of the same dimensionality as the block's numeric parameters.

Example 15.6

For the model shown in Figure 15.13 the parameters for the **Sine Wave** blocks are specified as follows:

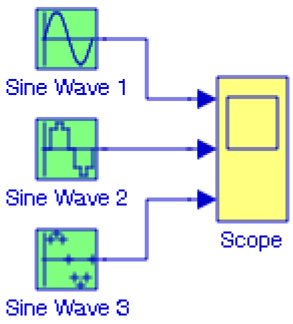


Figure 15.13. Model for Example 15.6

Sine Wave 1 block – All parameters in their default state.

Sine Wave 2 block – Sample time: 0.25. All other parameters in default state.

Sine Wave 3 block – Sine type: Sample based, Sample time: 0.25. All other parameters in default state.

The waveform for each is shown in Figure 15.14.

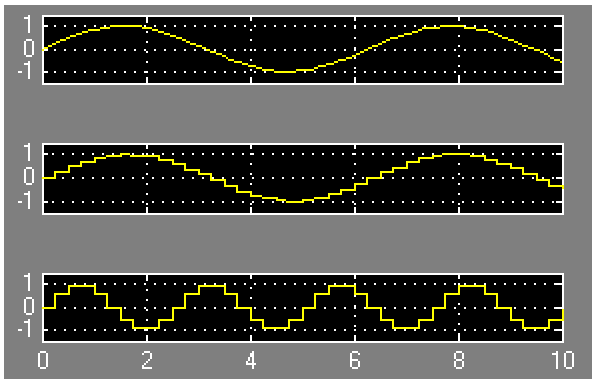
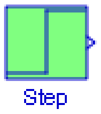


Figure 15.14. Waveforms for the model in Figure 15.13

The Simulink documentation includes the **Bus Signal Demonstration** demo and the **Vertical Displacement of the Wheels of One Dimensional Car** demo. They can be accessed by typing busdemo and sldemo_VariableTransportDelay at the MATLAB command prompt respectively.

15.2.7 The Step Block



The **Step** block generates a step between two defined levels at some specified time. If the simulation time is less than the Step time parameter value, the block's output is the Initial value parameter value. For simulation time greater than or equal to the Step time, the output is the Final value parameter value.

Example 15.7

For the model shown in Figure 15.15 the parameters for the **Step** blocks are specified as follows:

Step 1 block – Step time: 1. All other parameters are in their default state.

Step 2 block – Step time: 5. All other parameters are in their default state.

Step 3 block – Step time: 10. All other parameters are in their default state.

The waveforms are shown in Figure 15.16.

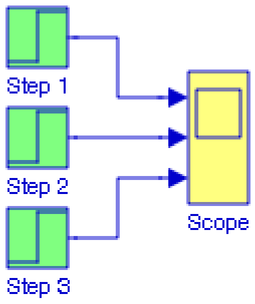


Figure 15.15. Model for Example 15.7

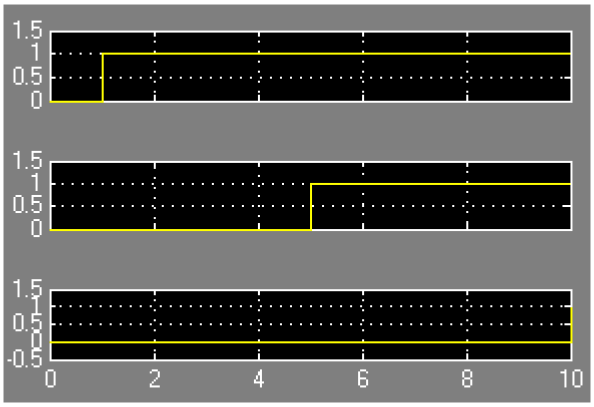
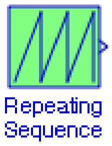


Figure 15.16. Waveforms for the model in Figure 15.15

The Simulink documentation includes the **Vehicle Suspension Model** demo. It can be accessed by typing sldemo_suspn at the MATLAB command prompt.

15.2.8 The Repeating Sequence Block



The **Repeating Sequence** block outputs a periodic waveform that we specify using the block dialog's Time values and Output values parameters. The default of the Time values and Output values parameters are both set to `[0 2]`. This setting specifies a sawtooth waveform that repeats every 2 seconds from the start of the simulation with a maximum amplitude of 2. This block uses linear interpolation to compute the value of the waveform between the specified sample points.

Example 15.8

For the model shown in Figure 15.17, the parameters for the **Repeating Sequence** blocks are as follows:

Repeating Sequence 1 block – Time values: `[0 2]`, Output values: `[0 2]`

Repeating Sequence 2 block – Time values: `[0 1 2]`, Output values: `[0 2 0]`

With these parameter specifications, the waveforms are as shown in Figure 15.18.

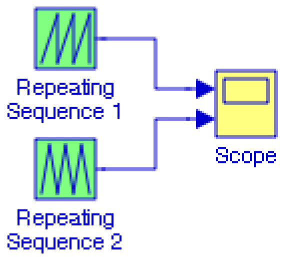


Figure 15.17. Model for Example 15.8

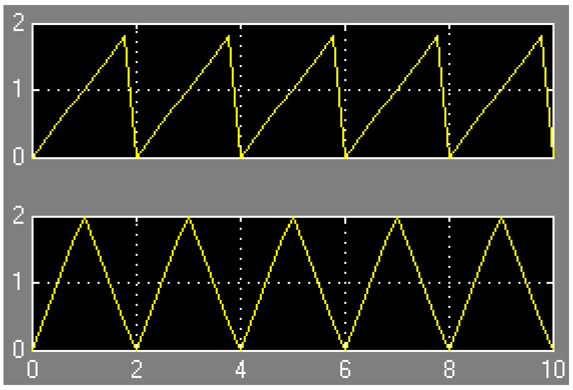


Figure 15.18. Waveforms for the model in Figure 15.17

The Simulink documentation includes the **Merge Block Demonstration** demo and the **Vertical Displacement of the Wheels of One Dimensional Car** demo. They can be accessed by typing mergedemo and sldemo_VariableTransportDelay at the MATLAB command prompt respectively.

15.2.9 The Chirp Signal Block

Chirp Signal

The **Chirp Signal** block generates a sine wave whose frequency increases at a linear rate with time. The model of Figure 15.19 displays the waveform shown in Figure 15.20.

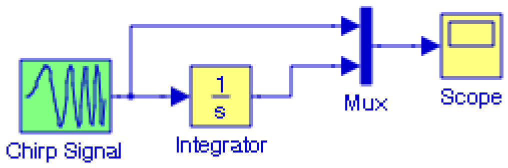


Figure 15.19. Model for displaying the output of the Chirp Signal block and its integral

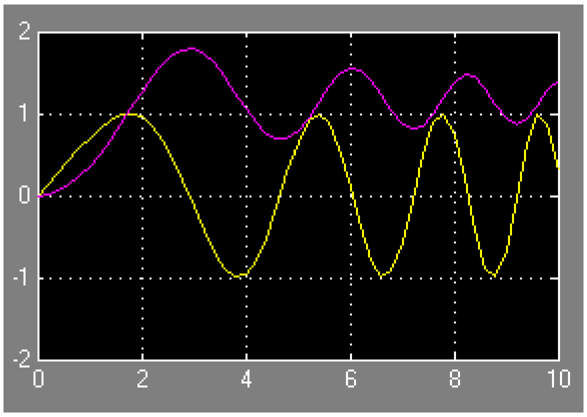


Figure 15.20. Output waveforms of the model in Figure 15.19

Chirp signals[*] can be used for analyzing the spectral components of a variety of nonlinear systems. They offer practical solutions to problems arising in radar and sonar systems design.

The Simulink documentation includes the **Bus Signal Demonstration** demo and it can be accessed by typing busdemo at the MATLAB command prompt. The associated **From** block is inside the **Subsystem** block.

15.2.10 The Random Number Block

Random
Number

The **Random Number** block generates normally distributed random numbers. The seed[†] is reset to the specified value each time a simulation starts. By default, the sequence produced has a mean of 0 and a variance of 1, but we can specify other values for these parameters. The sequence of numbers is repeatable and can be produced by any **Random Number** block with the same seed and parameters. To generate a vector of random numbers with the same mean and variance, we specify the Initial seed parameter as a vector. To generate uniformly distributed random numbers, we use the **Uniform Random Number** block which is described in Section 15.2.11, this chapter.

For a discussion and an example of generating a sequence for a random number generator, please refer to Appendix C.

* *Another Chirp block is included in the Signal Processing Sources library of the Signal Processing Blockset. This block outputs a swept–frequency cosine (chirp) signal with unity amplitude and continuous phase. We can see an example by typing doc_chirp_ref at the MATLAB command prompt.*

† *The seed is defined in Appendix C.*

Example 15.9

With the **Random Number** block Sample time parameter specified as 0.25 and the remaining at their default states, the **Scope** block in Figure 15.21 displays the waveform shown in Figure 15.22.

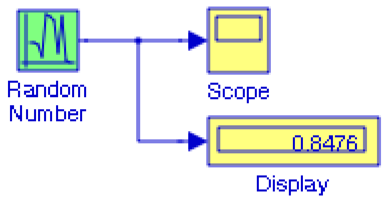


Figure 15.21. Model for Example 15.9

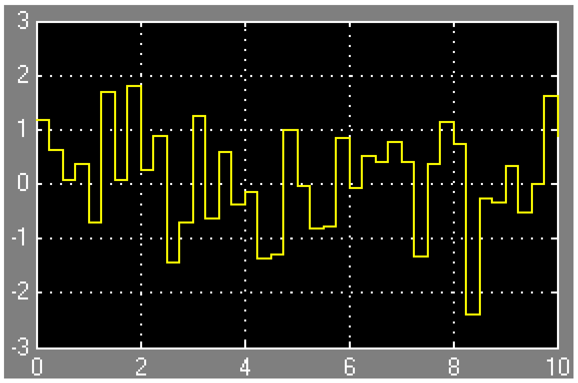
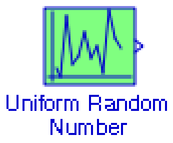


Figure 15.22. Waveform for the model in figure 15.21

15.2.11 The Uniform Random Number Block



The **Uniform Random Number** block generates uniformly distributed[*] random numbers over a specified interval with a specified starting seed. The seed is reset each time a simulation starts. The generated sequence is repeated and can be produced by any Uniform Random Number block with the same seed and parameters. To generate normally distributed random numbers, we use the **Random Number** block which is described in Subsection 15.2.10, this chapter.

* *For a detailed discussion on uniform and normal distributions, please refer to Mathematics for Business, Science, and Technology, ISBN 978–1–934404–01–0*

Example 15.10

For comparison, the model of Figure 15.23 contains the **Random Number** (normally distributed) block and the **Uniform Random Number** block. With the Sample time parameter at 0.25 for both blocks and the remaining at their default states, the **Scope** block in Figure 15.23 displays the waveforms shown in Figure 15.24.

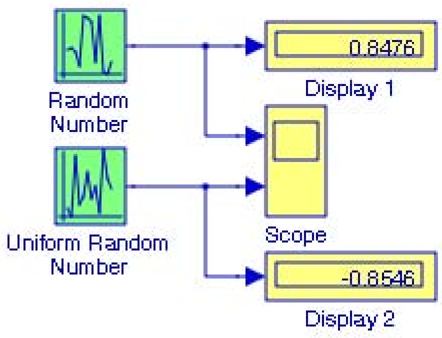


Figure 15.23. Model for Example 15.10

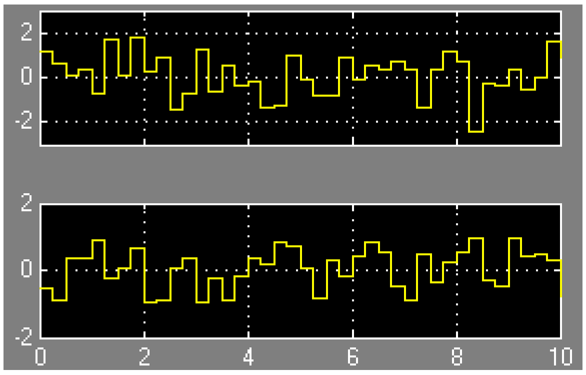
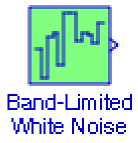


Figure 15.24. Waveforms for the model in Figure 15.23

15.2.12 The Band Limited White Noise Block



White noise[*] has a constant power, usually denoted as P_0, over a bandwidth that theoretically extends from $-\infty$ to $+\infty$ as shown in Figure 15.25.

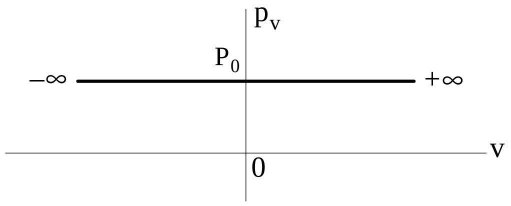


Figure 15.25. White noise in a theoretical sense

In a practical sense, white noise is limited is some way. For instance, the **thermal noise**[†] in a resistor is contained in a certain finite bandwidth extended from $-B$ to $+B$ as shown in Figure 15.26, and thus it is referred to as **band–limited white noise**.

In Simulink, the **Band–Limited White Noise** block is an implementation of white noise into **Zero–Order Hold** block. As described in Subsection 5.2.3, Chapter 5, the **Zero–Order Hold** block samples and holds its input for the specified sample period. The block accepts one input and generates one output, both of which can be scalar or vector.

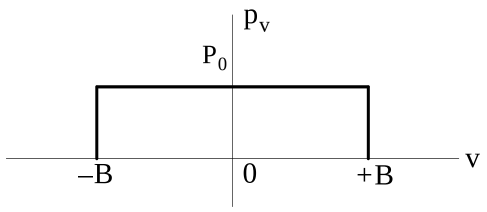


Figure 15.26. Band–limited white noise

* *The adjective "white" is used to describe this type of noise in analogy with the white light. White light is a blend of all the colors in the visual spectrum, resulting in the color white that is made up of all of the different colors (frequencies) of light combined together. As we know from physics, a prism separates white light back into its component colors.*

† *Thermal noise is the result of random fluctuations of the charge carriers in any conductive medium and is dependent on the temperature.*

In Simulink, we can simulate the effect of white noise by using a random sequence[*] with a correlation time[†] much smaller than the shortest time constant of the system. The **Band−Limited White Noise** block produces such a sequence. For good results, the Simulink documentation recommends that we use the relation

$$t_C = \frac{1}{100} \cdot \frac{2\pi}{\omega_{max}} \tag{15.1}$$

where t_C is the correlation time and ω_{max} is the bandwidth of the system in rad/sec.

Example 15.11

Consider an RC low−pass filter whose input is random noise denoted as $n_{in}(t)$ and the filtered output is denoted as $n_{out}(t)$. The constants are $R = 1\ M\Omega$ and $C = 1\ \mu F$. This network is referred to as **first order low−pass filter**. For this filter we will:

a. Derive the transfer function for this filter and create a model to display the output when the input is a **Band−Limited White Noise** block.

b. Use the bilinear transformation[‡] to derive the equivalent discrete time transfer function and create a model to display the output when the input is a **Band−Limited White Noise** block. For simplicity, we will neglect the effect of warping.[**]

The s−domain transformed filter is shown in Figure 15.27.

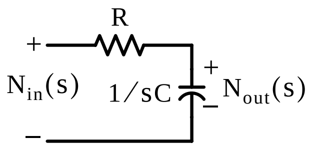


Figure 15.27. The transformed first order RC low−pass filter

1. By the voltage division expression,

$$N_{out}(s) = \frac{1/sC}{R + 1/sC} N_{in}(s) \tag{15.2}$$

* *The Random Number block, described in Subsection 15.2.10, this chapter, Page15−14, produces random sequences also. The primary difference is that the Band−Limited White Noise block produces an output at a specific sample rate, which is related to the correlation time of the noise.*
† *The correlation time of the noise is the sample rate of the Band−Limited White Noise block.*
‡ *For a detailed discussion on the bilinear transformation, please refer to Signals and Systems with MATLAB Computing and Simulink Modeling, ISBN 978−0−9744239−9−9.*
** *The continuous−time frequency to discrete−time frequency transformation results in a non−linear mapping and this condition is known as warping. A detailed discussion appears in the Signals and Systems text cited above.*

Rearranging, substituting the given values, and simplifying we obtain the continuous–time transfer function

$$G(s) = \frac{N_{out}(s)}{N_{in}(s)} = \frac{1}{s+1} \tag{15.3}$$

The Simulink block for this transfer function is found in the **Continuous** Library, Chapter 3, and thus we create the model shown in Figure 15.28.

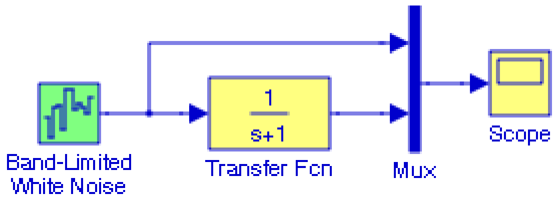


Figure 15.28. Model for Example 15.11 with continuous–time transfer function

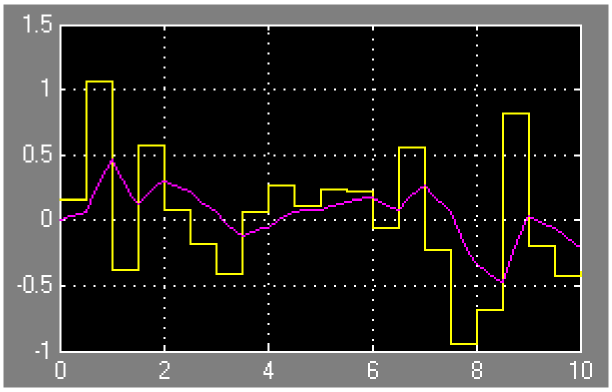


Figure 15.29. Input and output waveforms for the model in Figure 15.28

The parameters for the Band–Limited White Noise block in Figure 15.28 are specified as follows:

Noise power: [0.1] (default)

Sample time: 0.5

Seed: [23341] (default)

2. The bilinear transformation uses the relation

$$H(z) = H(s)\Big|_{s = \frac{2}{T_s} \cdot \frac{z-1}{z+1}} \tag{15.4}$$

For convenience, we will use MATLAB's **bilinear(Z,P,K,Fs)** function where column vectors **Z** and **P** specify the zeros and poles respectively, scalar **K** specifies the gain, and **Fs** is the sample frequency in Hz. In Part (1), the sample time is specified as $T_s = 0.5\ s$, therefore, we specify

$F_s = 2$ Hz for part (2). Denoting the numerator and denominator of (15.3) as numa = 1 and dena = [1 1], we type and execute the statement

```
numa=1; dena=[1 1]; Fs=2; [numd,dend]=bilinear(numa,dena,Fs)
```

and MATLAB displays the discrete–time coefficients as

```
numd =
    0.2000    0.2000
dend =
    1.0000   -0.6000
```

Our model with the discrete–time transfer function is as shown in Figure 15.30 where the **Discrete Transfer Fcn** block was dragged from the Discrete library and we substituted the values above into that block. The input and output waveforms are shown in Figure 15.31.

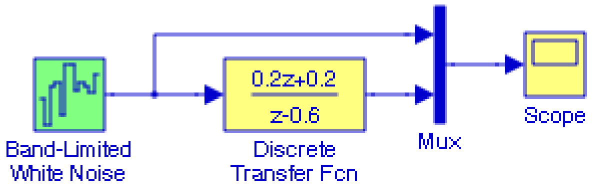


Figure 15.30. Model for Example 15.11 with discrete–time transfer function

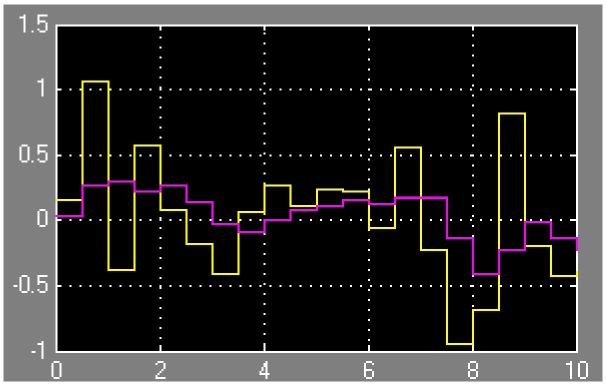
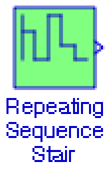


Figure 15.31. Input and output waveforms for the model in Figure 15.30

The Simulink documentation includes the **F–14 Tomcat Digital Flight Control System** demo, the **Radar Tracking Using Embedded MATLAB** demo, and the **Optical Sensor Vibration Model** demo. They can be accessed by typing `f14_digital`, `sldemo_radar_eml`, and `aero_pointer_tracker` at the MATLAB command prompt respectively.

15.2.13 The Repeating Sequence Stair Block



The **Repeating Sequence Stair** block outputs and repeats a discrete time sequence. We specify the stair sequence with the Vector of output values parameter.

Example 15.12

For the model shown in Figure 15.32, in the **Source Block Parameters** dialog box the **Vector of output values** parameter is specified as $[-4\ \ -2\ \ \ 0\ \ \ 2\ \ \ 4\ \ \ 2\ \ \ 0\ \ \ -2\ \ -4\ \ \ -2]$ and the **Sample time** as 0.5. The waveform produced is shown in Figure 15.33.

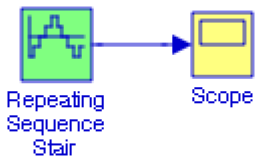


Figure 15.32. Model for Example 15.12

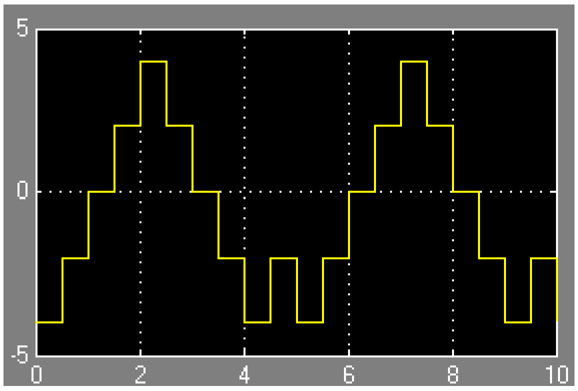
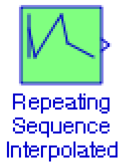


Figure 15.33. Waveform for the model in Figure 15.32

15.2.14 The Repeating Sequence Interpolated Block



The **Repeating Sequence Interpolated** block generates a repeating discrete–time sequence. This block uses any of the methods specified by the Lookup Method parameter.

Example 15.13

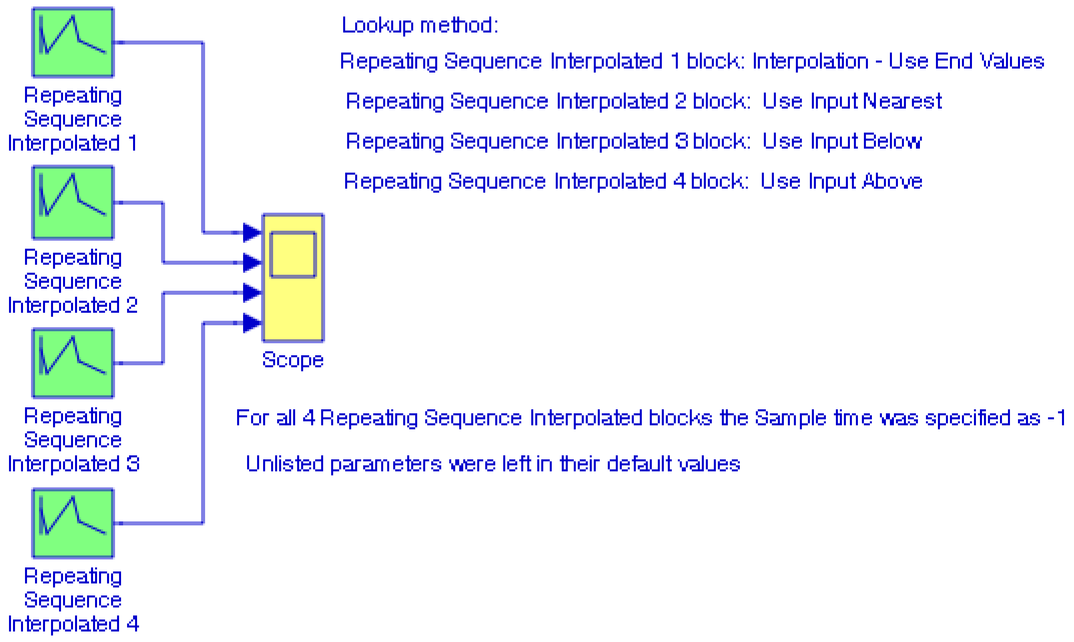
For the model shown in Figure 15.34, for all four **Repeating Sequence Interpolated** blocks, in the Source Block Parameters dialog box are specified as follows:

Vector of output values: [3 1 4 2 1]'

Vector of time values: [0 0.1 0.5 0.6 1]'

Lookup method: As annotated inside the model.

The waveforms generated by each of the **Repeating Sequence Interpolated** blocks are shown in Figure 15.35.


Repeating Sequence Interpolated 1
Repeating Sequence Interpolated 2
Repeating Sequence Interpolated 3
Repeating Sequence Interpolated 4
Scope

Lookup method:
Repeating Sequence Interpolated 1 block: Interpolation - Use End Values
Repeating Sequence Interpolated 2 block: Use Input Nearest
Repeating Sequence Interpolated 3 block: Use Input Below
Repeating Sequence Interpolated 4 block: Use Input Above

For all 4 Repeating Sequence Interpolated blocks the Sample time was specified as -1

Unlisted parameters were left in their default values

Figure 15.34. Model for Example 15.13

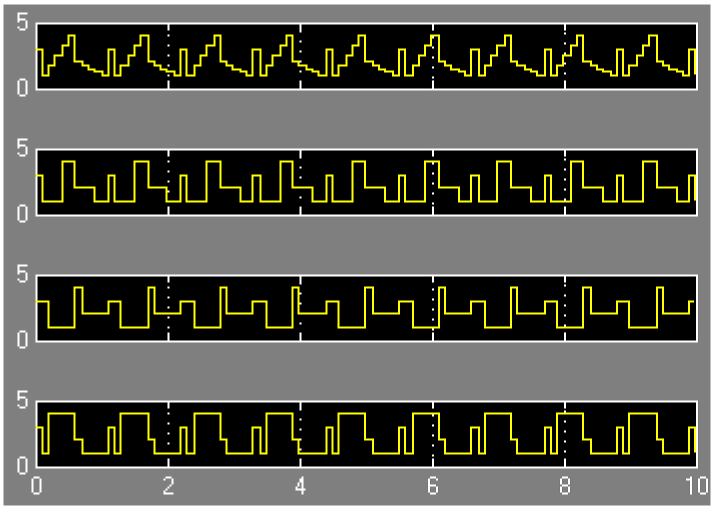


Figure 15.35. Waveforms for the model in Figure 15.34

15.2.15 The Counter Free–Running Block

The **Counter Free–Running** block counts up until the maximum possible value, $2^N - 1$, is reached, where N bits is the number of bits. The counter then returns to zero, and restarts counting up. It is always initialized to zero.

Example 15.14

For the model of Figure 15.36, in the **Counter Free–Running** block the Number of bits in the **Source Block Parameters** dialog box is specified $N = 5$, and thus $2^N - 1 = 2^5 - 1 = 31$. On the **Scope** block in Figure 15.37 we observe that the counter reaches the value of 31, resets to zero at approximately 6.5 seconds, and restarts counting up. At the end of the simulation time, the counter has reached the value of 18 and this is also indicated in the **Display** block.

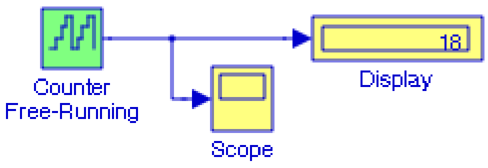


Figure 15.36. Model for Example 15.14

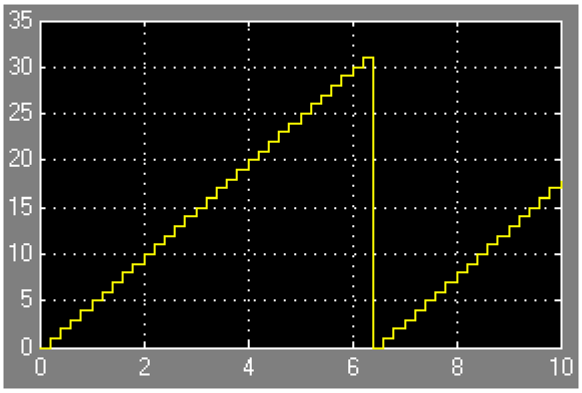
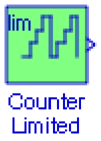


Figure 15.37. Waveform for the model in Figure 15.36

15.2.16 The Counter Limited Block



The **Counter Limited** block counts up until the specified upper limit is reached. Then the counter wraps back to zero, and restarts counting up. The counter is always initialized to zero.

Example 15.15

For the model of Figure 15.38, in the **Counter Limited block** the Upper limit in the **Source Block Parameters** dialog box is specified as 32, and as we observe on the **Scope** block in Figure 15.39 that the counter reaches the value of 32, resets to zero at approximately 6.6 seconds, and restarts counting up. At the end of the simulation time, that is, 10 sec, the counter has reached the value of 17 and this is also indicated in the **Display** block.

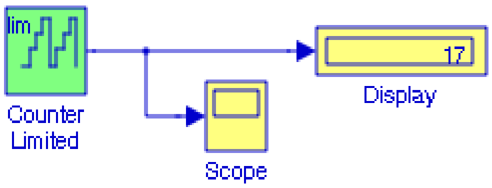


Figure 15.38. Model for Example 15.15

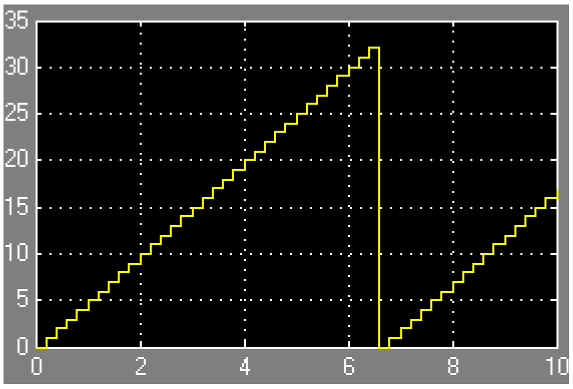


Figure 15.39. Waveform for the model of Figure 15.38

The Simulink documentation includes the **Comparison in approximate sine wave accuracy between direct look–up and linear interpolation** demo. It can be accessed by typing sl_demo_tonegen at the MATLAB command prompt.

15.2.17 The Clock Block

Clock

The **Clock** block outputs the current simulation time at each simulation step. This block is useful for other blocks that need the simulation time. For discrete–time systems we use the **Digital Clock** block which is described in Subsection 15.2.18, this chapter, Page 15–27. We use the Display time check box to display the current simulation time inside the **Clock** icon. The Decimation parameter value is the increment at which the clock is updated and it can be any positive integer.

Example 15.16

In the model of Figure 15.40, for all three **Clock** blocks in the **Source Block Parameters** dialog box the Display time check box is checked to display the simulation time. The Decimation parameter in **Clock 1** block is specified as 10, and this is the increment at which the clock is updated. Thus, for a fixed integration step of 1 second, the clock updates at 1 second, 2 seconds, and so on. The Decimation parameter in **Clock 2** block is specified as 100 and this is the increment at which the clock is updated. Thus, for a fixed integration step of 1/100 second, the clock updates at 1/100 second, 2/100 second, and so on. The Decimation parameter in **Clock 3** block has been set to 1000 and this is the increment at which the clock is updated. Thus, for a fixed integration step of 1/1000 second, the clock updates at 1/1000 second, 2/1000 second, and so on. The waveforms are shown in Figure 15.41.

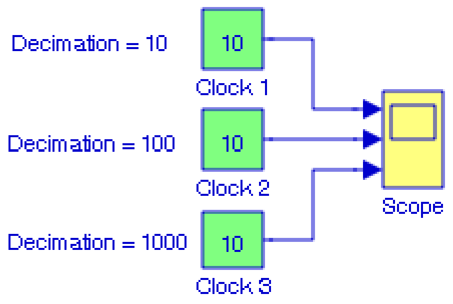


Figure 15.40. Model for Example 15.16

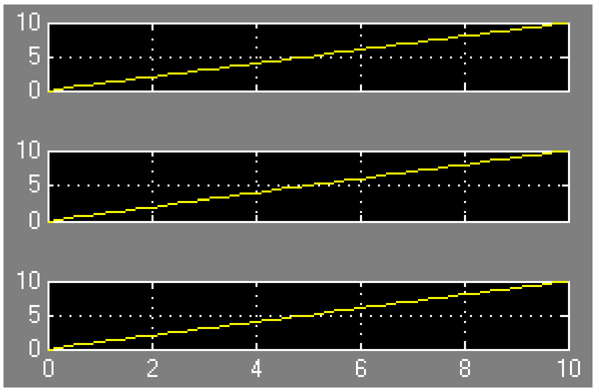


Figure 15.41. Waveforms for the model in Figure 15.40

The Simulink documentation includes the **Comparison in approximate sine wave accuracy between direct look–up and linear interpolation** demo and the **Bus Signal Demonstration** demo. They can be accessed by typing sl_demo_tonegen, and busdemo at the MATLAB command prompt respectively.

15.2.18 The Digital Clock Block

The **Digital Clock** block displays the simulation time at a specified sampling interval. At all other times, the output is held at the previous value. This block is useful when we desire to know the current time within a discrete system.

Example 15.17

For the model of Figure 15.42, for the **Digital Clock** block in the **Source Block Parameters** dialog box the Sample time is specified as 0.25. Its output is displayed on the **Scope** block in Figure 15.43.

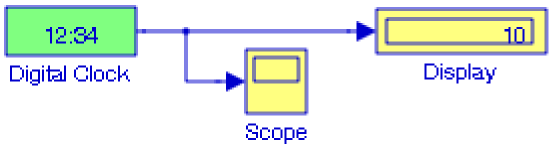


Figure 15.42. Model for Example 15.17

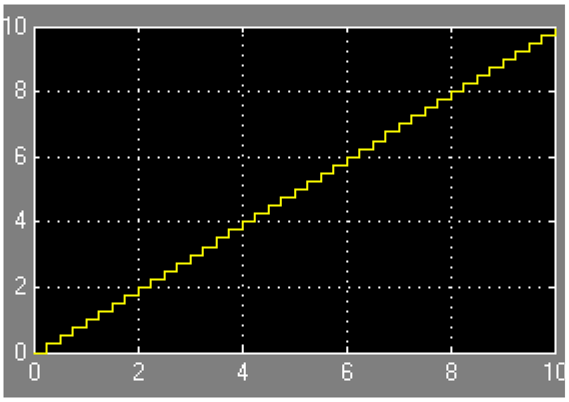


Figure 15.43. Waveform for the model in Figure 15.42

15.3 Summary

- The **Inport** block creates an input port for a subsystem or an external input.
- The **Ground** block grounds an unconnected input port.
- The **From File** block outputs data read from a MAT file. The name of the file is displayed inside the block.
- The **From Workspace** block reads data from the MATLAB workspace. The workspace data are specified in the block's Data parameter via a MATLAB expression that evaluates to a 2–D array.
- The **Constant** block generates a real or complex constant value.
- The **Signal Generator** block can produce one of four different waveforms: sine wave, square wave, sawtooth wave, and random wave.
- The **Pulse Generator** block generates square wave pulses at regular intervals. The shape of the generated waveform depends on the parameters, Amplitude, Pulse Width, Period, and Phase Delay.
- The **Signal Builder** block allows us to create interchangeable groups of piece wise linear signal sources and use them in a model.
- The **Ramp** block generates a signal that starts at a specified time and value and changes by a specified rate. The characteristics of the generated signal are determined by the specified Slope, Start time, Duty Cycle, and Initial output parameters.
- The **Sine Wave** block generates a sine wave. The Sine type can be either time–based or sample–based mode.
- The **Step** block provides a step between two definable levels at a specified time.
- The **Repeating Sequence** block outputs a periodic waveform that we specify using the block dialog's Time values and Output values parameters.
- The **Chirp Signal** block generates a sine wave whose frequency increases at a linear rate with time.
- The **Random Number** block generates normally distributed random numbers. The seed is reset to the specified value each time a simulation starts. By default, the sequence produced has a mean of 0 and a variance of 1, but we can specify other values for these parameters. The sequence of numbers is repeatable and can be produced by any Random Number block with the same seed and parameters.
- The **Uniform Random Number** block generates uniformly distributed random numbers over a specifiable interval with a specifiable starting seed. The seed is reset each time a simulation starts. The generated sequence is repeatable and can be produced by any Uniform Random

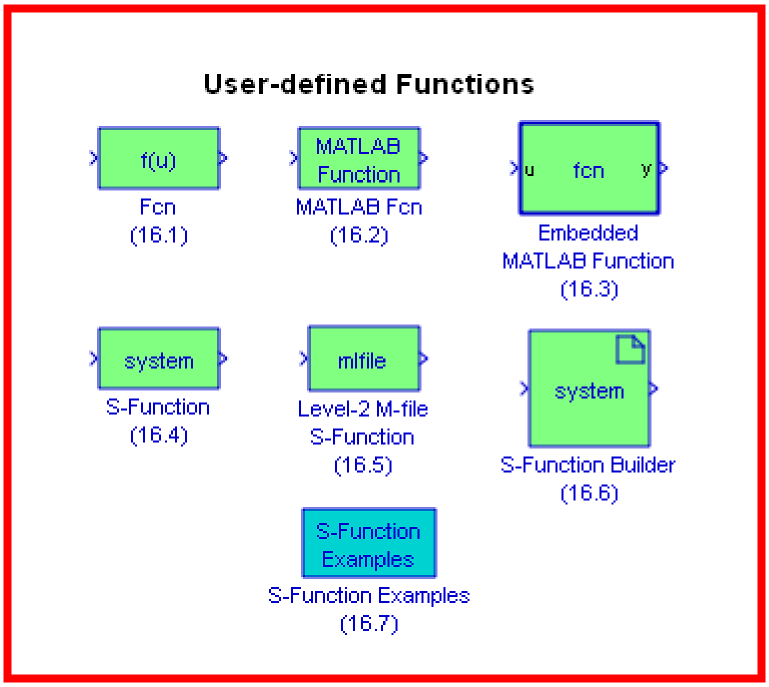
Number block with the same seed and parameters. To generate normally distributed random numbers, we use the Random Number block.

- The **Band–Limited White Noise** block is an implementation of white noise into Zero–Order Hold block.
- The **Repeating Sequence Stair** block outputs and repeats a discrete time sequence.
- The **Repeating Sequence Interpolated** block outputs a discrete–time sequence and then repeats it.
- The **Counter Free–Running** block counts up until the maximum possible value, $2^N - 1$, is reached, where N bits is the number of bits. Then the counter overflows to zero, and restarts counting up. The counter is always initialized to zero.
- The **Counter Limited** block counts up until the specified upper limit is reached. Then the counter wraps back to zero, and restarts counting up. The counter is always initialized to zero.
- The **Clock** block outputs the current simulation time at each simulation step. For discrete–time systems we use the Digital Clock block.
- The **Digital Clock** block displays the simulation time at a specified sampling interval. At all other times, the output is held at the previous value.

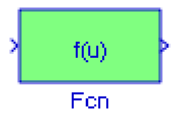
Chapter 16

The User–Defined Functions Library

This chapter is an introduction to the **User–Defined Functions** Library**.** This is the fifteenth library in the Simulink group of libraries and contains the blocks shown below. Their functions are illustrated with examples.



16.1 The Fcn Block



The **Fcn** block applies a specified expression to its input denoted as u. If u is a vector, u(i) represents the ith element of the vector; u(1) or u alone represents the first element. The specified expression can consist of numeric constants, arithmetic operators, relational operators, logical operators, and the math functions abs, acos, asin, atan, atan2, ceil, cos, cosh, exp, fabs, floor, hypot, ln, log, log10, pow, power, rem, sgn, sin, sinh, sqrt, tan, and tanh.

Example 16.1

It can be shown that the solution[*] of the differential equation

$$\frac{d^2y}{dt^2} + 4y = \tan 2t \tag{16.1}$$

is

$$y = -(1/4)\cos 2t \cdot \ln(\sec 2t + \tan 2t) + k_1 \cos 2t + k_2 \sin 2t \tag{16.2}$$

where the constants k_1 and k_2 can be evaluated from the initial conditions. Then we can compute and display any value of y by specifying t, k_1, and k_2, using the model shown in Figure 16.1.

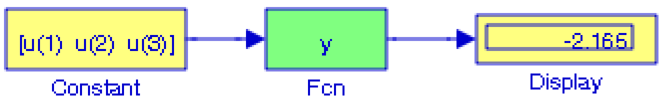


Figure 16.1. Model for Example 16.1

For the model of Figure 16.1 the values are assigned as $u(1) = t = \pi/6$, $u(2) = k_1 = -1$, $u(3) = k_2 = -3$, where at the MATLAB command prompt we enter:

```
u(1)=pi/6; u(2)=–1; u(3)=–3;
y=–(1/4)*cos(2*u(1))*log(sec(2*u(1))+tan(2*u(1)))+u(2)*cos(2*u(1))+u(3)*cos(2*u(1));
```

The Simulink documentation includes the **Modeling Engine Timing Using Triggered Subsystems** demo. It can be accessed by typing sldemo_engine at the MATLAB command prompt, and clicking the Combustion block.

* *The analytical solution of this differential equation is presented in Example 5.13, Section 5, Page 5–22, Numerical Analysis Using MATLAB and Excel text, ISBN 978–1–934404–03–4.*

16.2 The MATLAB Fcn Block

MATLAB Function
MATLAB Fcn

The **MATLAB Fcn** block applies the specified MATLAB function or expression to the input. This block is slower than the **Fcn** block because it calls the MATLAB parser during each integration step. As an alternative, we can use built–in blocks such as the **Fcn** block or a **Math Function** block, or writing the function as an M–file S–function, then accessing it using the **S–Function** block.

Example 16.2

In the model of Figure 16.2, the function in the MATLAB Fcn block is specified as eig and outputs the eigenvalues of Matrix A.

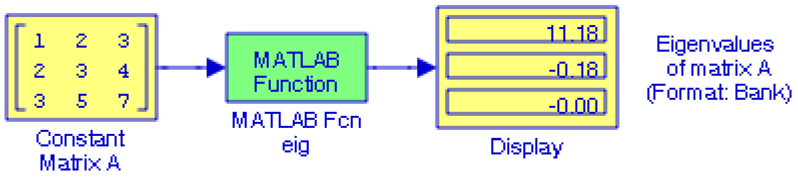
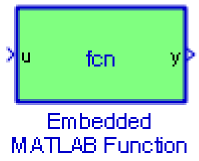


Figure 16.2. Model for Example 16.2

16.3 The Embedded MATLAB Function Block



The **Embedded MATLAB Function** block contains a MATLAB language function in a Simulink model. This block accepts multiple input signals and produces multiple output signals. For more information and an example, please refer to the Simulink User's Manual.

Example 16.3

In this example we will create a model using an **Embedded MATLAB Function** block to accept a 3×3 matrix and output the value of its determinant and its inverse matrix.

We begin with a model that contains a **Constant** block, an **Embedded MATLAB Function** block, and two **Display** blocks as shown in Figure 16.3. We save this model as **matrix_det_inv.mdl**

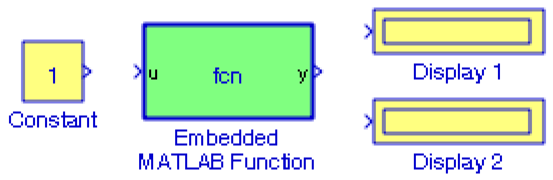
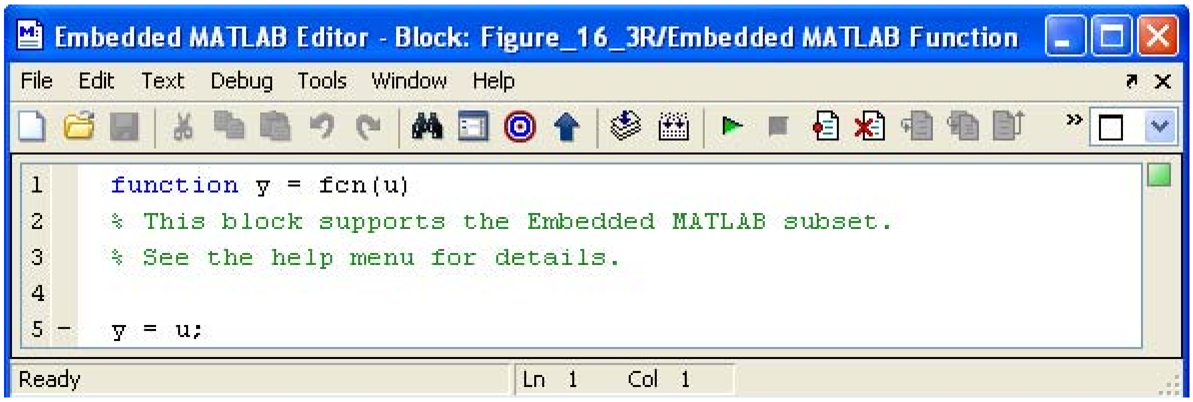


Figure 16.3. Blocks for the model in Example 16.3

We double–click the **Embedded MATLAB Function** block to open it for editing, and the Embedded MATLAB Editor window appears as shown in Figure 16.4.


Embedded MATLAB Editor - Block: Figure_16_3R/Embedded MATLAB Function
File
Edit
Text
Debug
Tools
Window
Help
Ready
Ln 1
Col 1

```
function y = fcn(u)
% This block supports the Embedded MATLAB subset.
% See the help menu for details.

y = u;
```

Figure 16.4. The Embedded MATLAB Editor window

Using MATLAB's Editor, we define a new function file as

function [det, inv] = matrix(A)

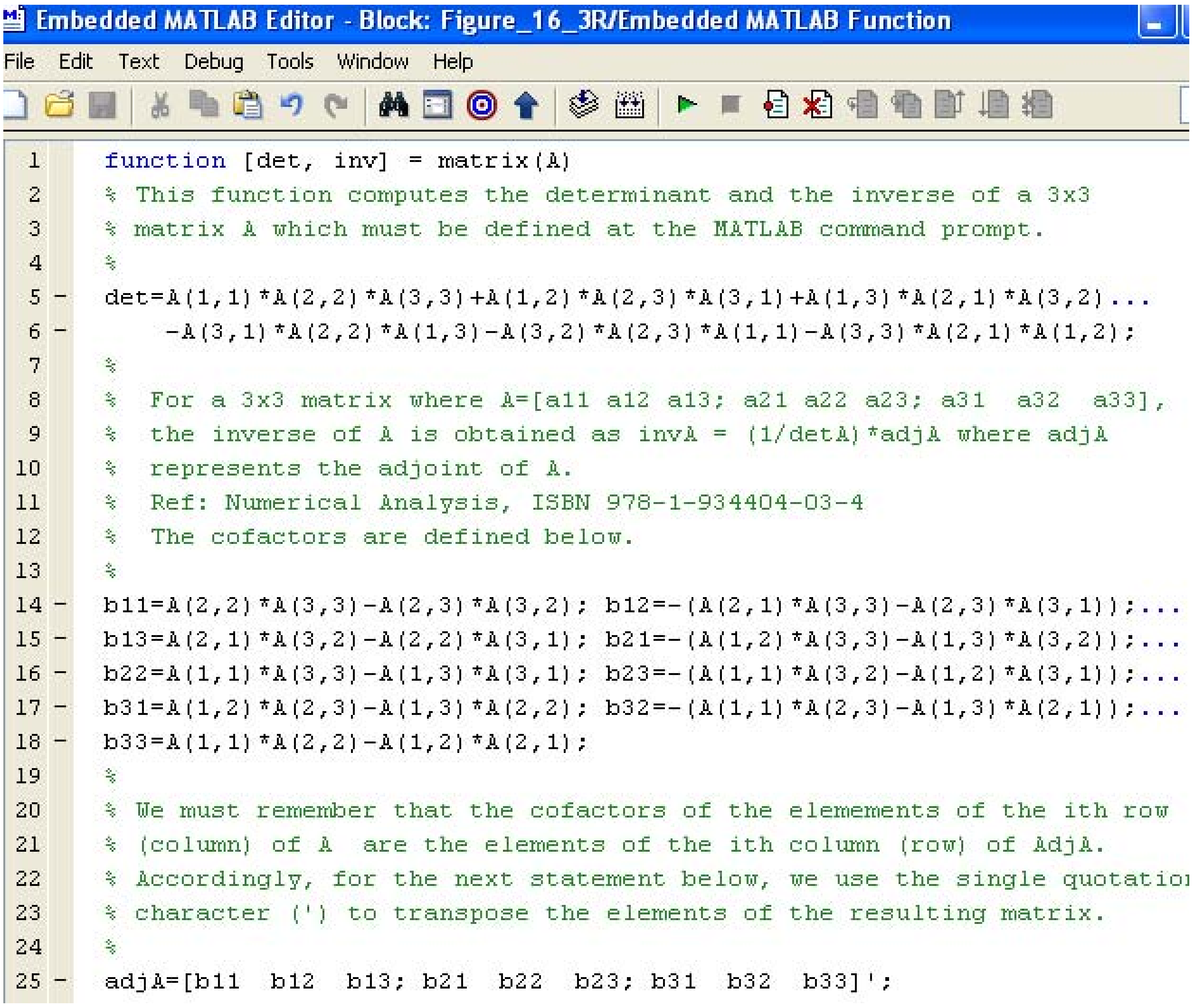
The contents of this function file are as follows:[*]

```
function [det, inv] = matrix(A)
% This function computes the determinant and the inverse of a 3x3
% matrix A which must be defined at the MATLAB command prompt.
%
det=A(1,1)*A(2,2)*A(3,3)+A(1,2)*A(2,3)*A(3,1)+A(1,3)*A(2,1)*A(3,2)...
   –A(3,1)*A(2,2)*A(1,3)–A(3,2)*A(2,3)*A(1,1)–A(3,3)*A(2,1)*A(1,2);
%
%  For a 3x3 matrix where A=[a11 a12 a13; a21 a22 a23; a31  a32  a33],
%  the inverse of A is obtained as invA = (1/detA)*adjA where adjA
%  represents the adjoint of A. Ref: Numerical Analysis, ISBN 978–1–934404–03–4
%  The cofactors are defined below.
%
b11=A(2,2)*A(3,3)–A(2,3)*A(3,2); b12=–(A(2,1)*A(3,3)–A(2,3)*A(3,1)); b13=A(2,1)*A(3,2)–A(2,2)*A(3,1);
```

[*] *The script for the user defined function used in this example is not the best choice. For the computation of the determinant of a square matrix of any size, we could use the* **for loops** *method such as* for i=1:n*, and for the computation of the inverse of a square matrix of any size, we can use the LU decomposition method. These methods are described in Numerical Analysis Using MATLAB and Excel, ISBN 978–1–934404–03–4*

```
b21=–(A(1,2)*A(3,3)–A(1,3)*A(3,2)); b22=A(1,1)*A(3,3)–A(1,3)*A(3,1); b23=–(A(1,1)*A(3,2)–A(1,2)*A(3,1));
b31=A(1,2)*A(2,3)–A(1,3)*A(2,2); b32=–(A(1,1)*A(2,3)–A(1,3)*A(2,1)); b33=A(1,1)*A(2,2)–A(1,2)*A(2,1);
%
% We must remember that the cofactors of the elemements of the ith row (column) of A  are the
% elements of the ith column (row) of AdjA. Accordingly, for the next statement below, we use the
% single quotation character (') to transpose the elements of the resulting matrix.
%
adjA=[b11  b12  b13; b21  b22  b23; b31  b32  b33]';
%
inv=(1/det)*adjA
```

We delete the contents shown in Figure 16.4, we copy the above script into the **Embedded MATLAB Editor**, from the **File** menu we select **Save as Model,** and we save it as **matrix_det_inv01.mdl**. The content of the modified **Embedded MATLAB Editor** is now as shown in Figure 16.5.


Embedded MATLAB Editor - Block: Figure_16_3R/Embedded MATLAB Function
File Edit Text Debug Tools Window Help

```
function [det, inv] = matrix(A)
% This function computes the determinant and the inverse of a 3x3
% matrix A which must be defined at the MATLAB command prompt.
%
det=A(1,1)*A(2,2)*A(3,3)+A(1,2)*A(2,3)*A(3,1)+A(1,3)*A(2,1)*A(3,2)...
    -A(3,1)*A(2,2)*A(1,3)-A(3,2)*A(2,3)*A(1,1)-A(3,3)*A(2,1)*A(1,2);
%
%  For a 3x3 matrix where A=[a11 a12 a13; a21 a22 a23; a31  a32  a33],
%  the inverse of A is obtained as invA = (1/detA)*adjA where adjA
%  represents the adjoint of A.
%  Ref: Numerical Analysis, ISBN 978-1-934404-03-4
%  The cofactors are defined below.
%
b11=A(2,2)*A(3,3)-A(2,3)*A(3,2); b12=-(A(2,1)*A(3,3)-A(2,3)*A(3,1));...
b13=A(2,1)*A(3,2)-A(2,2)*A(3,1); b21=-(A(1,2)*A(3,3)-A(1,3)*A(3,2));...
b22=A(1,1)*A(3,3)-A(1,3)*A(3,1); b23=-(A(1,1)*A(3,2)-A(1,2)*A(3,1));...
b31=A(1,2)*A(2,3)-A(1,3)*A(2,2); b32=-(A(1,1)*A(2,3)-A(1,3)*A(2,1));...
b33=A(1,1)*A(2,2)-A(1,2)*A(2,1);
%
% We must remember that the cofactors of the elemements of the ith row
% (column) of A  are the elements of the ith column (row) of AdjA.
% Accordingly, for the next statement below, we use the single quotatio
% character (') to transpose the elements of the resulting matrix.
%
adjA=[b11  b12  b13; b21  b22  b23; b31  b32  b33]';
```

Figure 16.5. Function definition for the computation of the determinant and inverse of a 3x3 matrix

From the MATLAB Command Window we open a new file, and at the Editor window we copy the contents of the Embedded MATLAB Editor shown in Figure 16.5. We save this file as matrix_det_inv01.

Next, we return to the model in Figure 16.3, and we observe that the **Embedded MATLAB Function** block appears as shown in Figure 16.6.

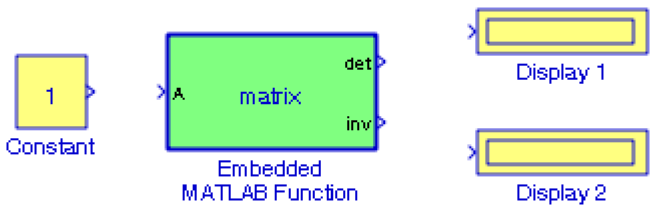


Figure 16.6. Modified model for Example 16.3

Now, we connect the blocks shown in Figure 16.6 as shown in Figure 16.7 where in the **Constant** block we have assigned matrix A defined at the MATLAB command prompt as

```
A=[1  2  3; 1  3  4; 1  4  3];
```

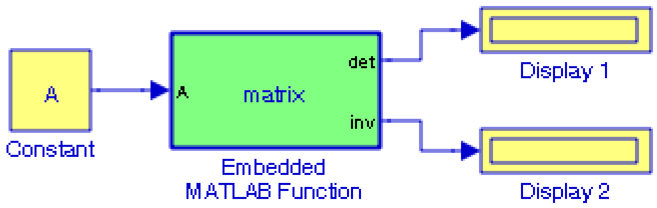


Figure 16.7. The connected blocks for the model in Example 16.3

Finally, at the MATLAB command prompt we type and execute the command

```
matrix_det_inv01
```

After execution of the simulation command in Figure 16.7, the model appears as shown in Figure 16.8.

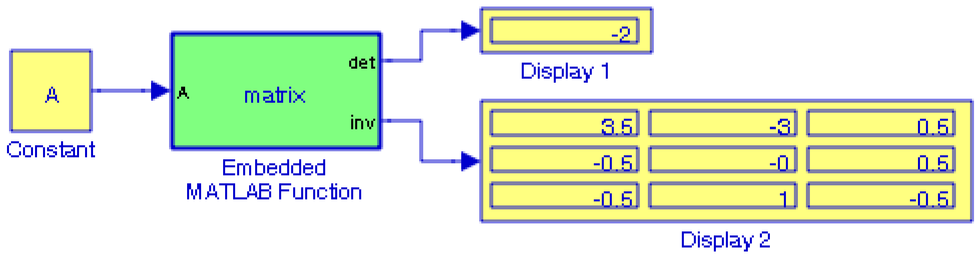
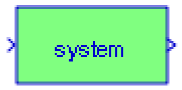


Figure 16.8. The model for Example 16.3 in its final form

The functions det(A) and inv(A) are defined in MATLAB but are not included in the **Embedded MATLAB Run–Time Function Library** List. This list includes common functions as sqrt, sin, cos, and others. Thus, had we issued the simulation command in the model in Figure 16.7 without first defining the function [det, inv] = matrix(A), Simulink would have issued the following warnings:

```
Output det must be assigned before returning from the function
Output inv must be assigned before returning from the function
```

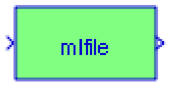
16.4 The S–Function Block



S-Function

The **S–Function** block provides access to S–functions. An S–function can be a Level–1 M–file or a Level–1 or Level–2 C MEX–file S–function. We should use the M–File **S–Function** block to include a Level–2 M–file S–function in a block diagram. This block is described in Section 11.18, Chapter 11.

16.5 The Level–2 M–file S–Function Block



Level-2 M-file S-Function

We introduced the S–Function blocks in Section 11.18, Chapter 11. We will now describe some additional blocks.

A Level–2 M–file S–function is an M–file that defines the properties and behavior of an instance of a Level–2 M–File S–Function block that references the M–file in a Simulink model.

The **Level–2 M–file S–Function** block allows us to use a Level–2 M–file S–function in a model. We do this by creating an instance of this block in the model. Then, we enter the name of the Level–2 M–File S–function in the M–file name field of the block's parameter dialog box.

For a Level–1 M–file S–function we use the S–Function block.

To become familiar with this block, let us review the demos as we did in Section 11.17, Chapter 11. At the MATLAB command prompt we type:

```
sfundemos
```

and MATLAB displays the S–Function directory blocks shown in Figure 16.9. In this text we will be concerned with the M–file S–Functions only.

Next, we double–click the M–file S–Functions block of Figure 16.9 and MATLAB displays the Level–1 and Level–2 M–file S–Functions shown in Figure 16.10.

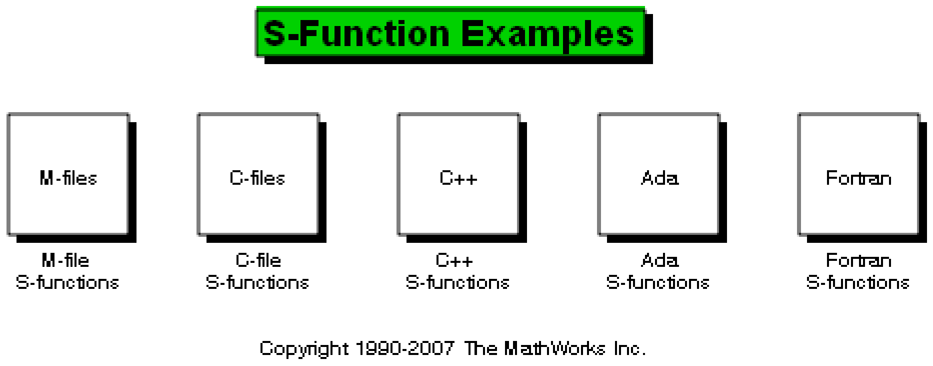
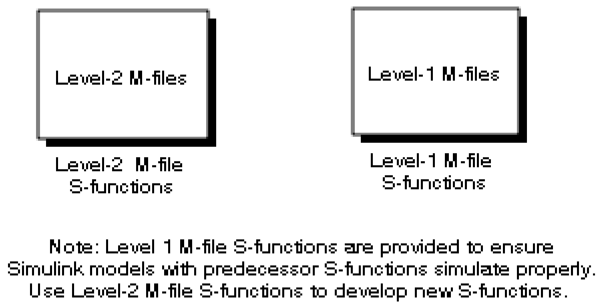


Figure 16.9. S–Function directory blocks



Note: Level 1 M-file S-functions are provided to ensure Simulink models with predecessor S-functions simulate properly. Use Level-2 M-file S-functions to develop new S-functions.

Figure 16.10. Levels of M–file S–Functions

The Level–1 M–file S–Functions are shown in Figure 16.11 and the Level–2 M–file S–Functions are shown in Figure 16.12. We observe that the first 5 models of the Level–2 M–file S–Functions and the same as those of the Level–1 M–file S–Functions but of course are implemented differently in each case.

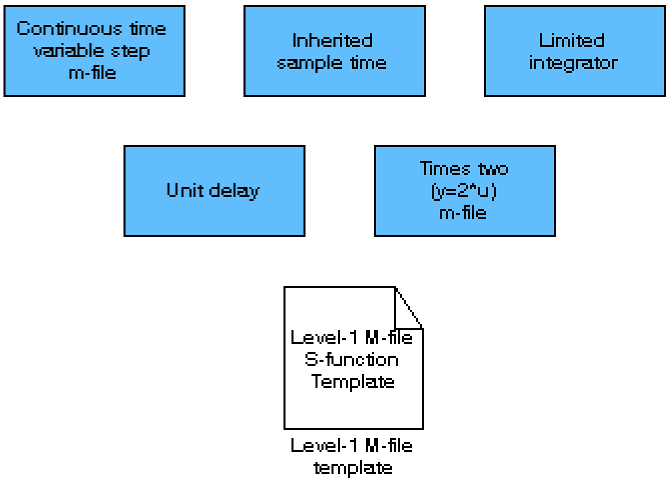


Figure 16.11. List of Level–1 M–file S–Functions

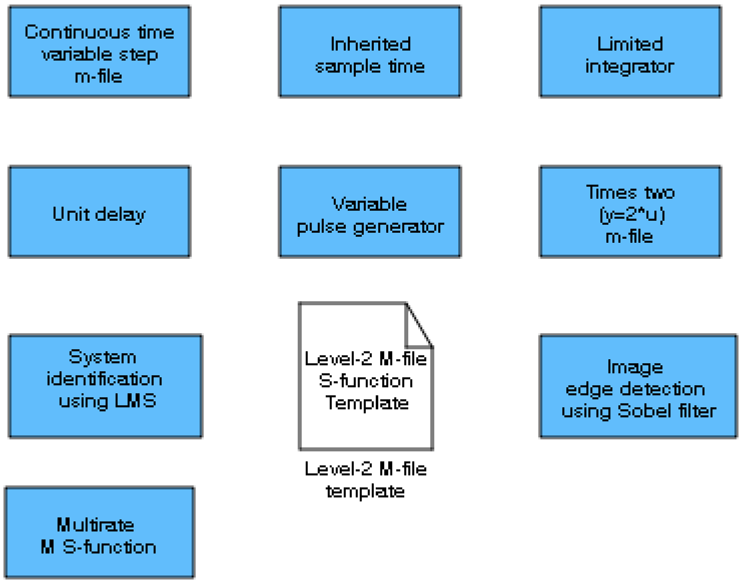


Figure 16.12. List of Level–2 M–file S–Functions

The Level–2 M–file S–function Application Programming Interface (API) allows us to use the MATLAB language to create custom blocks with multiple inputs and outputs and capable of handling any type of signal produced by a Simulink model, including matrix and frame signals of any data type. The Level–2 M–file S–Functions resemble those defined by the C MEX–file S–functions and consist of a set of callback methods that Simulink invokes when updating or simulating the model. The **callback methods** perform the actual work of initializing and computing the outputs of the block defined by the S–function. Thus, the Level–2 M–file S–function API specifies a set of callback methods that an M–file S–function must implement and others that it may choose to omit, depending on the requirements of the block that the S–function defines.

To create an Level–2 M–file S–function, we can begin by making a copy of the template that Simulink provides and edit the copy as necessary to reflect the desired behavior of the S–function you are creating. The comments in the template explain how it is done. To access this template, we double–click the Level–2 M–file template block shown in Figure 16.11.

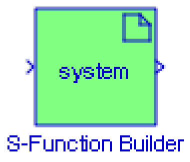
To access the Level–1 M–file S–function template, we double–click the Level–1 M–file template block shown in Figure 16.10.

Table 16.1 lists the Level–2 M–file S–function callback methods and their C MEX–file equivalents.

TABLE 16.1 Level–2 M–file S–Function and corresponding C MEX–file callback methods

Level–2 M–file callback method	C MEX–file callback method
setup method (see Setup Method)	mdlInitializeSizes
CheckParameters	mdlCheckParameters
Derivatives	mdlDerivatives
Disable	mdlDisable
Enable	mdlEnable
InitializeCondition	mdlInitializeConditions
Outputs	mdlOutputs
ProcessParameters	mdlProcessParameters
SetInputPortComplexSignal	mdlSetInputPortComplexSignal
SetInputPortDataType	mdlSetInputPortDataType
SetInputPortDimensions	mdlSetInputPortDimensionInfo
SetInputPortSampleTime	mdlSetInputPortSampleTime
SetInputPortSamplingMode	mdlSetInputPortFrameData
SetOutputPortComplexSignal	mdlSetOutputPortComplexSignal
SetOutputPortDataType	mdlSetOutputPortDataType
SetOutputPortDimensions	mdlSetOutputPortDimensionInfo
SetOutputPortSampleTime	mdlSetOutputPortSampleTime
Start	mdlStart
Update	mdlUpdate
WriteRTW	mdlRTW
ZeroCrossings	mdlZeroCrossings

16.6 The S–Function Builder Block



The **S–Function Builder** block creates a C MEX–file S–function from specifications and C source code that we provide. As stated earlier, we will not discuss C MEX–files in this text. To view some examples we type

```
sfundemos
```

at the MATLAB Command window, and we choose the appropriate block from those shown in Figure 16.13 below.

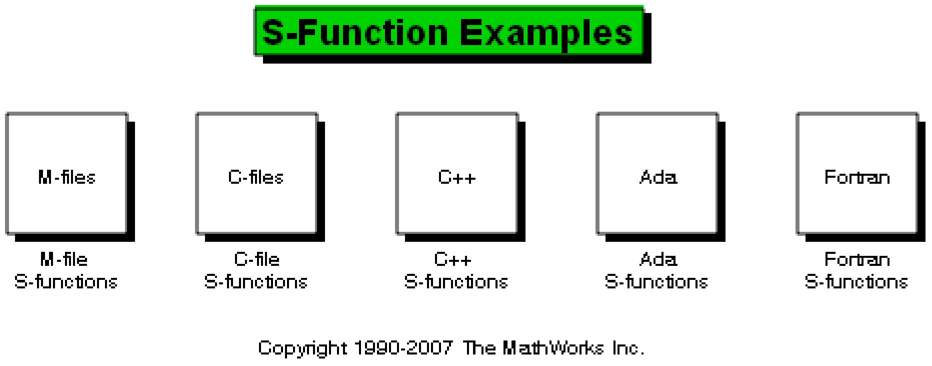
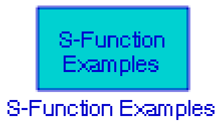


Figure 16.13. Examples of S–Functions

16.7 The S–Function Examples Block



The **S–Function Examples** block displays M–file S–Function, C–file S–Function, C++ S–Function, Ada S–Function, and Fortran S–Function examples shown in Figure 16.13 above.

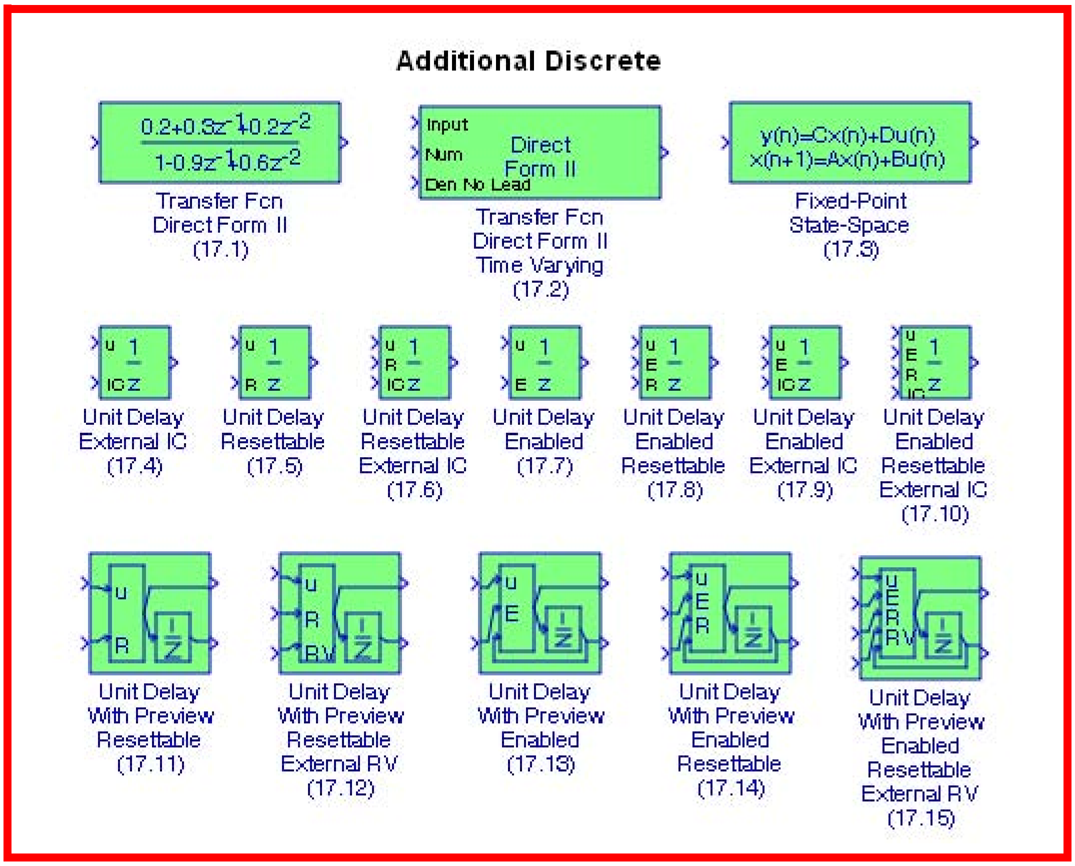
16.8 Summary

- The **Fcn** block applies a specified expression to its input denoted as u.
- The **MATLAB Fcn** block applies the specified MATLAB function or expression to the input.
- The **Embedded MATLAB Function** block contains a MATLAB language function in a Simulink model. This block accepts multiple input signals and produces multiple output signals.
- The **S–Function** block provides access to S–functions. The S–function named as the S–function name parameter can be a Level–1 M–file or a Level–1 or Level–2 C MEX–file S–function.
- The **Level–2 M–file S–Function** block allows us to use a Level–2 M–file S–function in a model.
- The **S–Function Builder** block creates a C MEX–file S–function from specifications and C source code that we provide.
- The **S–Function Examples** block displays M–file S–Function, C–file S–Function, C++ S–Function, Ada S–Function, and Fortran S–Function examples.

Chapter 17

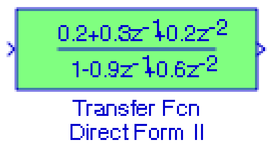
The Additional Discrete Library

This chapter is an introduction to the **Additional Discrete** Library**.** This is the sixteenth library in the Simulink group of libraries and contains the blocks shown below. Their functions are illustrated with examples.



Additional Discrete
0.2+0.3z-1+0.2z-2 / 1-0.9z-1+0.6z-2
Transfer Fcn Direct Form II (17.1)
Input
Num
Den No Lead
Direct Form II
Transfer Fcn Direct Form II Time Varying (17.2)
y(n)=Cx(n)+Du(n)
x(n+1)=Ax(n)+Bu(n)
Fixed-Point State-Space (17.3)
Unit Delay External IC (17.4)
Unit Delay Resettable (17.5)
Unit Delay Resettable External IC (17.6)
Unit Delay Enabled (17.7)
Unit Delay Enabled Resettable (17.8)
Unit Delay Enabled External IC (17.9)
Unit Delay Enabled Resettable External IC (17.10)
Unit Delay With Preview Resettable (17.11)
Unit Delay With Preview Resettable External RV (17.12)
Unit Delay With Preview Enabled (17.13)
Unit Delay With Preview Enabled Resettable (17.14)
Unit Delay With Preview Enabled Resettable External RV (17.15)

17.1 The Transfer Fcn Direct Form II Block



The **Transfer Fcn Direct Form II** block implements a Direct Form II realization of the transfer function specified by the Numerator coefficients and the Denominator coefficients without the leading[*] coefficient in the Denominator.

Example 17.1

The model in Figure 17.1 implements the discrete–time function

$$H(z) = \frac{0.5276 - 1.5828z^{-1} + 1.5828z^{-2}}{1 - 1.7600z^{-1} + 1.1829z^{-2}} \tag{17.1}$$

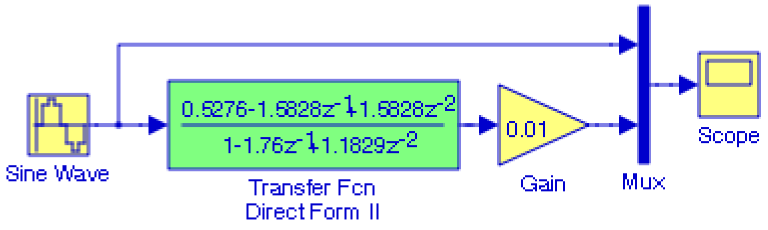


Figure 17.1. Model for Example 17.1

In Figure 17.1, the Sample time for the **Sine Wave** block is specified as 0.1. The $num(z)$ for the **Transfer Fcn Direct Form II** block is specified as $[0.5276 \ \ -1.5828 \ \ 1.5828]$, and the $den(z)$ is specified as $[-1.7600 \ \ 1.1829]$. The leading coefficient 1 in the denominator is excluded. The input and output waveforms are shown in Figure 17.2.

* *By lead we mean that the leading coefficient 1 in the denominator which has the form* $1 + z^{-1} + z^{-2}$.

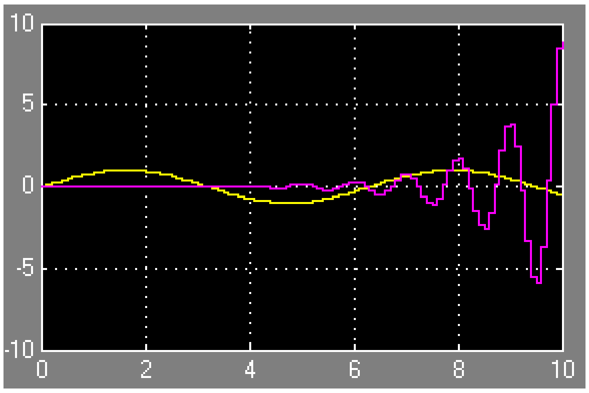
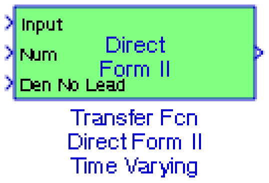


Figure 17.2. Input and output waveforms for the model in Figure 17.1

17.2 The Transfer Fcn Direct Form II Time Varying Block



The **Transfer Fcn Direct Form II Time Varying** block implements a Direct Form II realization of a specified transfer function. Essentially, this block performs the same function as that of the Transfer Fcn Direct Form II block which is described in the previous section, except that the numerator and denominator coefficients of the discrete–time transfer function are specified externally by the inputs Num and Den.

Example 17.2

The model of Figure 17.3 is essentially the same as that of Figure 17.1 and thus the input and output waveforms of Figure 17.4 are the same as those in Figure 17.2.

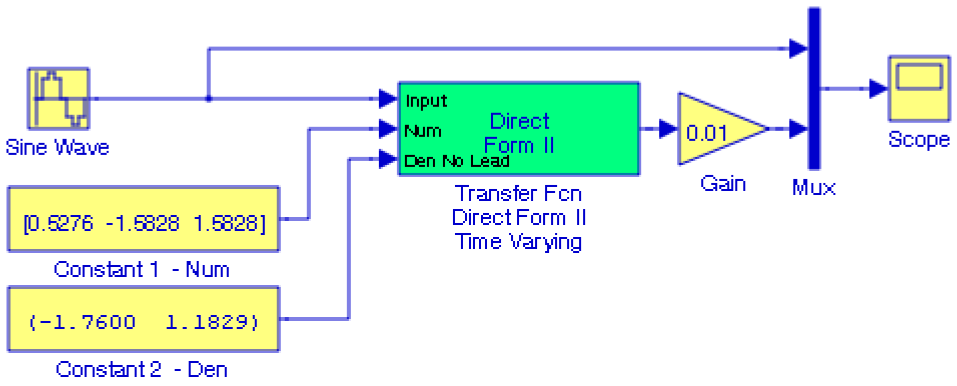


Figure 17.3. Model for Example 17.2

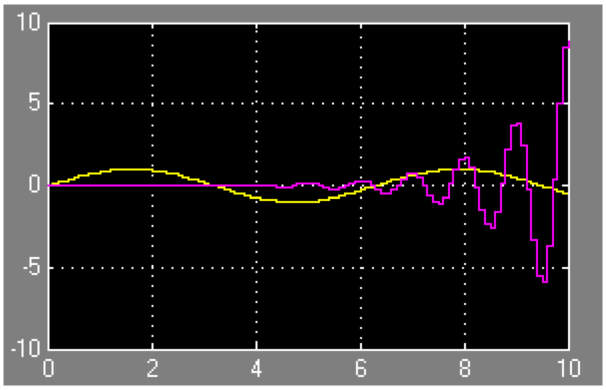
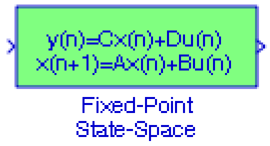


Figure 17.4. Input and output waveforms for the model in Figure 17.3

17.3 The Fixed–Point State–Space Block



The **Fixed–Point State–Space** block implements the system described by

$$\begin{aligned} x[n+1] &= Ax[n]+Bu[n] \\ y[n] &= Cx[n]+Du[n] \end{aligned} \tag{17.2}$$

where:

A is a matrix with dimensions $n \times n$, n = number of states, B is a matrix with dimensions $n \times m$, m = number of inputs, C is a matrix with dimensions $r \times n$, r = number of outputs, D

is a matrix with dimensions $r \times m$, x = state, an $n \times 1$ vector, u = input, an $m \times 1$ vector, and y = output, an $r \times 1$ vector.

Example 17.3

The matrix form of a 3–input 2–output 3–state discrete–time system is specified as

$$\begin{bmatrix} x_1[n+1] \\ x_2[n+1] \\ x_3[n+1] \end{bmatrix} = \underbrace{\begin{bmatrix} 0.25 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & -0.25 & -0.75 \end{bmatrix}}_{\mathbf{A}} \cdot \begin{bmatrix} x_1[n] \\ x_2[n] \\ x_3[n] \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix}}_{\mathbf{B}} \cdot \begin{bmatrix} u_1[n] \\ u_2[n] \\ u_3[n] \end{bmatrix}$$

$$\begin{bmatrix} y_1[n] \\ y_2[n] \end{bmatrix} = \underbrace{\begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}}_{\mathbf{C}} \cdot \begin{bmatrix} x_1[n] \\ x_2[n] \\ x_3[n] \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\mathbf{D}} \cdot \begin{bmatrix} u_1[n] \\ u_2[n] \\ u_3[n] \end{bmatrix} \tag{17.3}$$

In the model of Figure 17.5 we enter the values of matrices A, B, C, and D in the **Fixed–Point State–Space** block parameters dialog box, and we specify initial condition 0. The values for the input vector $[u_1[n], u_2[n], u_3[n]]$ are as shown in the **Constant** block, and after the simulation command is issued, the input and output waveforms are as shown in Figure 17.6.

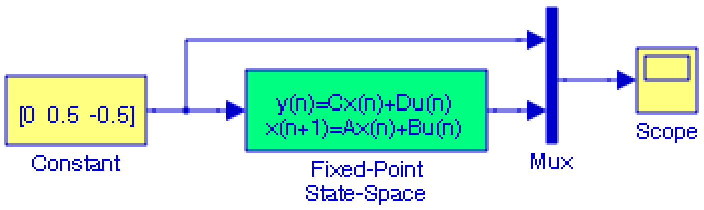


Figure 17.5. Model for Example 17.3

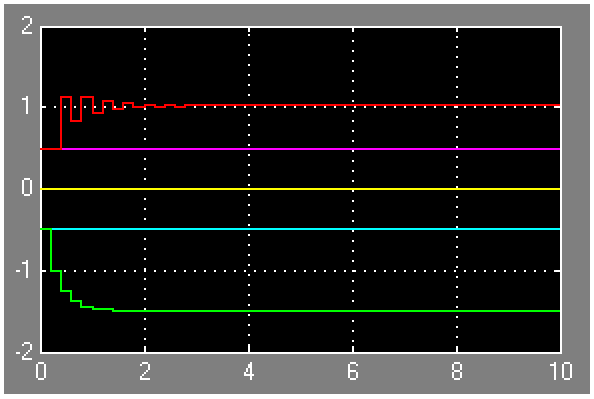
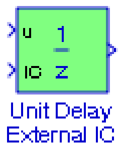


Figure 17.6. Input and output waveforms for the model in Figure 17.5

17.4 The Unit Delay External IC Block



The **Unit Delay External IC** (Initial Condition) block delays its input by one sample period. This block is equivalent to the z^{-1} discrete–time operator. The block accepts one input and generates one output, both of which can be scalar or vector. If the input is a vector, all elements of the vector are delayed by the same sample period. The block's output for the first sample period is equal to the signal IC. The input u and initial condition IC data types must be the same.

Example 17.4

In the model of Figure 17.7, the **Pulse Generator** block is specified for a period 2 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.8.

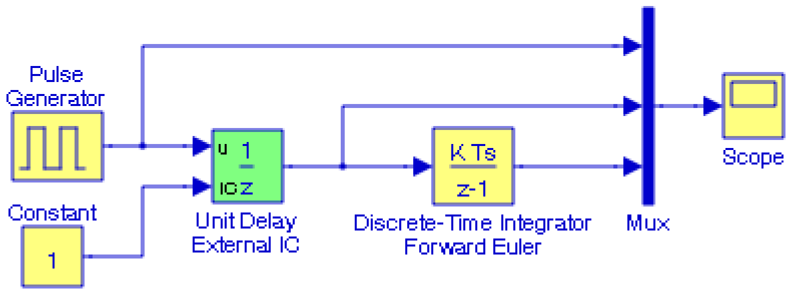


Figure 17.7. Model for Example 17.4

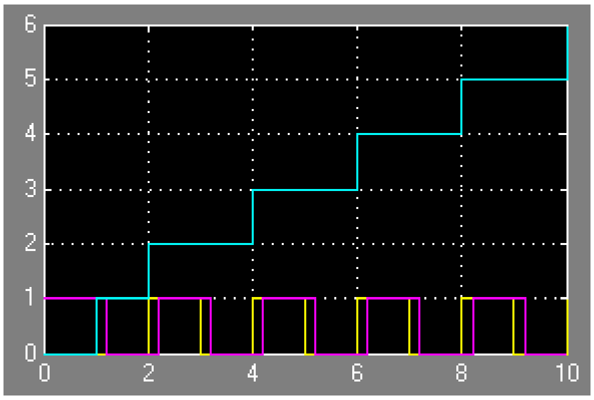
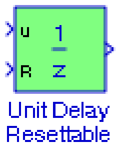


Figure 17.8. Input and output waveforms for the model in Figure 17.7

17.5 The Unit Delay Resettable Block



The **Unit Delay Resettable** block delays a signal one sample period. If the reset input signal is false, the block outputs the input signal delayed by one time step. If the reset signal is true, the block resets the current state to the initial condition, specified by the Initial condition parameter, and outputs that state delayed by one time step.

Example 17.5

In the model of Figure 17.9, the **Pulse Generator 1** block is specified for a period 2 sec. and the **Pulse Generator 2** block is set for a period 4 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.10.

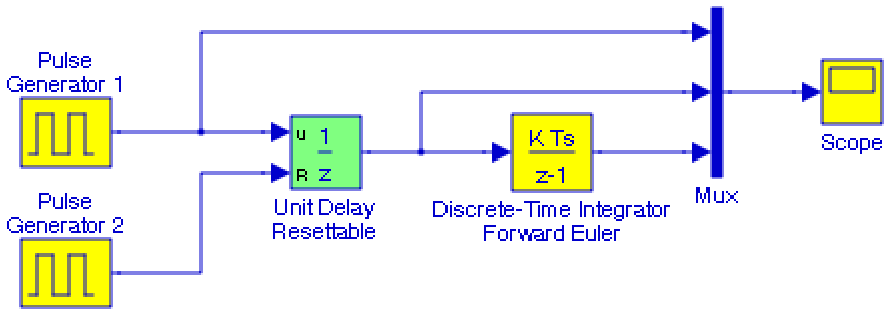


Figure 17.9. Model for Example 17.5

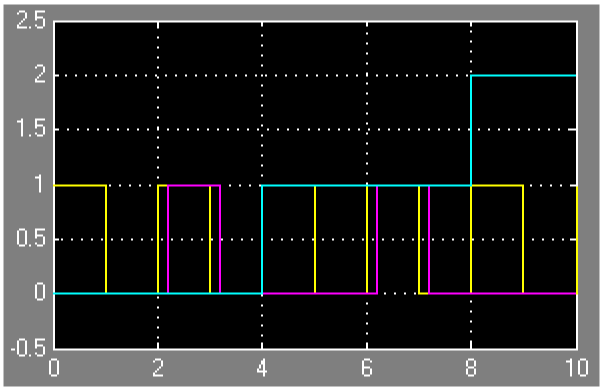
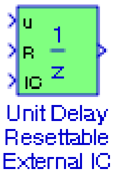


Figure 17.10. Input and output waveforms for the model in Figure 17.9

17.6 The Unit Delay Resettable External IC Block



The **Unit Delay Resettable External IC** block delays a signal one sample period. The block can be reset by the external reset signal R. The block has two input ports, one for the input signal u and the other for the reset signal R. When the reset signal is false, the block outputs the input signal delayed by one time step. When the reset signal is true, the block resets the current state to the initial condition given by the signal IC and outputs that state delayed by one time step.

Example 17.6

In the model of Figure 17.11, the **Pulse Generator 1** block is set for a period 2 sec. and the Pulse **Generator 2** block is set for a period 4 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.12.

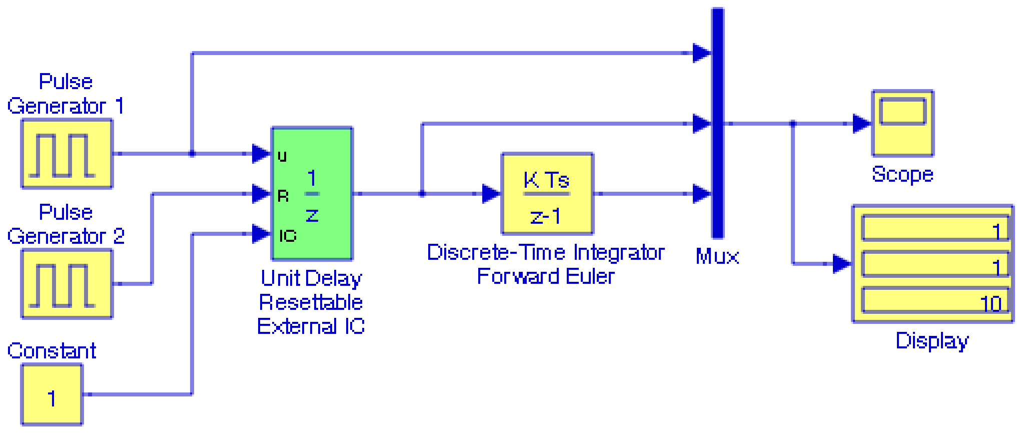


Figure 17.11. Model for Example 17.6

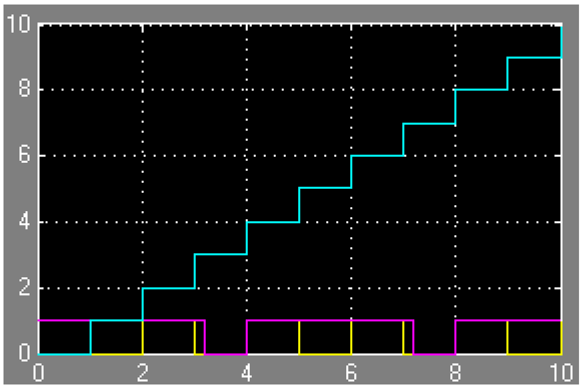
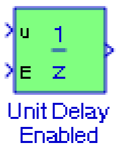


Figure 17.12. Input and output waveforms for the model in Figure 17.11

17.7 The Unit Delay Enabled Block



The **Unit Delay Enabled** block delays a signal by one sample period when the external enable signal E is on. When the enable signal E is off, the block is disabled. The block holds the current state at the same value and outputs that value. The enable signal is on when E is not 0, and is off when E is 0.

Example 17.7

Figure 17.13 contains two models where in the upper model the **Unit Delay Enabled 1** block is disabled and thus its output is zero. In the lower model the **Unit Delay Enabled 2** block is enabled and causes a delay in the input signal before being propagated to the **Discrete Time Integrator Forward Euler 2** block. The inputs and outputs are shown in Figure 17.14.

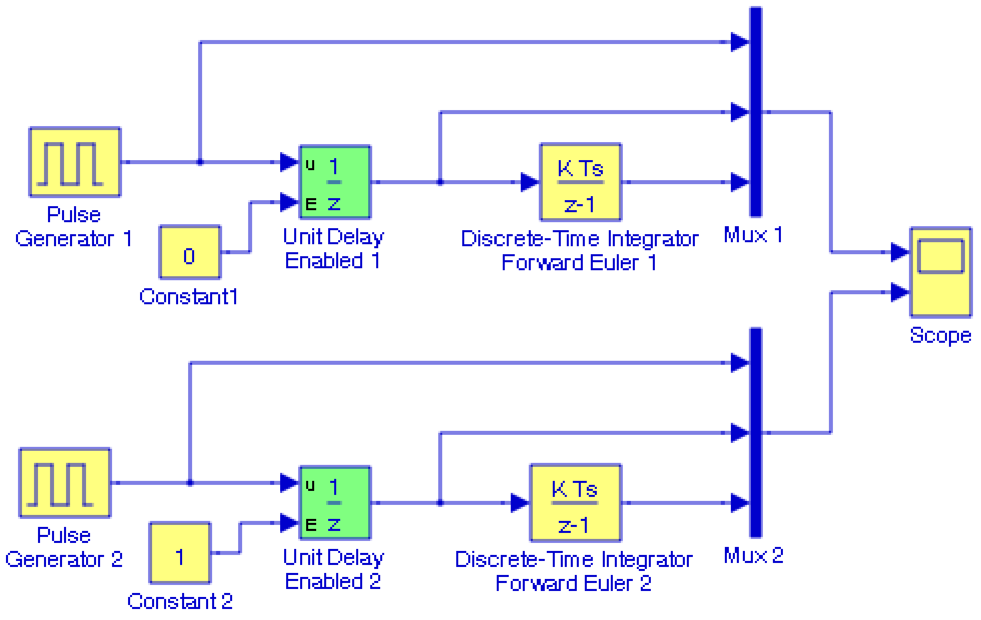


Figure 17.13. Models for Example 17.7

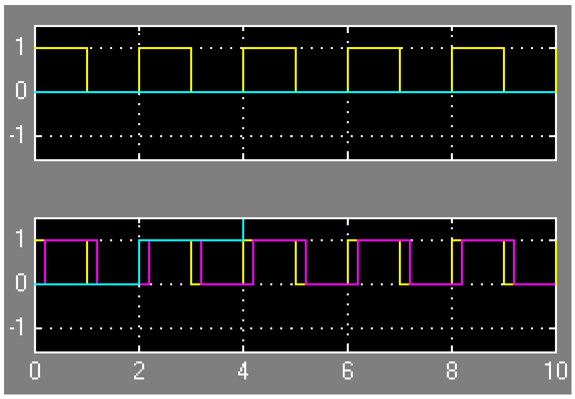
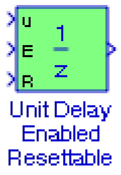


Figure 17.14. Input and Output waveforms for the models in Figure 17.13

17.8 The Unit Delay Enabled Resettable Block



The **Unit Delay Enabled Resettable** block delays a signal one sample period, if the external enable signal is on. This block combines the features of the Unit Delay Enabled and Unit Delay Resettable blocks. When the enable signal E is on and the reset signal R is false, the block outputs the input signal delayed by one sample period. When the enable signal E is on and the reset signal R is true, the block resets the current state to the initial condition, specified by the Initial condition parameter, and outputs that state delayed by one sample period. When the enable signal is off, the block is disabled, and the state and output do not change except for resets. The enable signal is on when E is not 0, and off when E is 0.

Example 17.8

In the model of Figure 17.15, the **Pulse Generator 1** block is specified for a period 2 sec., the **Pulse Generator 2** block is specified for a period 3 sec., and the **Pulse Generator 3** block is specified for a period 4 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.16. The **Display** block shows the value of the output of the **Discrete–Time Integrator** block at the end of the simulation time (20 sec).

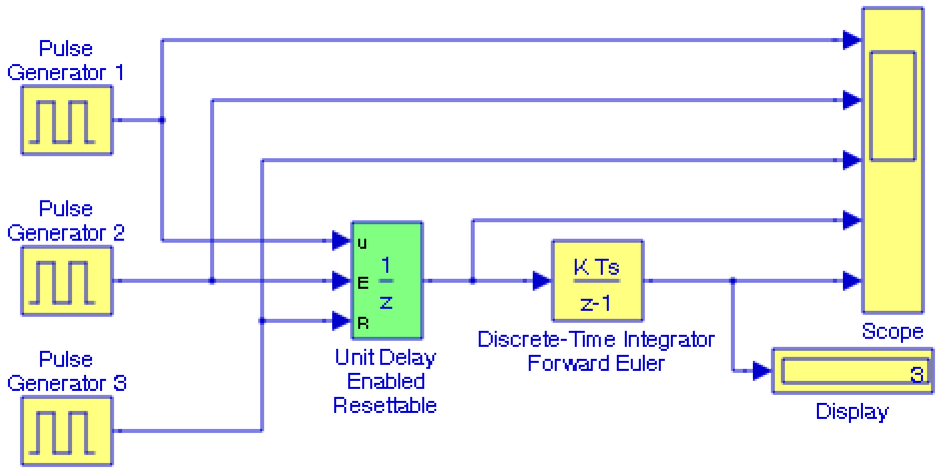


Figure 17.15. Model for Example 17.8

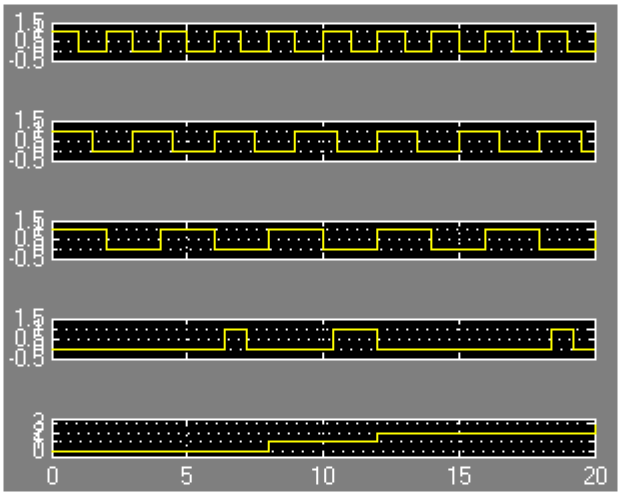
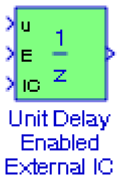


Figure 17.16. Input and output waveforms for the model in Figure 17.15

17.9 The Unit Delay Enabled External IC Block



The **Unit Delay Enabled External IC** block delays a signal by one sample period when the enable signal E is on. When the enable is off, the block holds the current state at the same value and outputs that value. The enable E is on when E is not 0, and off when E is 0. The initial condition of this block is specified by the input signal IC. Essentially, this block is the same as the **Unit Delay Enabled** block which we described in the previous section of this chapter except that the initial condition is specified by an external block.

Example 17.9

In the model of Figure 17.17, the **Constant 1** block enables the **Unit Delay Enabled External IC** block while the **Constant 2** block is set to 1 to specify the initial condition. The input and output waveforms are shown in Figure 17.18.

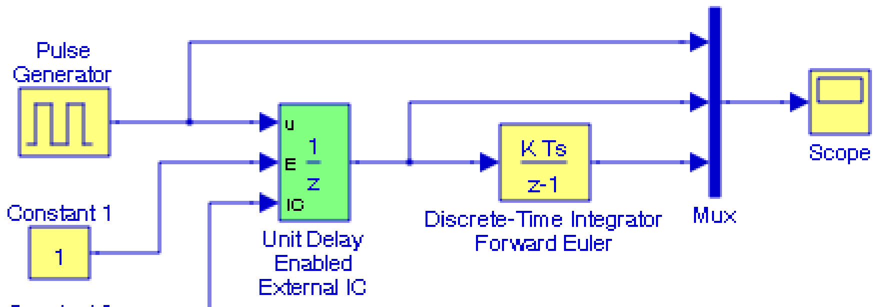

Pulse Generator
Constant 1
1
Constant 2
1
u
E
IC
1/z
Unit Delay Enabled External IC
K Ts / z-1
Discrete-Time Integrator Forward Euler
Mux
Scope

Figure 17.17. Model for Example 17.9

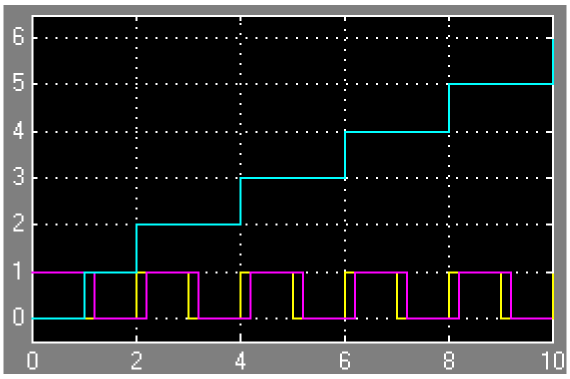
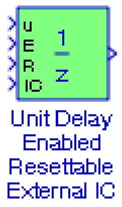


Figure 17.18. Input and output waveforms for the model in Figure 17.17

17.10 The Unit Delay Enabled Resettable External IC Block



The **Unit Delay Enabled Resettable External IC** block is a combination of the functions performed by the **Unit Delay Enabled**, **Unit Delay External IC**, and **Unit Delay Resettable** blocks. The block can reset its state based on an external reset signal R. When the enable signal E is on and the reset signal R is false, the block outputs the input signal delayed by one sample period. When the enable signal E is on and the reset signal R is true, the block resets the current state to the initial condition given by the signal IC, and outputs that state delayed by one sample period. When the enable signal is off, the block is disabled, and the state and output do not change except for resets. The enable signal is on when E is not 0, and off when E is 0.

Example 17.10

In the model of Figure 17.19, the **Pulse Generator 1** block is specified for a period 2 sec., the **Pulse Generator 2** block is specified for a period 3 sec., and the **Pulse Generator 3** block is specified for a period 4 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.20. The **Display** block shows the value of the output of the **Discrete–Time Integrator** block at the end of the simulation time (10 sec).

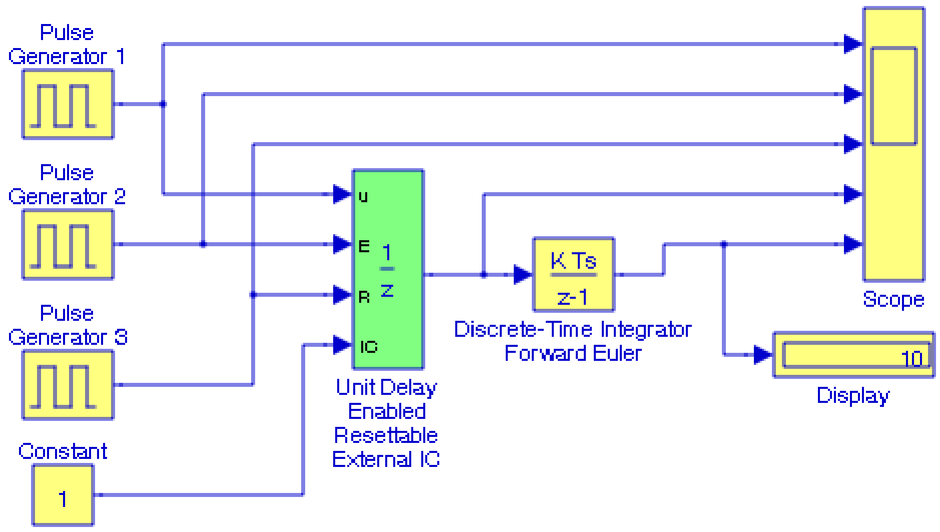


Figure 17.19. Model for Example 17.10

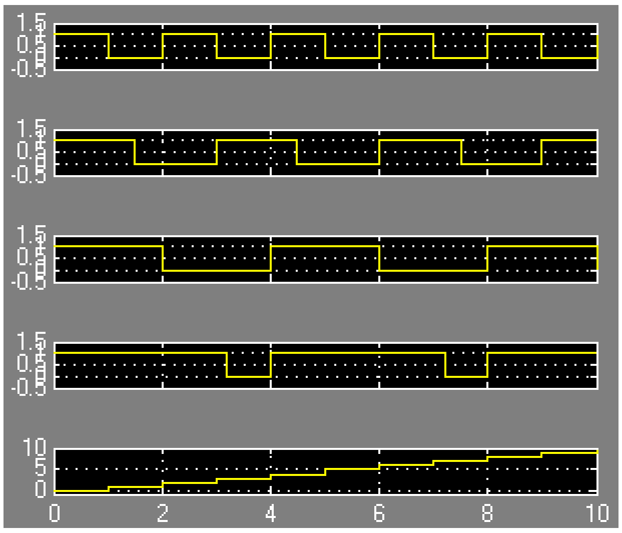
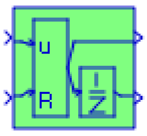


Figure 17.20. Input and output waveforms for the model in Figure 17.19

17.11 The Unit Delay With Preview Resettable Block



Unit Delay
With Preview
Resettable

The **Unit Delay With Preview Resettable** block can reset its state based on an external reset signal R. The block has two output ports. When the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the reset R is true, the block resets the current state to the initial condition given by the Initial condition parameter. The block outputs that state delayed by one sample time through the lower output port, and outputs the state without a delay through the upper output port.

Example 17.11

In the model of Figure 17.21, the **Pulse Generator 1** block is specified for a period 2 sec. and the **Pulse Generator 2** block is specified for a period 4 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.22.

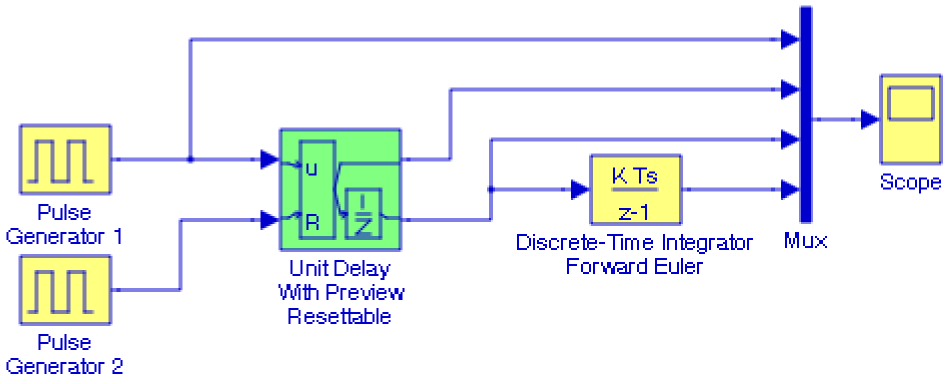

Pulse Generator 1
Pulse Generator 2
u
R
1/z
Unit Delay With Preview Resettable
K Ts
z-1
Discrete-Time Integrator Forward Euler
Mux
Scope

Figure 17.21. Model for Example 17.11

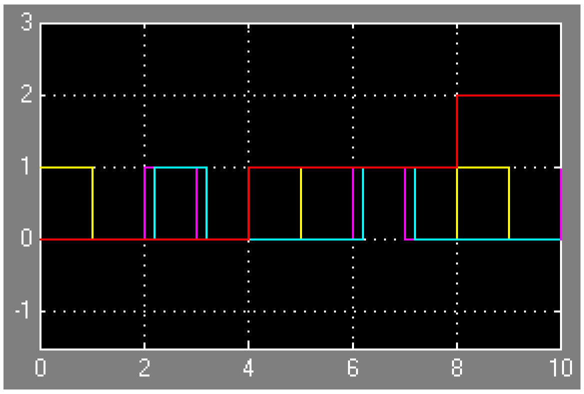
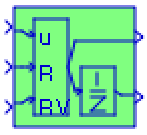


Figure 17.22. Waveforms for the model in Figure 17.21

17.12 The Unit Delay With Preview Resettable External RV Block



The **Unit Delay With Preview Resettable External RV** block has three input and two output ports. This block can reset its state based on the state of the an external input reset signal R. When the external reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the external reset R is true, the upper output signal is forced to equal the external input reset signal RV. The lower output signal is not affected until one time step later, at which time it is equal to the external reset signal RV at the previous time step. The block uses the internal Initial condition only when the model starts or when a parent enabled subsystem is used. The internal Initial condition only affects the lower output signal.

Example 17.12

In the model of Figure 17.23, the **Pulse Generator** 1, 2, and 3 blocks are specified for the periods shown on the model. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.24.

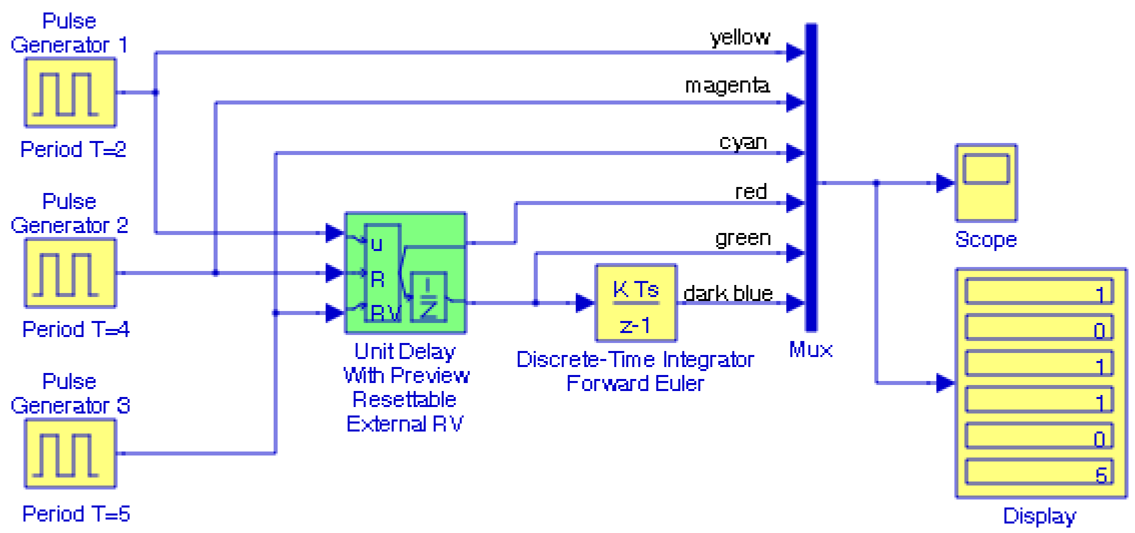


Figure 17.23. Model for Example 17.12

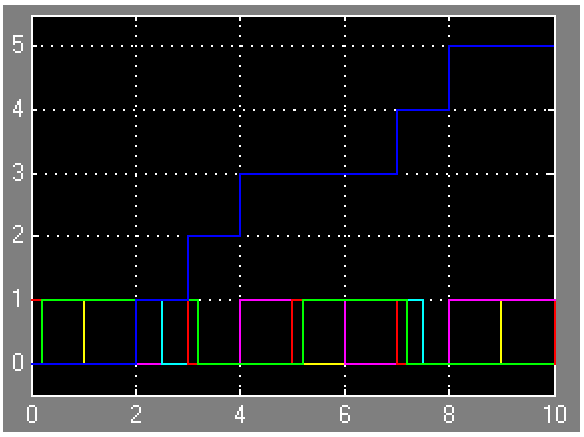
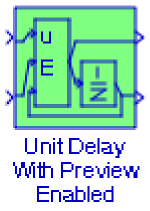


Figure 17.24. Waveforms for the model in Figure 17.23

17.13 The Unit Delay With Preview Enabled Block



The **Unit Delay With Preview Enabled** block has two input and two output ports. When the external input enable signal E is on, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the enable signal E is off, the block is disabled, and the state and output values do not change. The enable signal is on when E is not 0, and off when E is 0.

Example 17.13

In the model of Figure 17.25, the **Pulse Generator** block is set for a period 2 sec. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.26.

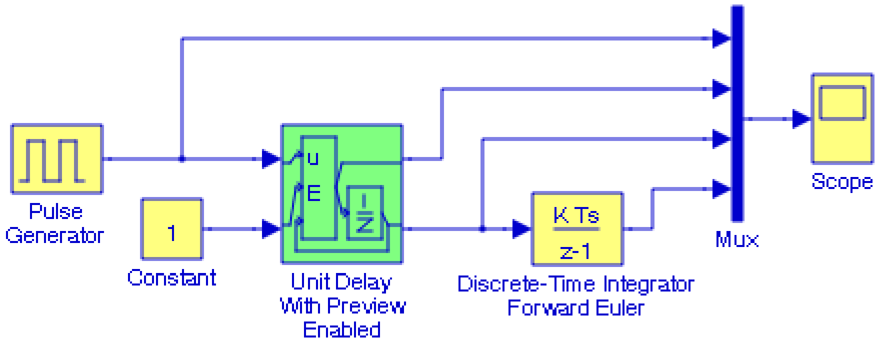

Pulse Generator
1
Constant
u
E
1/z
Unit Delay With Preview Enabled
K Ts / z-1
Discrete-Time Integrator Forward Euler
Mux
Scope

Figure 17.25. Model for Example 17.13

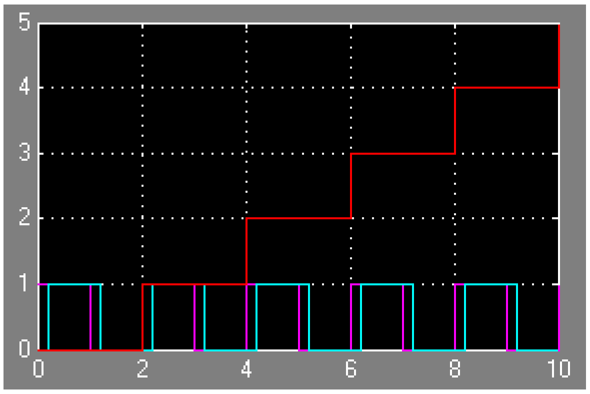


Figure 17.26. Waveforms for the model in Figure 17.25

17.14 The Unit Delay With Preview Enabled Resettable Block

U
E
R
1/z
Unit Delay With Preview Enabled Resettable

The **Unit Delay With Preview Enabled Resettable** block has three inputs and two outputs. This block can reset its state based on an external input reset signal R. When the external enable signal E is on and the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the enable input signal E is on and the reset R is true, the block resets the current state to the initial condition given by the Initial condition parameter. The block outputs that state delayed by one sample time through the lower output port, and outputs the state without a delay through the upper output port. When the Enable signal is off, the block is disabled, and the state and output values do not change, except for resets. The enable signal is on when E is not 0, and off when E is 0.

Example 17.14

In the model of Figure 17.27, the **Pulse Generator** 1, 2, and 3 blocks are specified for the period shown on the model. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.28.

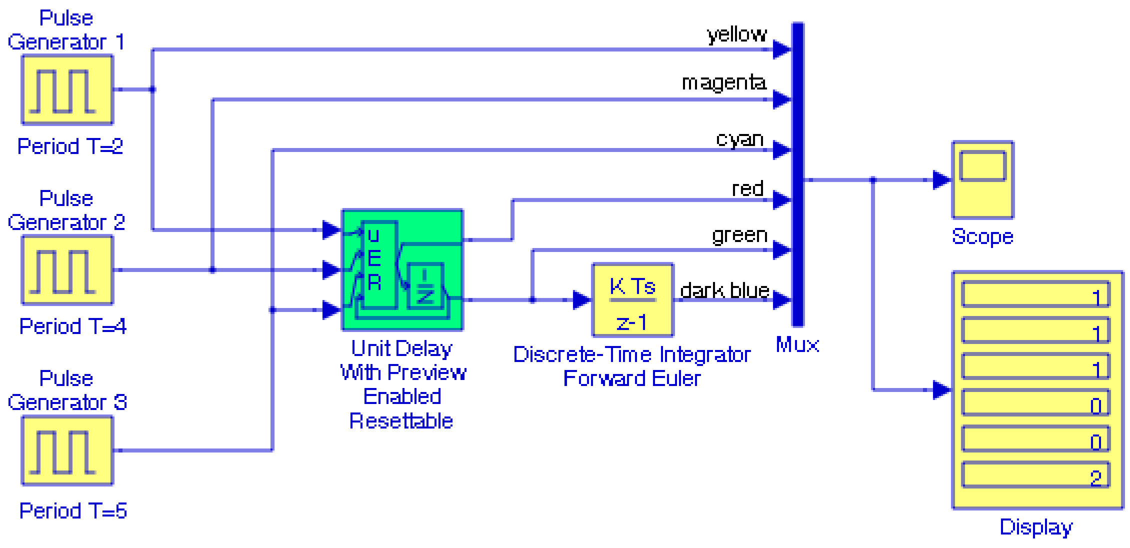


Figure 17.27. Model for Example 17.14

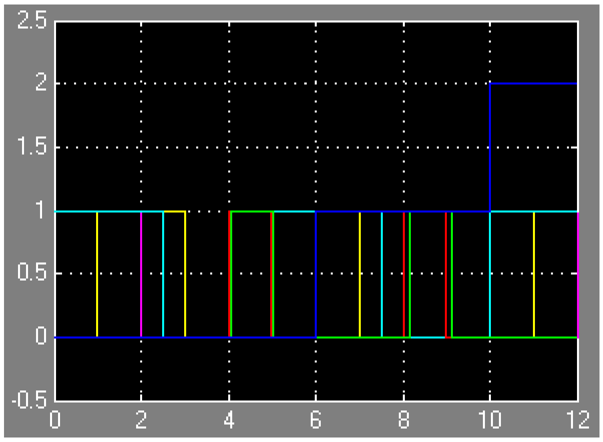
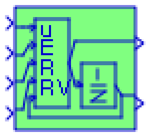


Figure 17.28. Waveforms for the model in Figure 17.27

17.15 The Unit Delay With Preview Enabled Resettable External RV Block



Unit Delay
With Preview
Enabled
Resettable
External RV

The **Unit Delay With Preview Enabled Resettable External RV** block has four inputs and two outputs. This block can reset its state based on an external reset signal R. When the external enable signal E is on and the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period.

When the enable signal E is on and the reset R is true, the upper output signal is forced to equal the external input reset signal RV. The lower output signal is not affected until one time step later, at which time it is equal to the external reset signal RV at the previous time step. The block uses the internal Initial condition only when the model starts or when a parent enabled subsystem is used. The internal Initial condition only affects the lower output signal. When the Enable signal is off, the block is disabled, and the state and output values do not change, except for resets. The enable signal is on when E is not 0, and off when E is 0.

Example 17.15

In the model of Figure 17.29, the **Pulse Generator** 1, 2, and 3 blocks are set for the periods shown in the model. All other parameters are in their default state. The input and output waveforms are shown in Figure 17.30. The **Display** block shows the output values at the end of the simulation time (12 sec).

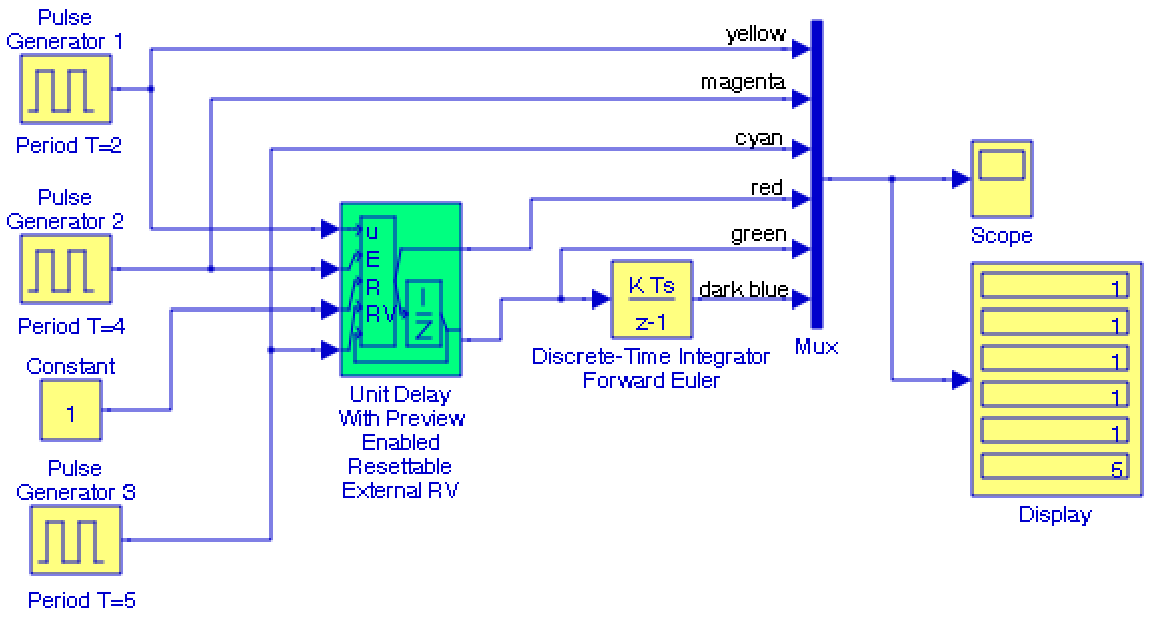


Figure 17.29. Model for Example 17.15

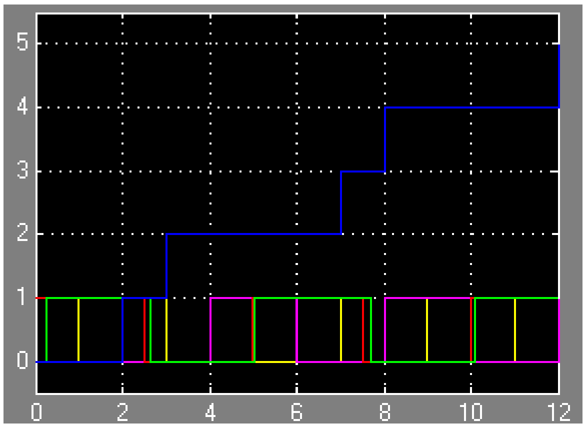


Figure 17.30. Waveforms for the model of Figure 17.29

17.16 Summary

- The **Transfer Fcn Direct Form II** block implements a Direct Form II realization of the transfer function specified by the Numerator coefficients and the Denominator coefficients without the leading coefficient in the Denominator.
- The **Transfer Fcn Direct Form II Time Varying** block implements a Direct Form II realization of a specified transfer function. Essentially, this block performs the same function as that of the Transfer Fcn Direct Form II block.
- The **Fixed–Point State–Space** block implements the system described by

$$\begin{aligned} x[n+1] &= Ax[n]+Bu[n] \\ y[n] &= Cx[n]+Du[n] \end{aligned}$$

- The **Unit Delay External IC** (Initial Condition) block delays its input by one sample period. This block is equivalent to the z^{-1} discrete–time operator. The block accepts one input and generates one output, both of which can be scalar or vector. If the input is a vector, all elements of the vector are delayed by the same sample period. The block's output for the first sample period is equal to the signal IC. The input u and initial condition IC data types must be the same.
- The **Unit Delay Resettable** block delays a signal one sample period. If the reset input signal is false, the block outputs the input signal delayed by one time step. If the reset signal is true, the block resets the current state to the initial condition, specified by the Initial condition parameter, and outputs that state delayed by one time step.
- The **Unit Delay Resettable External IC** block delays a signal one sample period. The block can be reset by the external reset signal R. The block has two input ports, one for the input signal u and the other for the reset signal R. When the reset signal is false, the block outputs the input signal delayed by one time step. When the reset signal is true, the block resets the current state to the initial condition given by the signal IC and outputs that state delayed by one time step.
- The **Unit Delay Enabled** block delays a signal by one sample period when the external enable signal E is on. When the enable signal E is off, the block is disabled. The block holds the current state at the same value and outputs that value. The enable signal is on when E is not 0, and is off when E is 0.
- The **Unit Delay Enabled Resettable** block delays a signal one sample period, if the external enable signal is on. This block combines the features of the Unit Delay Enabled and Unit Delay Resettable blocks.
- The **Unit Delay Enabled External IC** block delays a signal by one sample period when the enable signal E is on. When the enable is off, the block holds the current state at the same

value and outputs that value. The enable E is on when E is not 0, and off when E is 0. The initial condition of this block is specified by the input signal IC.

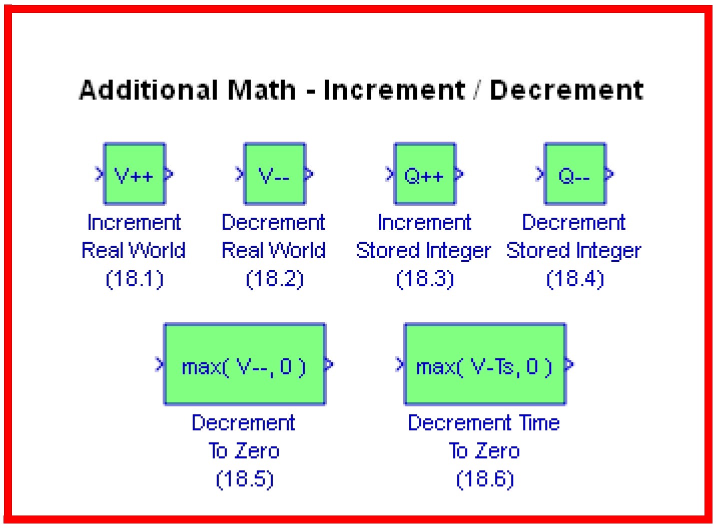
- The **Unit Delay Enabled Resettable External IC** block is a combination of the functions performed by the Unit Delay Enabled, Unit Delay External IC, and Unit Delay Resettable blocks.
- The **Unit Delay With Preview Resettable** block has two input and two output ports. This block can reset its state based on the state of the external input reset signal R. When the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the reset R is true, the block resets the current state to the initial condition given by the Initial condition parameter. The block outputs that state delayed by one sample time through the lower output port, and outputs the state without a delay through the upper output port.
- The **Unit Delay With Preview Resettable External RV** block has three input and two output ports. This block can reset its state based on the state of the an external input reset signal R. When the external reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the external reset R is true, the upper output signal is forced to equal the external input reset signal RV. The lower output signal is not affected until one time step later, at which time it is equal to the external reset signal RV at the previous time step. The block uses the internal Initial condition only when the model starts or when a parent enabled subsystem is used. The internal Initial condition only affects the lower output signal.
- The **Unit Delay With Preview Enabled** block has two input and two output ports. When the external input enable signal E is on, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the enable signal E is off, the block is disabled, and the state and output values do not change. The enable signal is on when E is not 0, and off when E is 0.
- The **Unit Delay With Preview Enabled Resettable** block has three inputs and two outputs. This block can reset its state based on an external input reset signal R. When the external enable signal E is on and the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the enable input signal E is on and the reset R is true, the block resets the current state to the initial condition given by the Initial condition parameter. The block outputs that state delayed by one sample time through the lower output port, and outputs the state without a delay through the upper output port. When the Enable signal is off, the block is disabled, and the state and output values do not change, except for resets. The enable signal is on when E is not 0, and off when E is 0.
- The **Unit Delay With Preview Enabled Resettable External RV** block has four inputs and two outputs. This block can reset its state based on an external reset signal R. When the external enable signal E is on and the reset R is false, the upper port outputs the signal and the lower port outputs the signal delayed by one sample period. When the enable signal E is on and the

reset R is true, the upper output signal is forced to equal the external input reset signal RV. The lower output signal is not affected until one time step later.

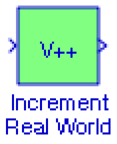
Chapter 18

The Additional Math – Increment / Decrement Library

This chapter is an introduction to the **Additional Math – Increment / Decrement** Library. This is the seventeenth library in the Simulink group of libraries and contains the blocks shown below. Their functions are illustrated with examples.


Additional Math - Increment / Decrement
V++
Increment Real World (18.1)
V--
Decrement Real World (18.2)
Q++
Increment Stored Integer (18.3)
Q--
Decrement Stored Integer (18.4)
max(V--, 0)
Decrement To Zero (18.5)
max(V-Ts, 0)
Decrement Time To Zero (18.6)

18.1 The Increment Real World Block



The **Increment Real World** block increases the real–world value of the signal by one.

Example 18.1

The model of Figure 18.1 implements the function $y = 3x + 5$ as indicated by the **XY Graph** in Figure 18.2.

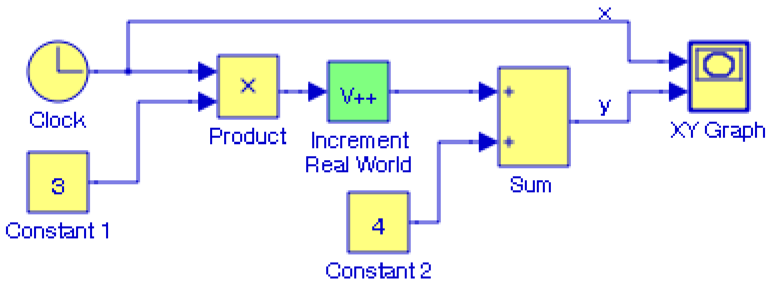


Figure 18.1. Model for Example 18.1

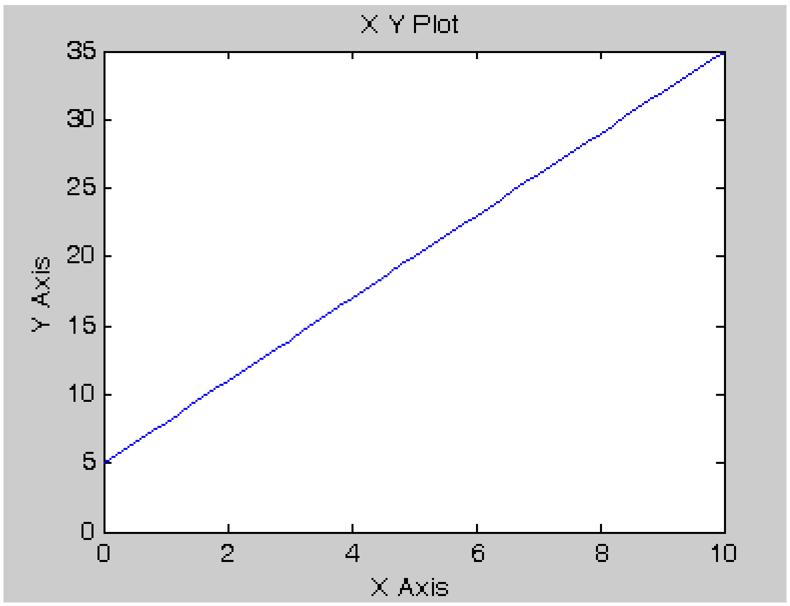
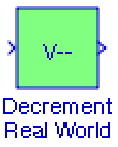


Figure 18.2. The XY graph for the model in Figure 18.1

18.2 The Decrement Real World Block



The **Decrement Real World** block decreases the real–world value of the signal by one.

Example 18.2

The model of Figure 18.3 implements the function $y = -3(x+1)$ as indicated by the **XY Graph** in Figure 18.4.

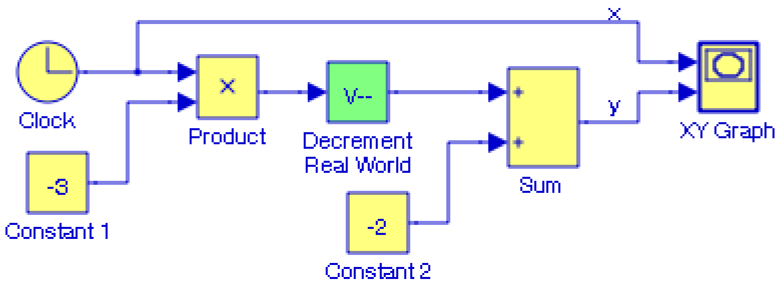


Figure 18.3. Model for Example 18.2

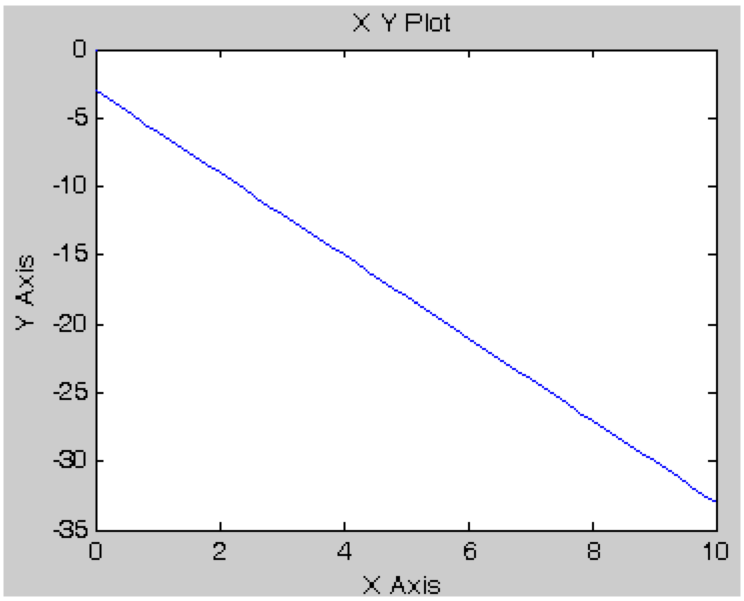
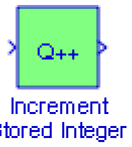


Figure 18.4. XY graph for the model in Figure 18.3

18.3 The Increment Stored Integer Block



The **Increment Stored Integer** block increases the stored integer value of a signal by one.

Example 18.3

The model of Figure 18.5 implements the function $y = (2+x)\sin x - 1$. The XY Graph for this model is shown in Figure 18.6.

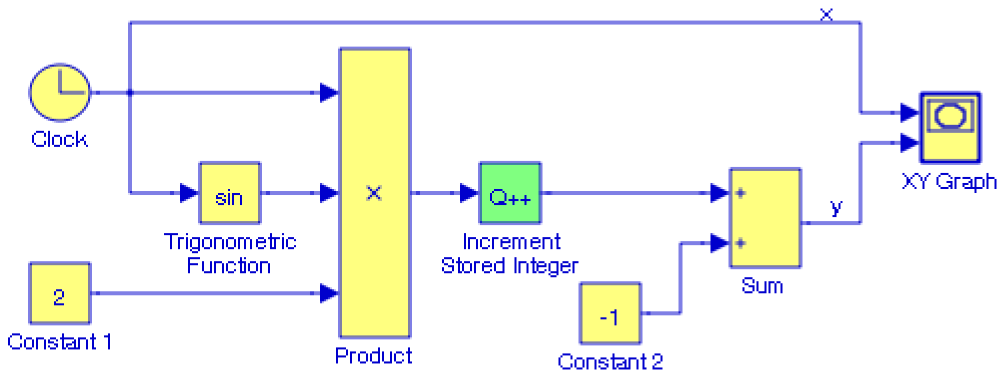


Figure 18.5. Model for Example 18.3

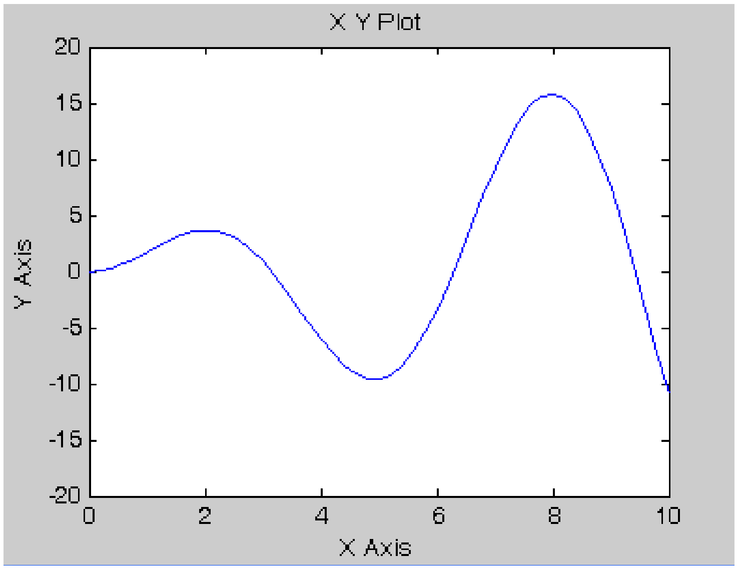
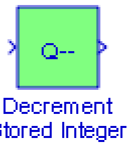


Figure 18.6. XY graph for the model in Figure 18.5

18.4 The Decrement Stored Integer Block



The **Decrement Stored Integer** block decreases the stored integer value of a signal by one.

Example 18.4

The model of Figure 18.7 implements the function $y = 2x^4 + 1$. The XY Graph for this model is shown in Figure 18.8.

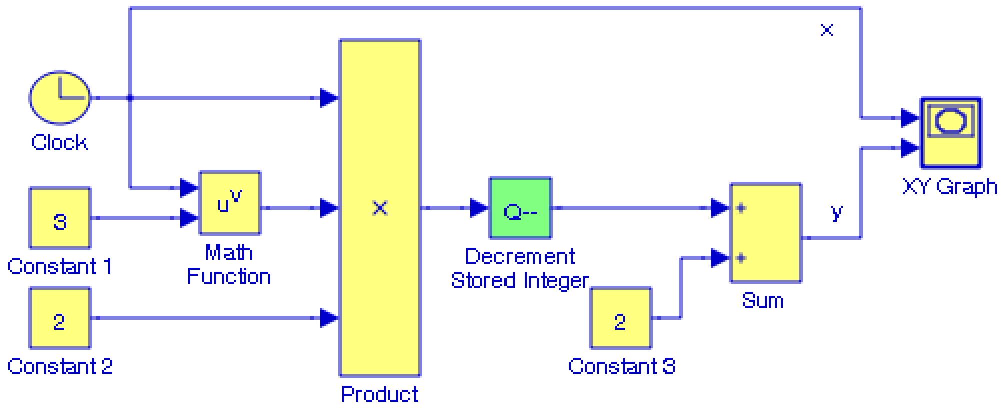


Figure 18.7. Model for Example 18.4

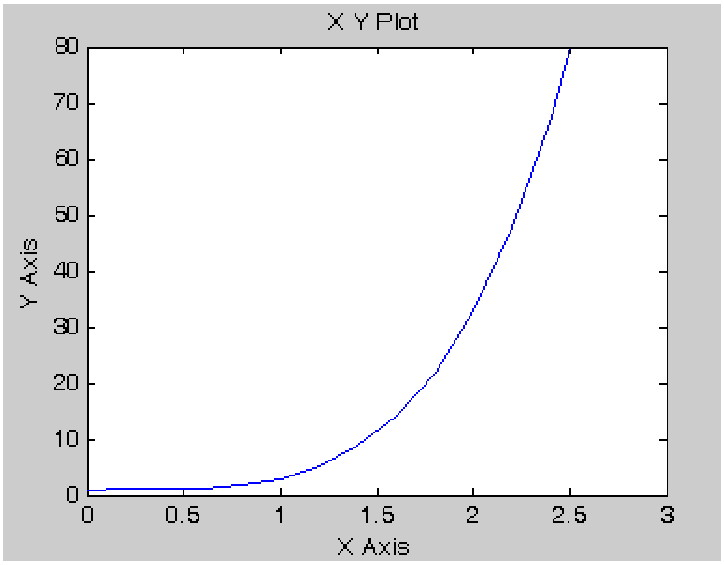
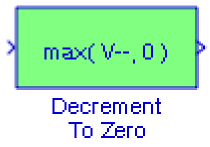


Figure 18.8. XY graph for the model in Figure 18.7

18.5 The Decrement to Zero Block



The **Decrement To Zero** block decreases the real–world value of the signal by one. The output never goes below zero.

Example 18.5

For the model of Figure 18.9, the output value never goes below zero as shown in Figure 18.10.

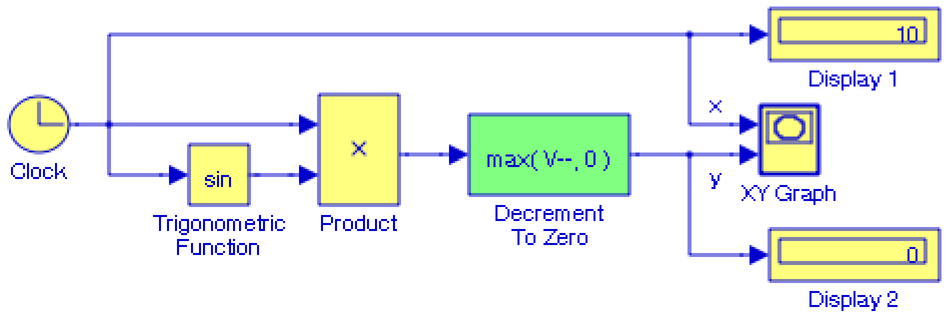


Figure 18.9. Model for Example 18.5

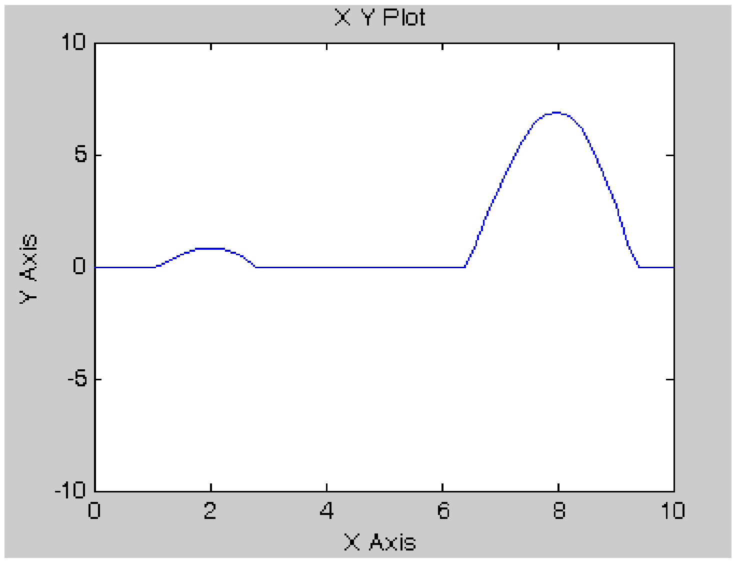
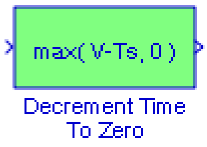


Figure 18.10. XY graph for the model in Figure 18.9

18.6 The Decrement Time To Zero Block



The **Decrement Time To Zero** block decreases the real–world value of the signal by the sample time, Ts . This block works only with fixed sample rates and the output never goes below zero.

Example 18.6

The model of Figure 18.11 implements the waveform shown in Figure 18.12.

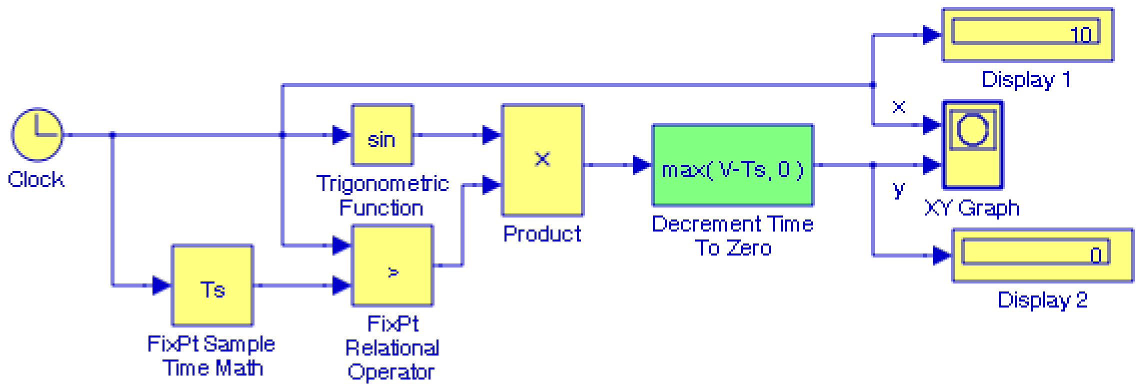


Figure 18.11. Model for Example 18.6

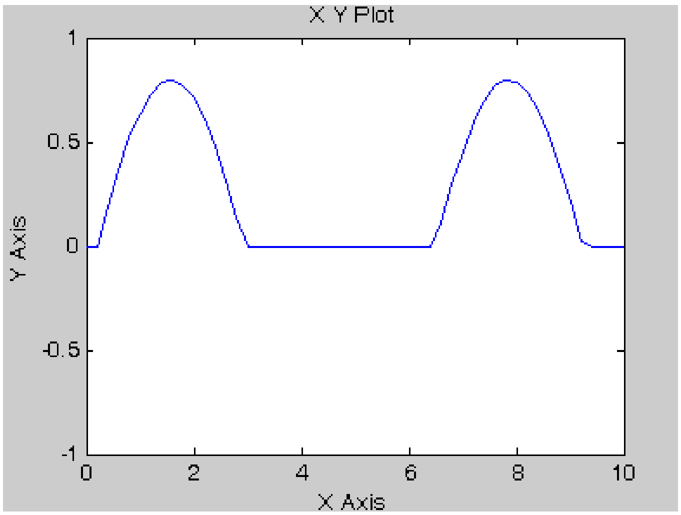


Figure 18.12. XY graph for the model in Figure 18.11

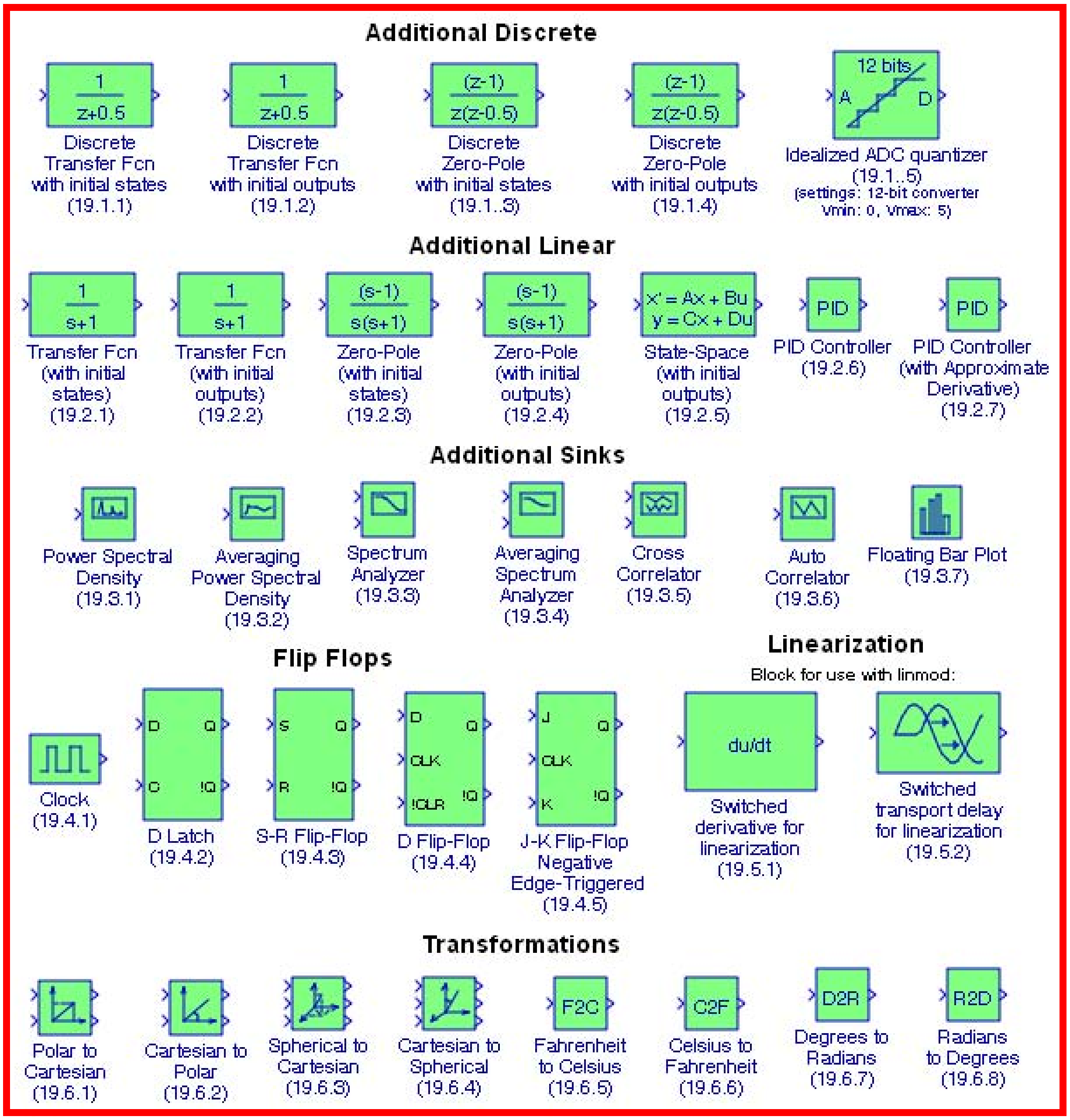
18.7 Summary

- The **Increment Real World** block increases the real–world value of the signal by one.
- The **Decrement Real World** block decreases the real–world value of the signal by one.
- The **Increment Stored Integer** block increases the stored integer value of a signal by one.
- The **Decrement Stored Integer** block decreases the stored integer value of a signal by one.
- The **Decrement To Zero** block decreases the real–world value of the signal by one. The output never goes below zero.
- The **Decrement Time To Zero** block decreases the real–world value of the signal by the sample time, `Ts`. This block works only with fixed sample rates and the output never goes below zero.

Chapter 19

The Simulink Extras Library

This chapter is an introduction to the **Simulink Extras** Library. This is a new library and was added to the Simulink 6.5 Version. It consists of six sub–libraries and contains the blocks shown below. Their functions are illustrated with examples.


Additional Discrete
1 / z+0.5
Discrete Transfer Fcn with initial states (19.1.1)
1 / z+0.5
Discrete Transfer Fcn with initial outputs (19.1.2)
(z-1) / z(z-0.5)
Discrete Zero-Pole with initial states (19.1.3)
(z-1) / z(z-0.5)
Discrete Zero-Pole with initial outputs (19.1.4)
12 bits A D
Idealized ADC quantizer (19.1.5) (settings: 12-bit converter Vmin: 0, Vmax: 5)
Additional Linear
1 / s+1
Transfer Fcn (with initial states) (19.2.1)
1 / s+1
Transfer Fcn (with initial outputs) (19.2.2)
(s-1) / s(s+1)
Zero-Pole (with initial states) (19.2.3)
(s-1) / s(s+1)
Zero-Pole (with initial outputs) (19.2.4)
x' = Ax + Bu y = Cx + Du
State-Space (with initial outputs) (19.2.5)
PID
PID Controller (19.2.6)
PID
PID Controller (with Approximate Derivative) (19.2.7)
Additional Sinks
Power Spectral Density (19.3.1)
Averaging Power Spectral Density (19.3.2)
Spectrum Analyzer (19.3.3)
Averaging Spectrum Analyzer (19.3.4)
Cross Correlator (19.3.5)
Auto Correlator (19.3.6)
Floating Bar Plot (19.3.7)
Flip Flops
Clock (19.4.1)
D Q C !Q
D Latch (19.4.2)
S Q R !Q
S-R Flip-Flop (19.4.3)
D Q CLK !CLR !Q
D Flip-Flop (19.4.4)
J Q CLK K !Q
J-K Flip-Flop Negative Edge-Triggered (19.4.5)
Linearization
Block for use with linmod:
du/dt
Switched derivative for linearization (19.5.1)
Switched transport delay for linearization (19.5.2)
Transformations
Polar to Cartesian (19.6.1)
Cartesian to Polar (19.6.2)
Spherical to Cartesian (19.6.3)
Cartesian to Spherical (19.6.4)
F2C
Fahrenheit to Celsius (19.6.5)
C2F
Celsius to Fahrenheit (19.6.6)
D2R
Degrees to Radians (19.6.7)
R2D
Radians to Degrees (19.6.8)

19.1 The Additional Discrete Group

The **Additional Discrete Group** contains the blocks described in Subsections 19.1.1 through 19.1.5 below.

19.1.1 The Discrete Transfer Fcn (with initial states) Block

1
z+0.5
Discrete
Transfer Fcn
with initial states

The Simulink documentation for the **Discrete Transfer Fcn (with initial states)** block provides the following description:

Specify the initial states for the transfer function. The state ordering is determined by the m–file tf2ss. There is no unique mapping of the states in a transfer function to states in a state–space representation. However, tf2ss will consistently use the same mapping for a given transfer function.

Example 19.1

Let us consider the three models shown in Figure 19.1 below. The first model (on the top) includes the **Discrete Transfer Fcn** block described in Chapter 5. There are no provisions for initial states in this block. The second model includes the **Discrete Transfer Fcn (with initial states)** block and it is equivalent to the **Discrete State–Space** block included in the third model. To prove the equivalence, we need to convert the discrete transfer function to its state–space presentation, and, as we know, this can be achieved with the MATLAB function **tf2ss**. Thus, at the MATLAB command prompt we enter:

```
Num=[0  0.951  0]; Den=[1  0.618  1]; [A  B  C  D]=tf2ss(Num,Den)
```

and MATLAB outputs the following:

```
A =
   -0.6180   -1.0000
    1.0000         0
B =
     1
     0
C =
    0.9510         0
D =
     0
```

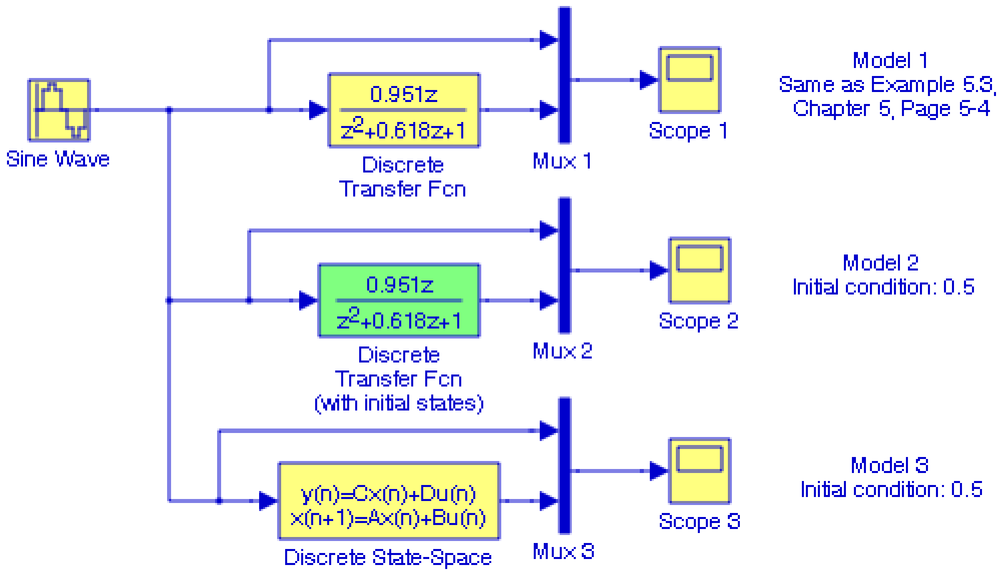


Figure 19.1. Models for Example 19.1

Next, in the **Function Block Parameters** dialog box for the **Discrete State–Space** block for the parameters A, B, C, and D, we enter:

A: [–0.618 –1; 1 0]
B: [1 0]'
C: [0.951 0]
D: [0]

and after execution of the simulation command, the **Scope 1**, **Scope 2**, and **Scope 3** blocks display the waveforms shown in Figures 19.2, 19.3, and 19.4 respectively where we observe that the waveforms in Figures 19.3 and 19.4 are the same.

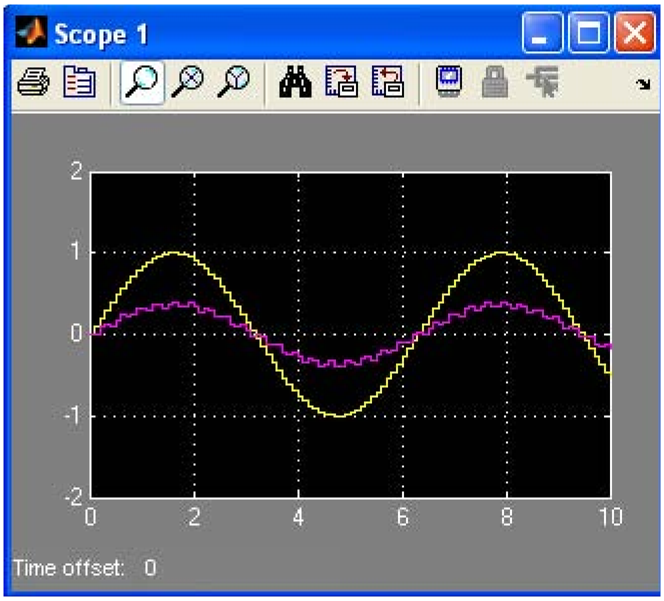


Figure 19.2. Input and output waveforms displayed on Scope 1 in Figure 19.1

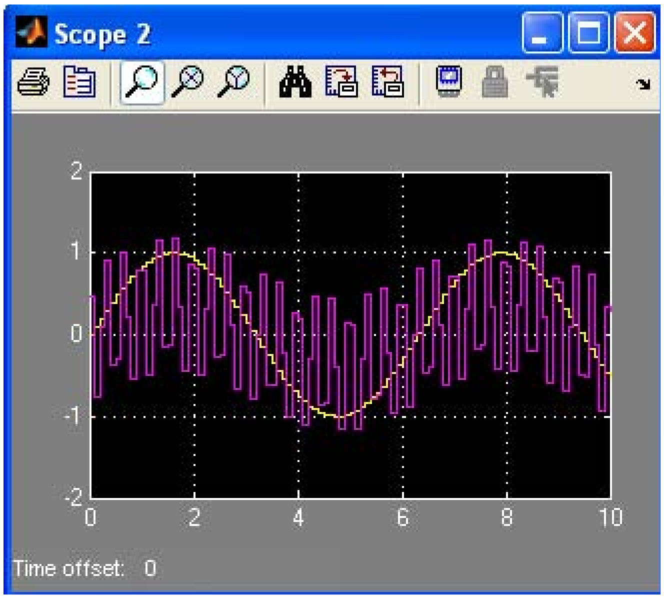


Figure 19.3. Input and output waveforms displayed on Scope 2 in Figure 19.1

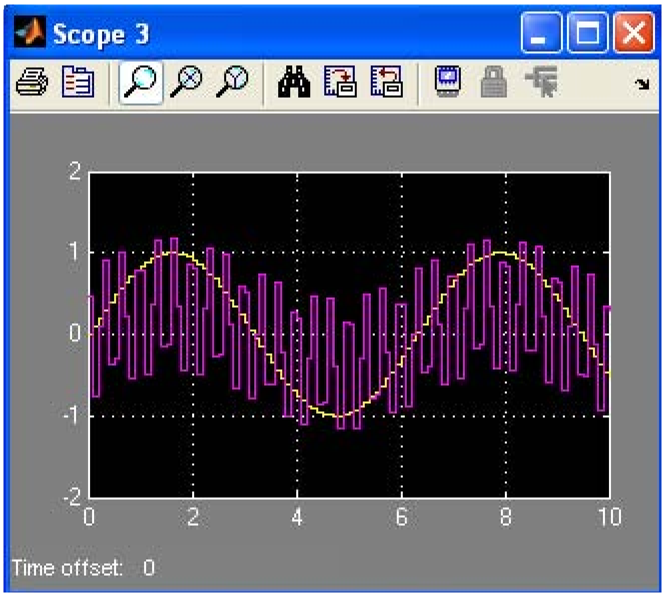
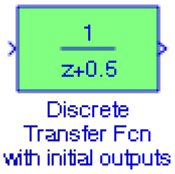


Figure 19.4. Input and output waveforms displayed on Scope 3 in Figure 19.1

19.1.2 The Discrete Transfer Fcn (with initial outputs) Block



The Simulink documentation for the **Discrete Transfer Fcn (with initial outputs)** block provides the following description:

Specify the initial output for the transfer function. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved. For more details, see the m–file getxo.m

Example 19.2

Let us consider the three models shown in Figure 19.5 below. The first model (on the top) includes the **Discrete Transfer Fcn** block described in Chapter 5. There are no provisions for initial outputs in this block. The second model includes the **Discrete Transfer Fcn (with initial outputs)** block and it is equivalent to the **Discrete State–Space** block included in the third model.

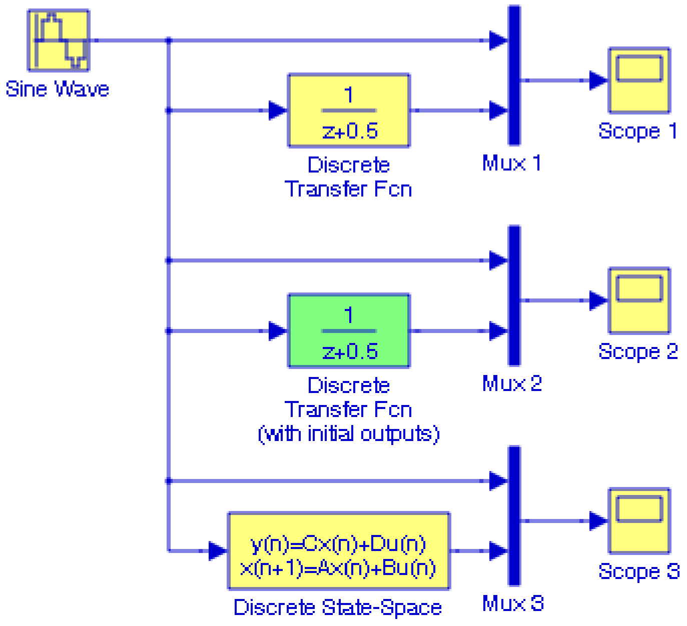


Figure 19.5. Models for Example 19.2

To prove the equivalence, we need to convert the discrete transfer function to its state–space presentation, and, as we know, this can be achieved with the MATLAB function **tf2ss**. Thus, at the MATLAB command prompt we enter:

```
num=[0  1]; den=[1  0.5]; [A  B  C  D]=tf2ss(num,den)
```

and MATLAB outputs the following:

```
A =
   -0.5000
B =
     1
C =
     1
D =
     0
```

Next, in the **Function Block Parameters** dialog box for the **Discrete State–Space** block for the parameters A, B, C, and D, we enter:

A: [–0.5]
B: [1]’
C: [1]
D: [0]

and after execution of the simulation command, the **Scope 1**, **Scope 2**, and **Scope 3** blocks display the waveforms shown in Figures 19.6, 19.7, and 19.8 respectively where we observe that the waveforms in Figures 19.7 and 19.8 are the same.

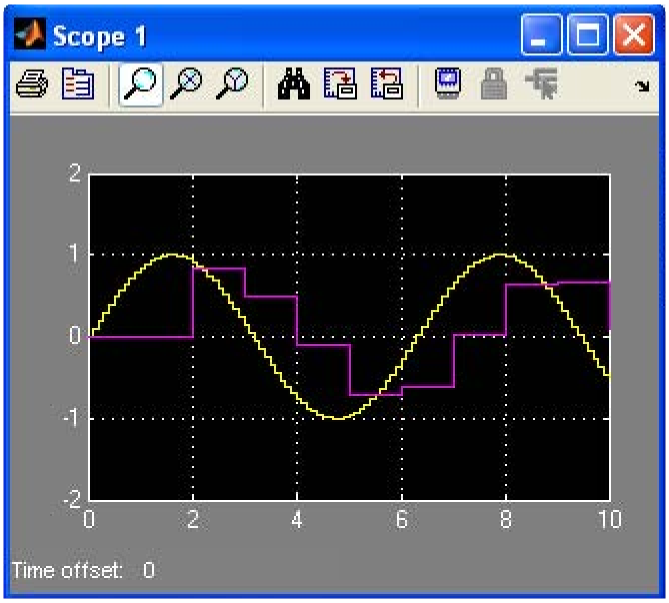


Figure 19.6. Input and output waveforms displayed on Scope 1 in Figure 19.5

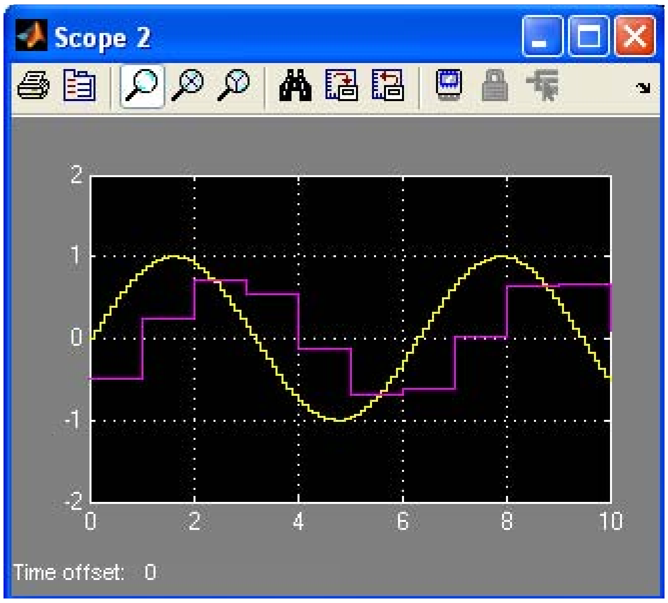


Figure 19.7. Input and output waveforms displayed on Scope 2 in Figure 19.5

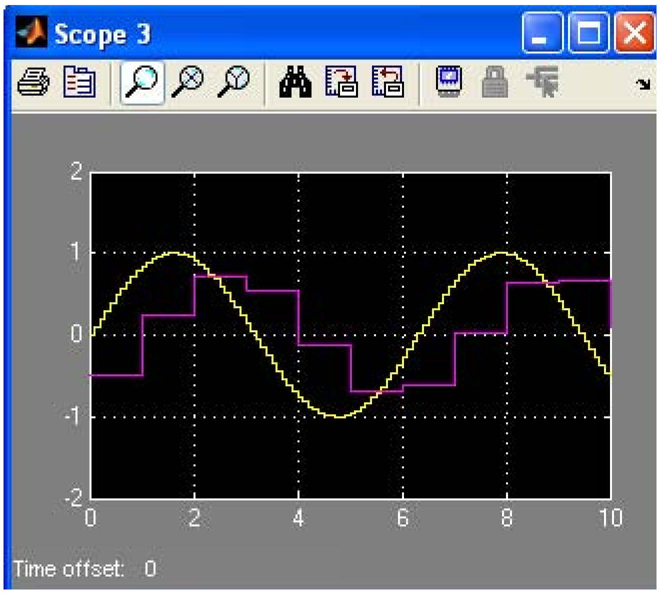
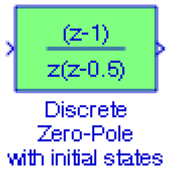


Figure 19.8. Input and output waveforms displayed on Scope 3 in Figure 19.5

19.1.3 The Discrete Zero-Pole (with initial states) Block



The Simulink documentation for the **Discrete Zero–Pole (with initial states)** block provides the following description:

Specify the initial states for the transfer function. The state ordering is determined by the m–file zp2ss. There is no unique mapping of the states in a zero–pole–gain representation to states in a state–space representation. However, zp2ss will consistently use the same mapping for a given transfer function.

Example 19.3

Let us consider the three models shown in Figure 19.9 below. The first model (on the top) includes the **Discrete Zero–Pole** block described in Chapter 5. There are no provisions for initial states in this block.

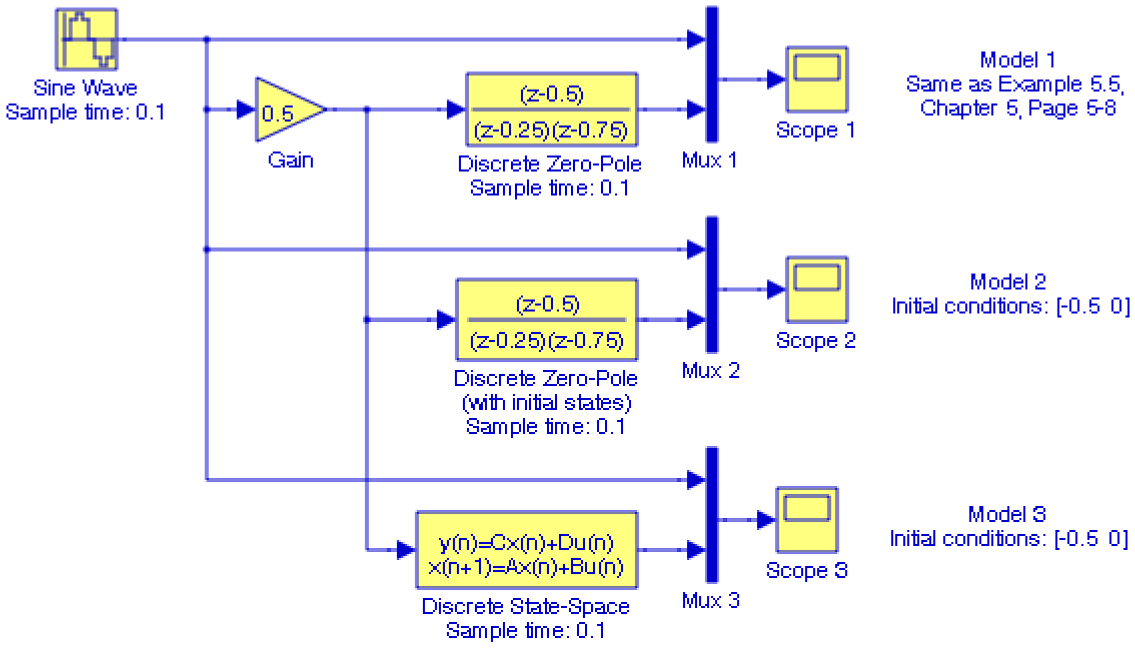


Figure 19.9. Models for Example 19.3

The second model includes the **Discrete Zero–Pole (with initial states)** block and it is equivalent to the **Discrete State–Space** block included in the third model. To prove the equivalence, we need to convert the discrete transfer function to its state–space presentation, and, as we know, this can be achieved with the MATLAB function **zp2ss**. Thus, at the MATLAB command prompt we enter:

```
z=[0.5]; p=[0.25  0.75]'; k=1; [A,B,C,D]=zp2ss(z,p,k)*
```

and MATLAB outputs the following:

```
A =
    1.0000   -0.4330
    0.4330         0
B =
     1
     0
C =
    1.0000   -1.1547
D =
     0
```

* *As stated in the MATLAB Help menu, the input argument* p *is a column vector.*

Next, in the Function Block Parameters dialog box for the **Discrete State–Space** block for the parameters A, B, C, and D, we enter:

A: [1 –0.433; 0.433 0]
B: [1 0]'
C: [1 –1.1547]
D: [0]

and after execution of the simulation command, the **Scope 1**, **Scope 2**, and **Scope 3** blocks display the waveforms shown in Figures 19.10, 19.11, and 19.12 respectively where we observe that the waveforms in Figures 19.11 and 19.12 are the same.

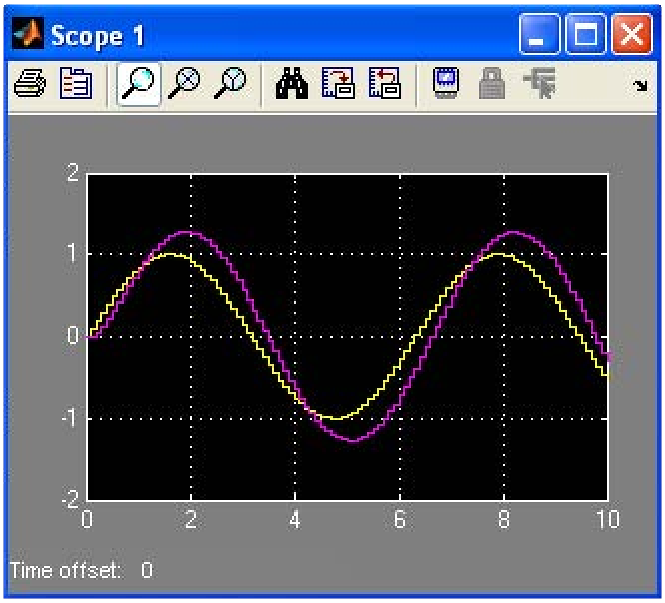


Figure 19.10. Input and output waveforms displayed on Scope 1 in Figure 19.9

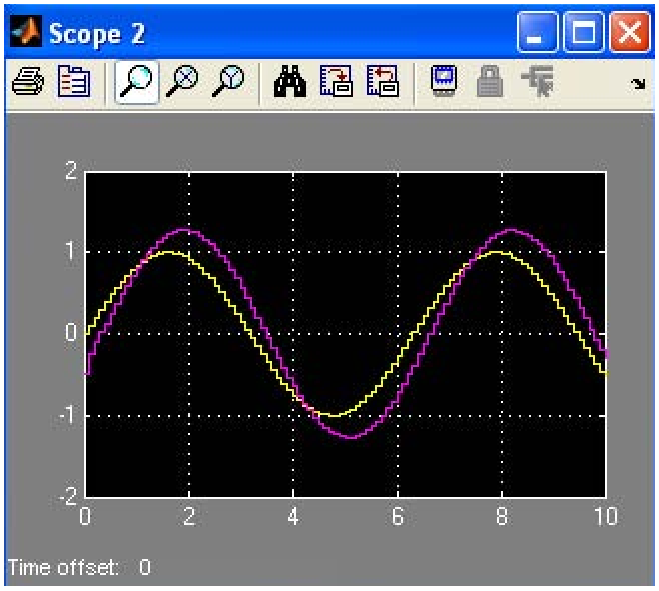


Figure 19.11. Input and output waveforms displayed on Scope 2 in Figure 19.9

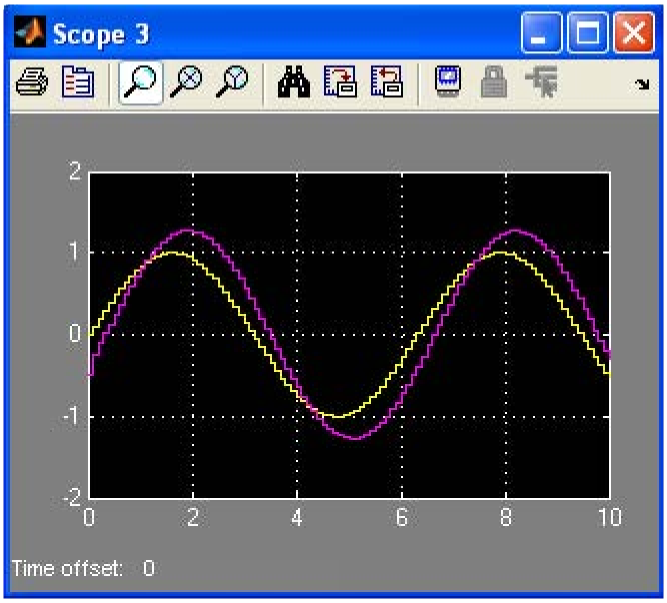
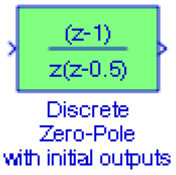


Figure 19.12. Input and output waveforms displayed on Scope 3 in Figure 19.9

19.1.4 The Discrete Zero–Pole (with initial outputs) Block



The Simulink documentation for the **Discrete Zero–Pole (with initial outputs)** block provides the following description:

Specify the initial output for the zero–pole–gain system. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved. For more details, see the m–file getxo.m

Example 19.4

Let us consider the three models shown in Figure 19.13 below. The first model (on the top) includes the **Discrete Zero–Pole** block described in Chapter 5. There are no provisions for initial outputs in this block. The second model includes the **Discrete Zero–Pole (with initial outputs)** block and it is equivalent to the **Discrete State–Space** block included in the third model.

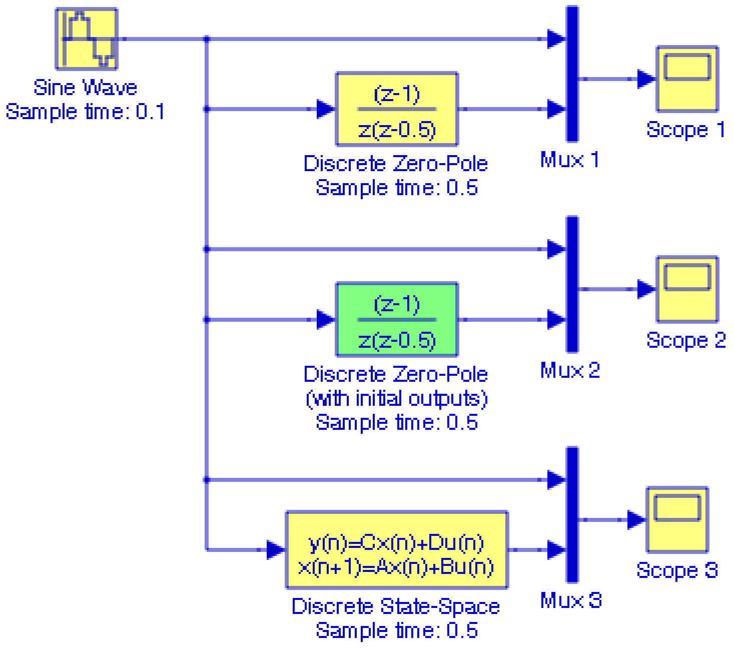


Figure 19.13. Models for Example 19.4

The second model includes the **Discrete Zero–Pole (with initial outputs)** block and it is equivalent to the **Discrete State–Space** block included in the third model. To prove the equivalence, we need to convert the discrete transfer function to its state–space presentation, and, as we know, this can be achieved with the MATLAB function **`zp2ss`**. Thus, at the MATLAB command prompt we enter:

```
z=[1]; p=[0   0.5]'; k=[1]; [A,B,C,D]=zp2ss(z,p,k)
```

and MATLAB outputs the following:

```
A =
    0.5000         0
    1.0000         0
B =
     1
     0
C =
     1    -1
D =
     0
```

Next, in the **Function Block Parameters** dialog box for the **Discrete State–Space** block for the parameters A, B, C, and D, we enter:

```
A: [0.5   0; 1  0]
B: [1 0]'
C: [1  -1]
D: [0]
```

and after execution of the simulation command, the **Scope 1**, **Scope 2**, and **Scope 3** blocks display the waveforms shown in Figures 19.14, 19.15, and 19.16 respectively where we observe that the waveforms in Figures 19.15 and 19.16 are the same.

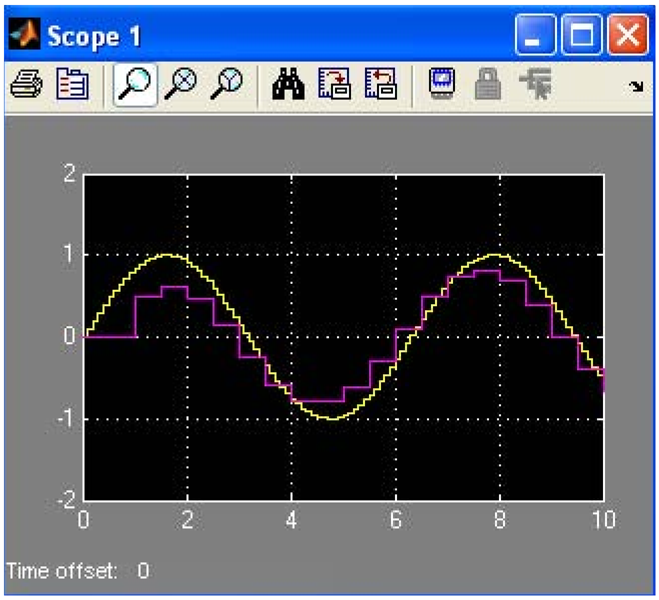


Figure 19.14. Input and output waveforms displayed on Scope 1 in Figure 19.13

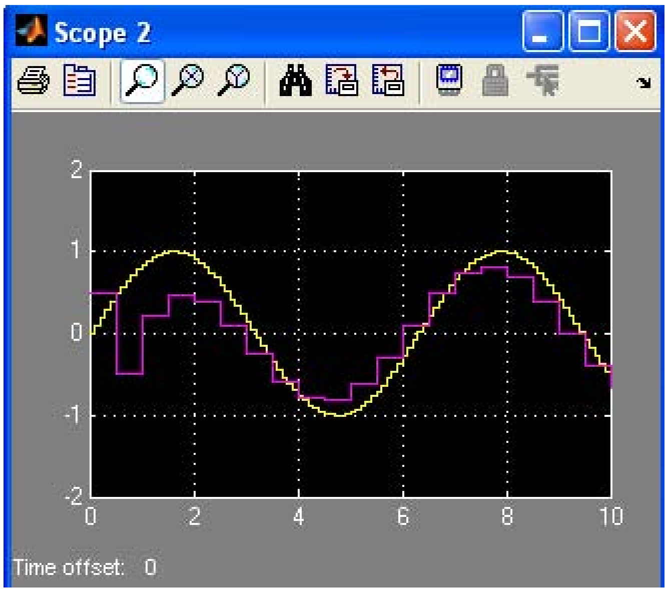


Figure 19.15. Input and output waveforms displayed on Scope 2 in Figure 19.13

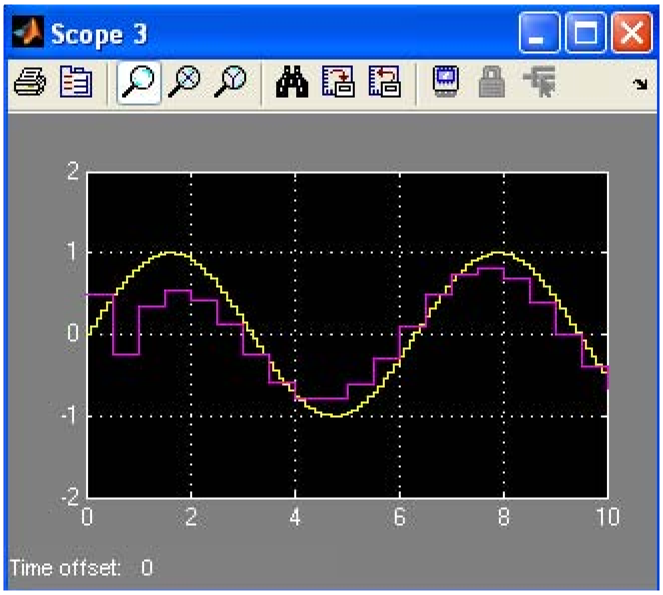
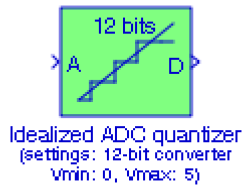


Figure 19.16. Input and output waveforms displayed on Scope 3 in Figure 19.13

19.1.5 The Idealized ADC Quantizer Block



The Simulink documentation for the **Idealized ADC Quantizer** block provides the following description:

Use this block to model an ideal analog to digital converter.* To model non–ideal converters, it is suggested to use a direct look–up table to represent static errors and dynamic models for transient error sources. Use a discrete delay of the appropriate duration to model conversion latency if this is a significant value in your application. If there is an input mux, model this with triggered latencies on the input side of the A/D block.

In Chapter 4, Section 4.9, Page 4–12, we described the **Quantizer** block which quantizes a signal into a stair–step output by specifying the quantization interval. In the Idealized ADC Quantizer block we specify the number of converter bits, the minimum input voltage at low output, and the

* *For a detailed discussion on analog–to–digital conversion, quantization, resolution, and accuracy, please refer to Electronic Devices and Amplifier Circuits with MATLAB Applications, ISBN 978–0–9709511–7–5.*

maximum input voltage at 2^n output.

Example 19.5

The model in Figure 19.17 compares the outputs of the Quantizer block with the Idealized ADC Quantizer when the signal provided by the Signal Builder block is a sampled sinusoid* as shown in Figure 19.18.

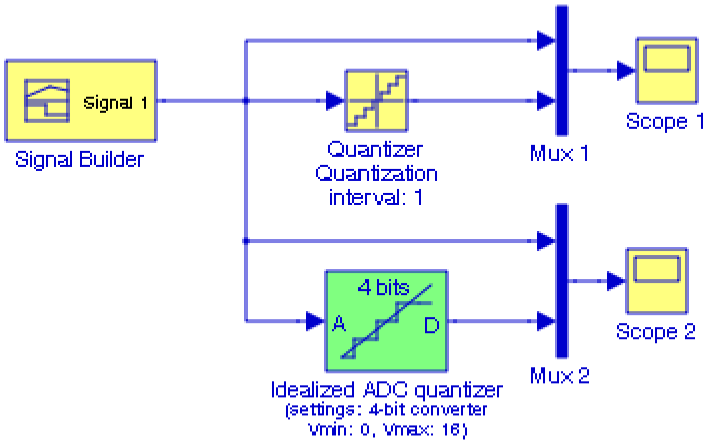


Figure 19.17. Model for Example 19.5

With the Function Block Parameters chosen as indicated in Figure 19.17, the **Scope 1** and **Scope 2** blocks display the waveforms shown in Figures 19.19 and 19.20 respectively.

* *This signal is displayed when from the Signal drop menu in the Signal Builder block we choose Sampled Sinewave.*

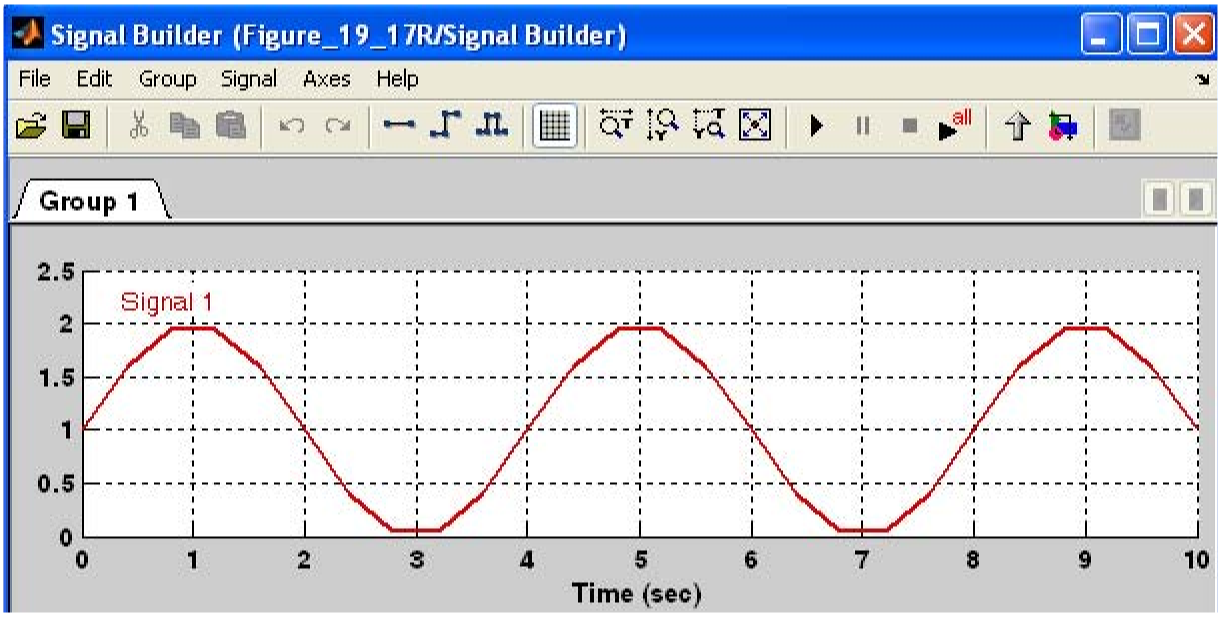

Signal Builder (Figure_19_17R/Signal Builder)
File Edit Group Signal Axes Help
Group 1
Signal 1
2.5
2
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10
Time (sec)

Figure 19.18. The waveform provided by the Signal Builder block for the model in Figure 19.17

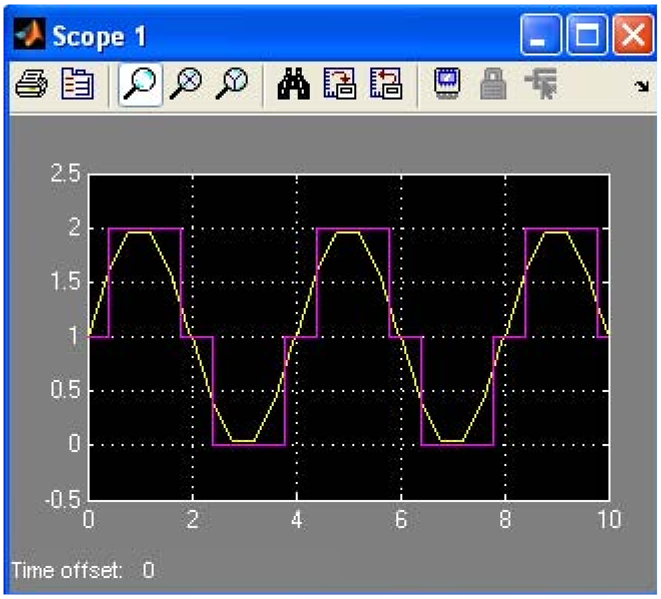


Figure 19.19. Input and output waveforms displayed on Scope 1 in Figure 19.17

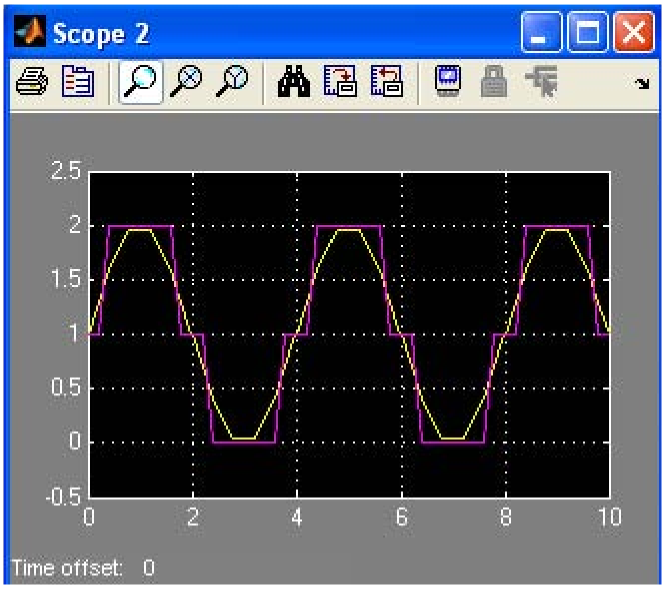
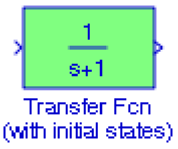


Figure 19.20. Input and output waveforms displayed on Scope 2 in Figure 19.17

19.2 The Additional Linear Group

The **Additional Linear Group** contains the blocks described in Subsections 19.2.1 through 19.2.7 below.

19.2.1 The Transfer Fcn (with initial states) Block



The Simulink documentation for the **Transfer Fcn (with initial states)** block provides the following description:

The **Transfer Fcn (with initial states)** block specifies the initial states for the transfer function. The state ordering is determined by the m–file **tf2ss**. There is no unique mapping of the states in a transfer function to states in a state–space representation. However, **tf2ss** will consistently use the same mapping for a given transfer function.

Example 19.6

Let us consider the three models in Figure 19.21. The **Transfer Fcn 1** block in model (a) makes no provision for initial states. But the **State–Space** block in model (b) does make provisions for initial states, and for this example we have assumed the initial state 0.5. We can determine the matrices A, B, C, and D using the MATLAB function **tf2ss**.

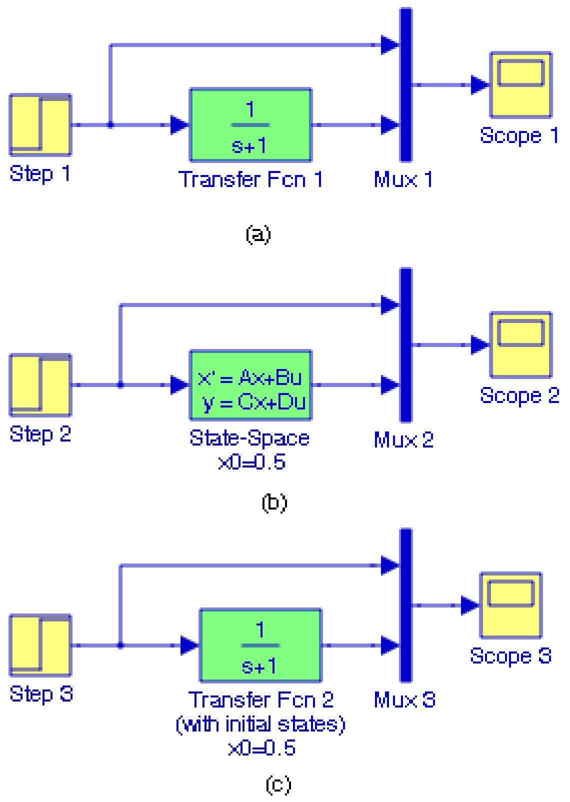


Figure 19.21. Models for Example 19.6

For this example, transfer function to states in a state–space representation is determined as follows:

```
num=[0  1]; den=[1  1]; [A B C D]=tf2ss(num,den)
```

and MATLAB outputs the following values:

```
A =
    -1
B =
     1
C =
     1
D =
     0
```

Next, we enter these values in the **State–Space Function Block Parameters** dialog box and we also specify the initial condition 0.5. The Transfer Fcn (with initial states) in model (c) in Figure 19.21 accomplishes the same by including a field for the initial state in its **Function Block Parameters** dialog box. The input and output waveforms for the three models in Figure 19.21 are shown in Figures 19.22 through 19.24.

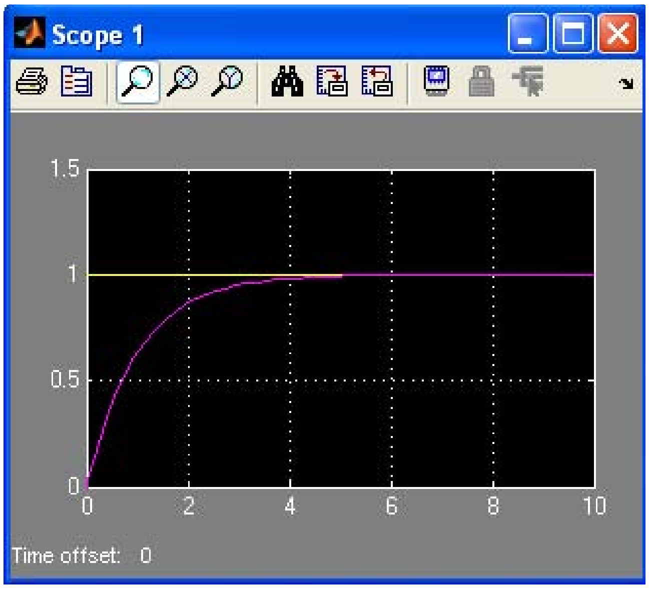


Figure 19.22. Input and output waveforms for model (a) in Figure 19.21

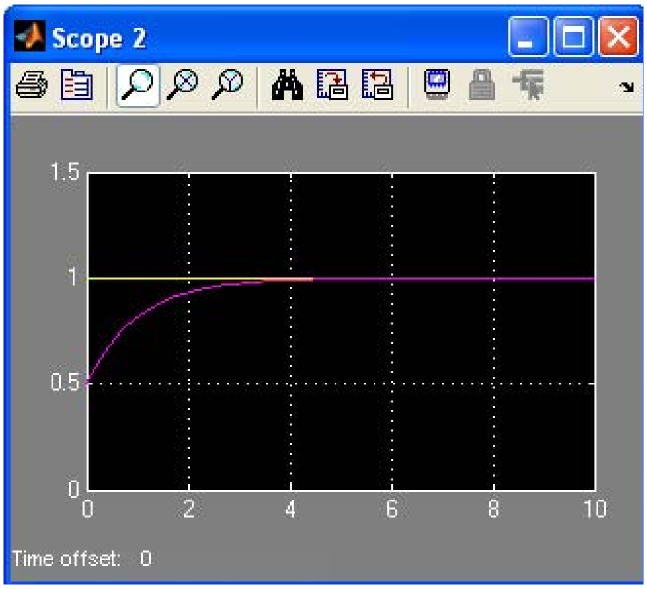


Figure 19.23. Input and output waveforms for model (b) in Figure 19.21

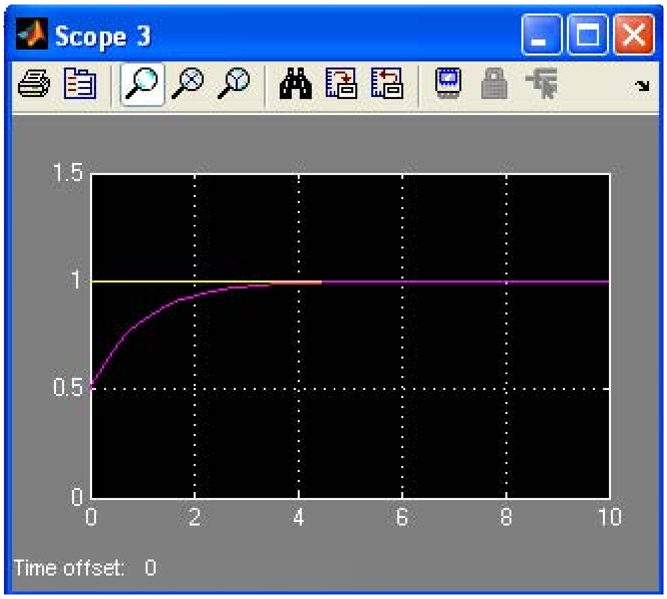
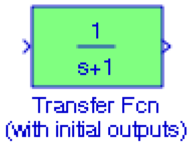


Figure 19.24. Input and output waveforms for model (c) in Figure 19.21

19.2.2 The Transfer Fcn (with initial outputs) Block



The Simulink documentation for the **Transfer Fcn (with initial outputs)** block provides the following description:

Specify the initial output for the transfer function. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved. For more details, see the m–file getxo.m

Example 19.7

In the electric RC circuit in Figure 19.25, the input and output signals are as shown in Figure 19.26.

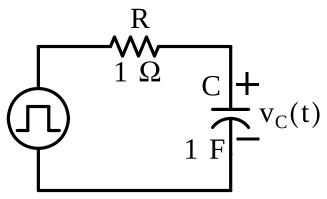


Figure 19.25. RC circuit for Example 19.7

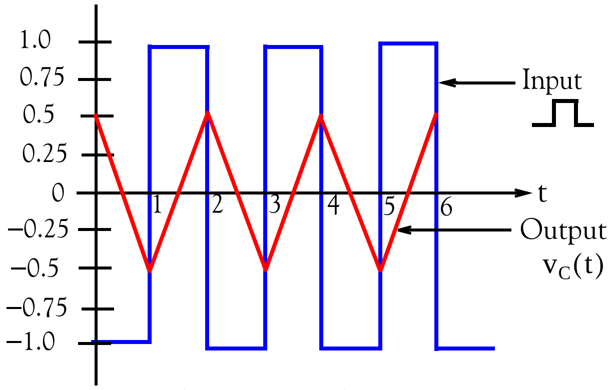


Figure 19.26. Input and output signals for RC circuit in Figure 19.25

The output waveform in Figure 19.26 indicates that the initial output is 0.5 volt. The RC circuit in Figure 19.25 can be simulated with the model shown in Figure 19.27 where in the **Function Block Parameters** dialog box for the **Transfer Fcn** (with initial outputs) block we have we have selected the parameters shown in the model.

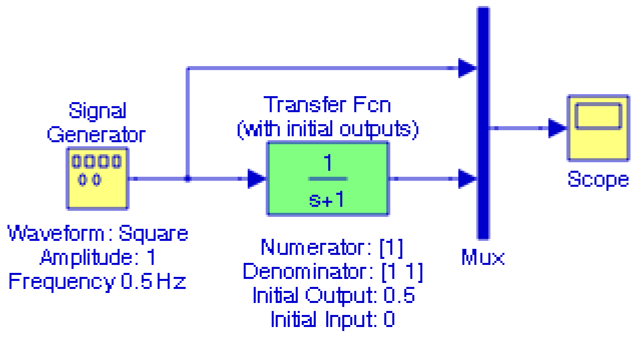


Figure 19.27. Model for Example 19.7

The **Scope** block in Figure 19.27 displays the input and output waveforms shown in Figure 19.28.

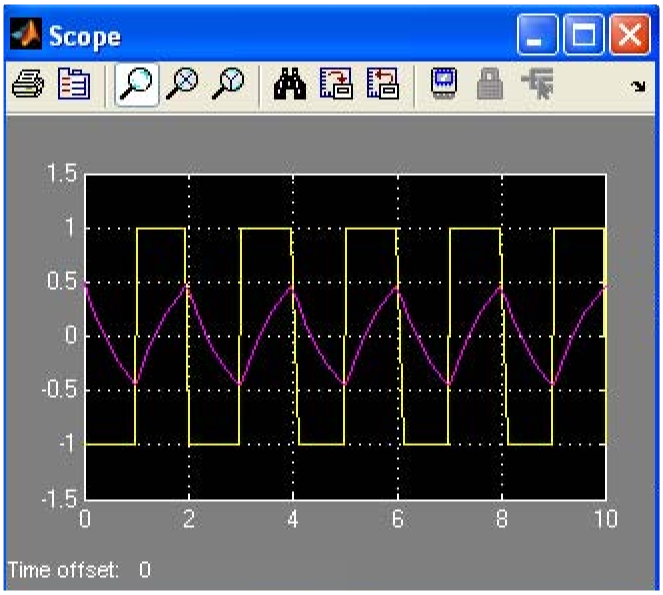
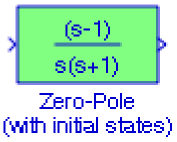


Figure 19.28. Input and output waveforms for the model in Figure 19.27

19.2.3 The Zero–Pole (with initial states) Block



The Simulink documentation for the **Zero–Pole (with initial states)** block provides the following description:

Specify the initial states for the transfer function. The state ordering is determined by the m–file zp2ss. There is no unique mapping of the states in a zero–pole–gain representation to states in a state–space representation. However, zp2ss will consistently use the same mapping for a given transfer function.

Example 19.8

It is known that the transfer function for a particular system is

$$G(s) = \frac{5s(s+3)}{(s+1)(s+2)(s+4)}$$

Let us consider the three models in Figure 19.29. The **Zero–Pole** block in model (a) makes no provision for initial states. But the State–Space block in model (b) does make provisions for initial states, and for this example we have assumed the initial states -0.1, 0, and 0. We can determine the matrices A, B, C, and D using the MATLAB function **zp2ss**.

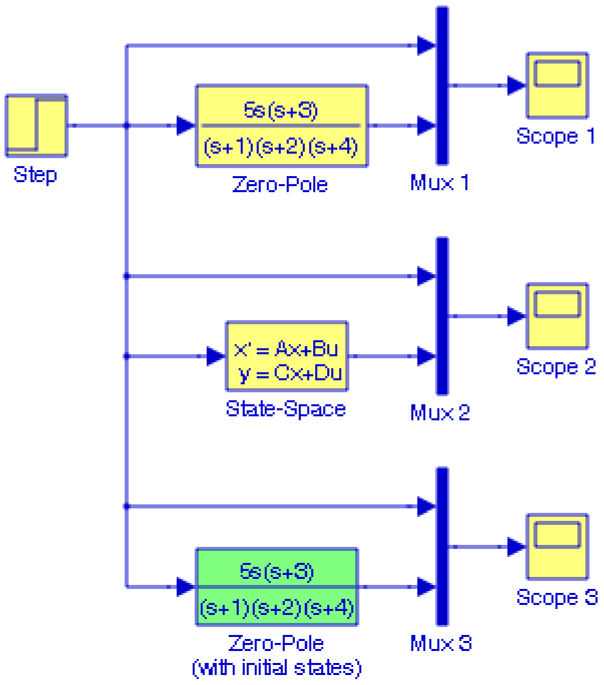


Figure 19.29. Models for Example 19.8

For this example, transfer function to states in a state–space representation is determined as follows:

```
z=[0  –3]; p=[–1  –2  –4]'; k=5; [A B C D]=zp2ss(z,p,k)
```

and MATLAB outputs the following values:

```
A =
   -1.0000         0         0
    1.0000   -6.0000   -2.8284
         0    2.8284         0
B =
     1
     0
     0
C =
    5.0000  -15.0000  -14.1421
D =
     0
```

Next, we enter these values in the **State–Space Function Block Parameters** dialog box and we also specify the initial conditions -0.1, 0, and 0. The **Transfer Fcn** (with initial states) in model (c) in Figure 19.21 accomplishes the same by including a field for the initial states in its **Function Block Parameters** dialog box. The input and output waveforms for the three models in Figure 19.29 are shown in Figures 19.30 through 19.32.

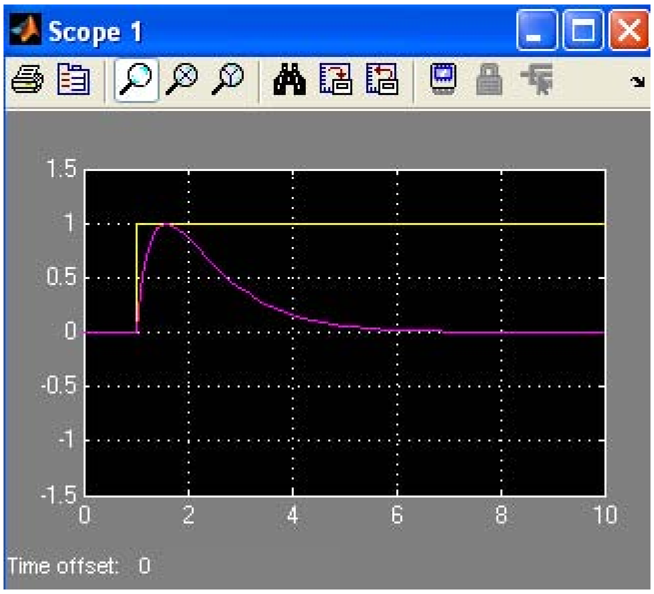


Figure 19.30. Input and output waveforms for the first model in Figure 19.29

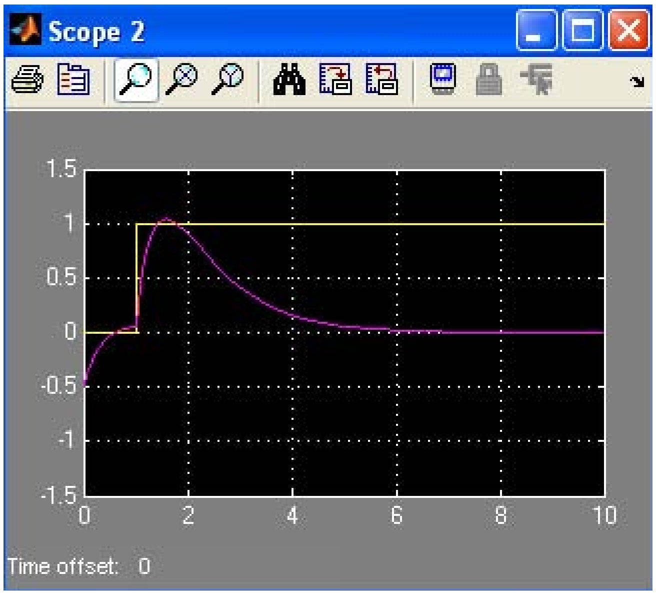


Figure 19.31. Input and output waveforms for the second model in Figure 19.29

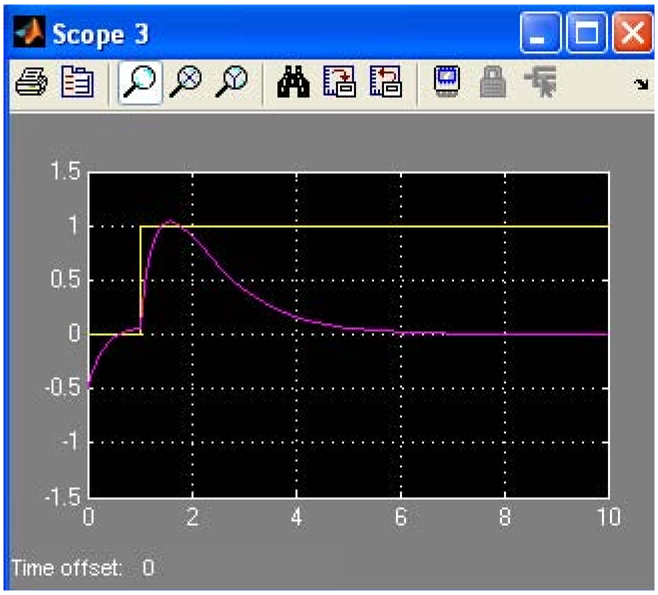
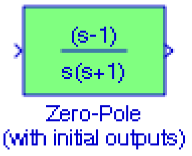


Figure 19.32. Input and output waveforms for the third model in Figure 19.29

19.2.4 The Zero–Pole (with initial outputs) Block



The Simulink documentation for the **Zero–Pole (with initial outputs)** block provides the following description:

Specify the initial output for the zero–pole–gain system. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved. For more details, see the m–file getxo.m.

Example 19.9

The specifications in the Function Block Parameters block for the **Zero–Pole** (with initial outputs) block in Figure 19.33 are as follows:

Zeros: [ ]
Poles: [0 –2]’
Gain: 2
Initial output: –0.5
Initial input: 0

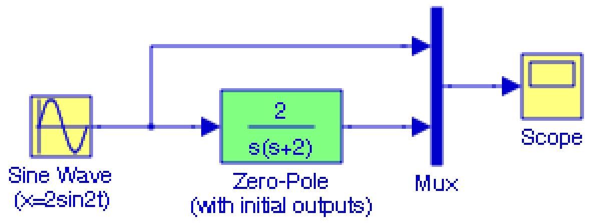


Figure 19.33. Model for Example 19.9

The input and output signals are as shown in Figure 19.34.

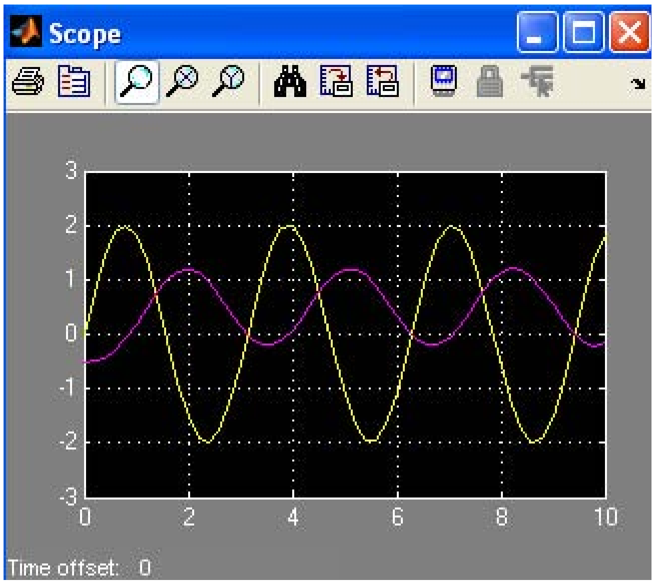
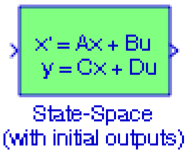


Figure 19.34. Input and output waveforms for the model in Figure 19.33

19.2.5 The State–Space (with initial outputs) Block



The Simulink documentation for the **State–Space (with initial outputs)** block provides the following description:

Specify an initial output. An optimization routine is used to attempt to find the steady state x values that satisfy the initial output. The block states will be initialized to these values.

Example 19.10

The specifications in the **Function Block Parameters** dialog box for the **State–Space** (with initial outputs) block in Figure 19.35 are as follows:

A: [0 1 0 0; 0 0 1 0; 0 0 0 1; –1 0 –2 0]
B: [0 0 0 1]'
C: [1 0 0 0]
D: [0]
Initial input: 0
Initial output: –0.5

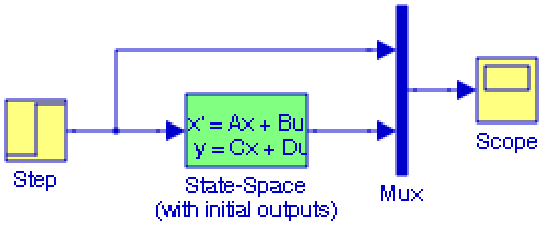


Figure 19.35. Model for Example 19.10

The input and output signals are as shown in Figure 19.36.

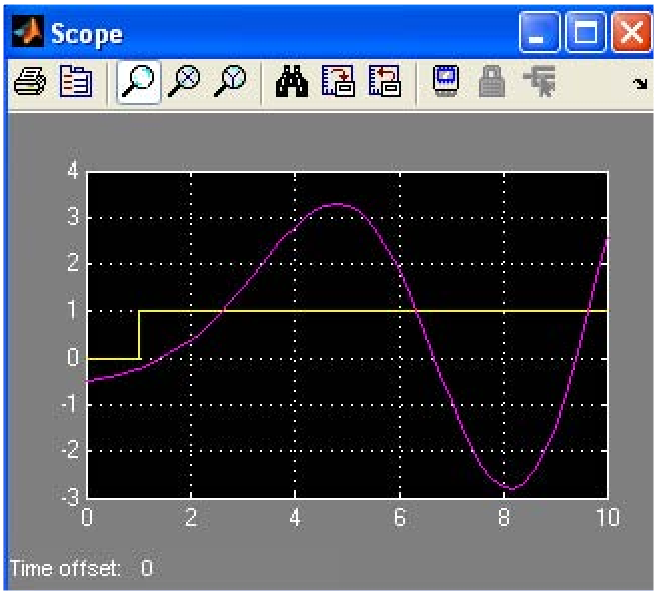
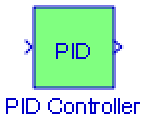


Figure 19.36. Input and output waveforms for the model in Figure 19.35

19.2.6 The PID Controller Block



The Simulink documentation for the **PID Controller** block provides the following description:

This block implements a PID controller where parameters are entered for the Proportional, Integral and Derivative terms.

A **proportional–integral–derivative (PID) controller** is a control loop feedback system used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired setpoint by calculating and then outputting a corrective action that can adjust the process accordingly.

The PID controller calculation contains three separate parameters; the **Proportional**, the **Integral**, and **Derivative** values as shown in Figure 19.37.

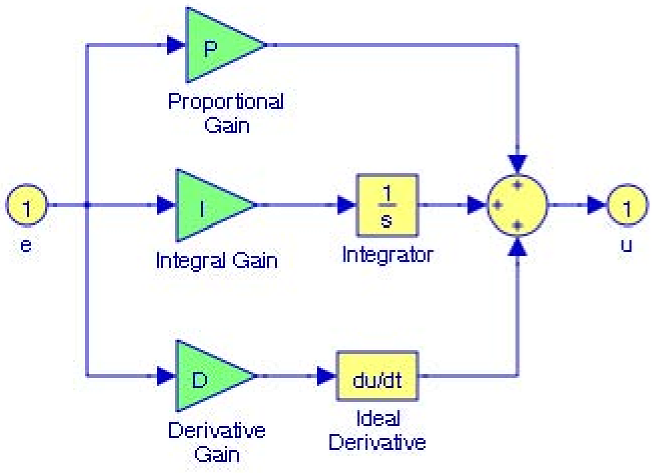


Figure 19.37. The components of a typical PID

The Proportional value determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors, and the Derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.

By adjusting the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. The use of the PID algorithm for control does not necessarily result in an optimal configuration for the system.

Some applications may require using only one or two modes to provide the appropriate system control. This is achieved by setting the gain of undesired control outputs to zero. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions. PI controllers are particularly common, since derivative action is very sensitive to measurement noise, and the absence of an integral value prevents the system from reaching its target value due to the control action.

Example 19.11

The model in Figure 19.38 produces the outputs of a transfer function without and with PID control. The output waveforms are shown in Figure 19.39.

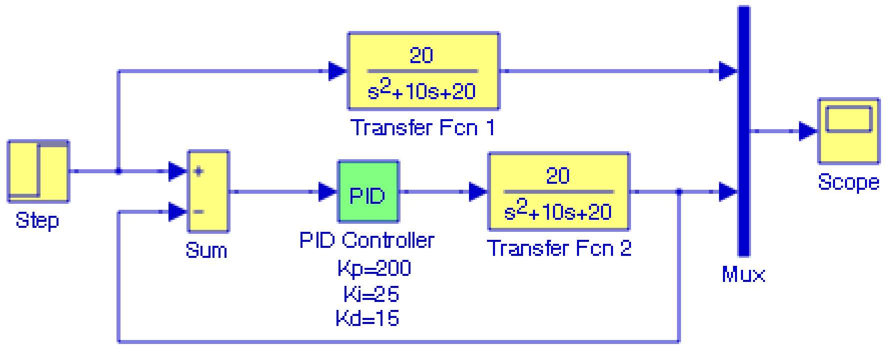


Figure 19.38. Model for Example 19.11

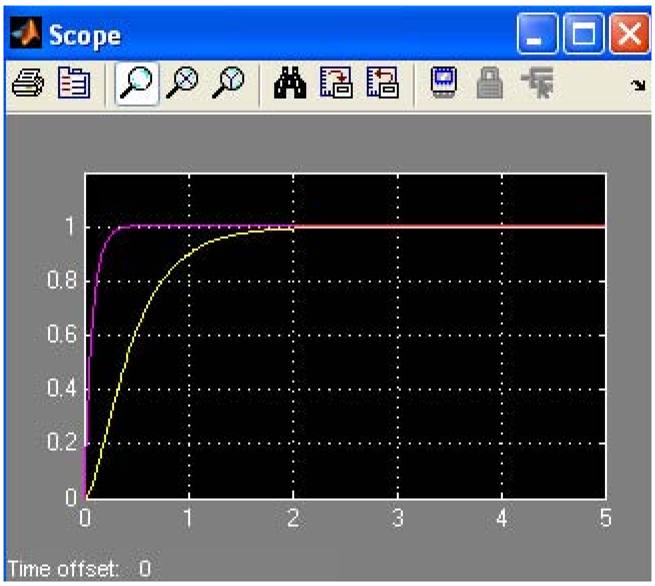


Figure 19.39. Output waveforms for the model in Figure 19.38 without and with PID control

19.2.7 The PID Controller (with Approximate Derivative) Block

The Simulink documentation for the **PID Controller (with Approximate Derivative)** block provides the following description:

This block implements a PID controller where parameters are entered for the Proportional, Integral and Derivative and divisor terms. Unmask this block to see how it works. The derivative term is implemented using an s/(s/N +1) transfer function block. Making N large can create a "stiff" system.

The PID controller with approximate derivative calculation contains the functional blocks shown in Figure 19.40.

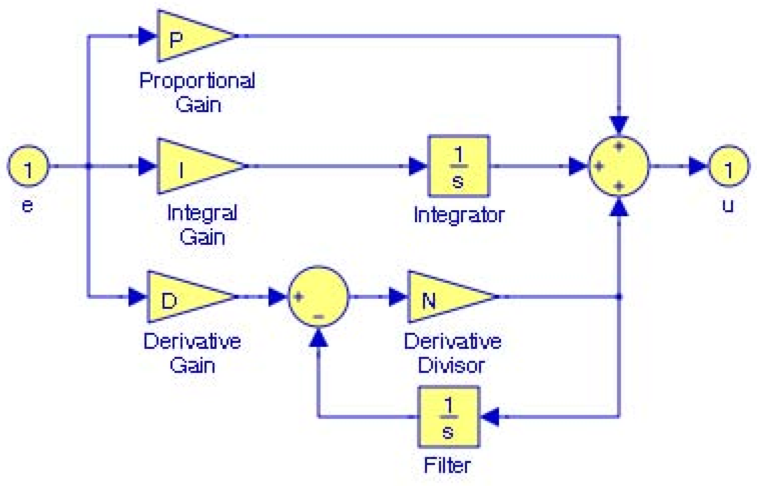


Figure 19.40. The components of a typical PID with approximate derivative

Example 19.12

The model in Figure 19.41 produces the outputs of a transfer function without and with PID control with approximate derivative. The output waveforms are shown in Figure 19.42.

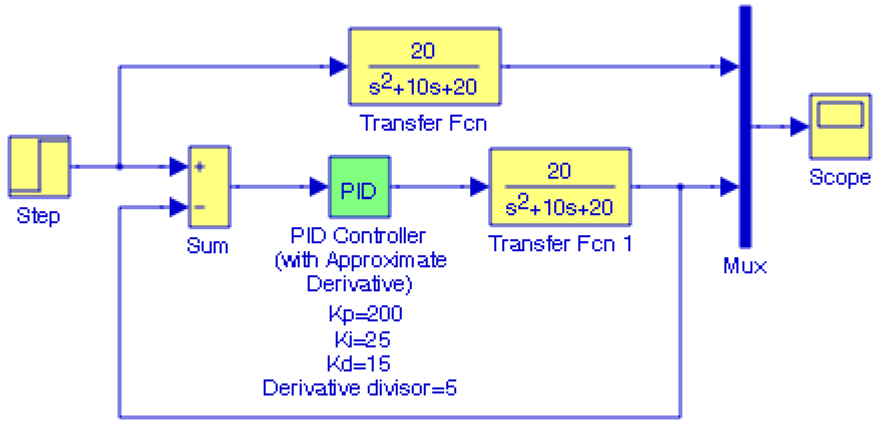


Figure 19.41. Model for Example 19.12

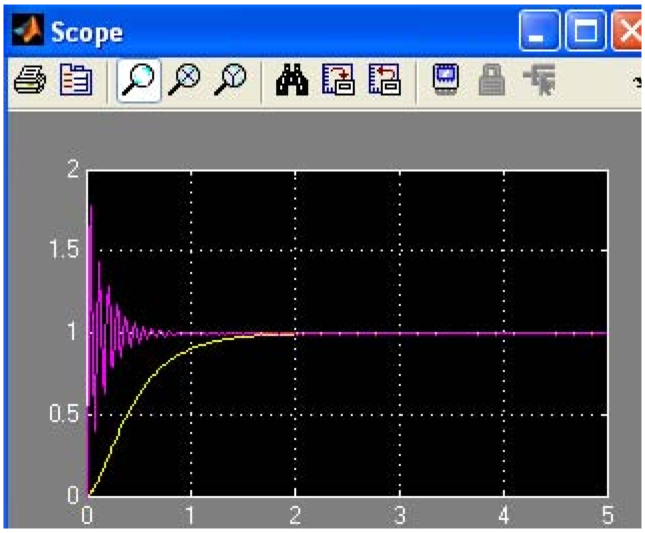


Figure 19.42. Output waveforms for the model in Figure 19.38 without and with PID control

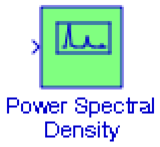
The reader should try to minimize the oscillations shown in Figure 19.42 by assigning other values for the Derivative divisor.

The last two examples indicate that the Proportional Gain Kp, Integral Gain Ki, and Derivative Gain Kd are dependent on each another. Generally, Kp and Ki will decrease the rise time and increase the overshoot, and Kd will cause a small change in rise time and decrease the overshoot.

19.3 The Additional Sinks Group

The **Additional Sinks Group** contains the blocks described in Subsections 19.3.1 through 19.3.7 below.

19.3.1 The Power Spectral Density Block



The Simulink documentation describes this block as follows:

This block when hooked to the output of a system displays the frequency content of the buffer in the graph window. For more see the m–file sfunpsd.

The **Power Spectral Density** block displays the Fourier transform of the auto correlation function described in Subsection 19.3.6 below.

Example 19.13

We will create a Simulink model that will produce the auto correlation function of a pulse, and then we will use this correlation function as an input to the **Power Spectral Density** block to display this function.

The model is shown in Figure 19.43 below.

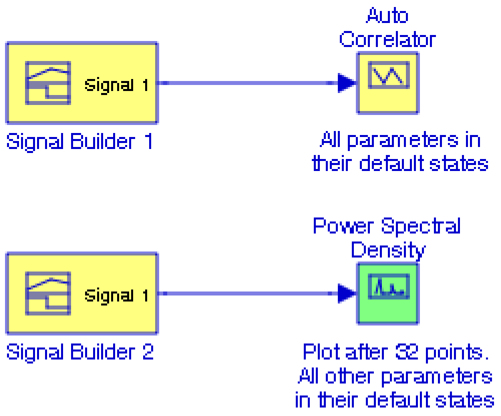


Figure 19.43. Model for Example 19.13

The **Signal Builder 1** block is configured to output the pulse waveform shown in Figure 19.44, and the **Auto Correlator** block produces the triangular waveform shown in Figure 19.45.

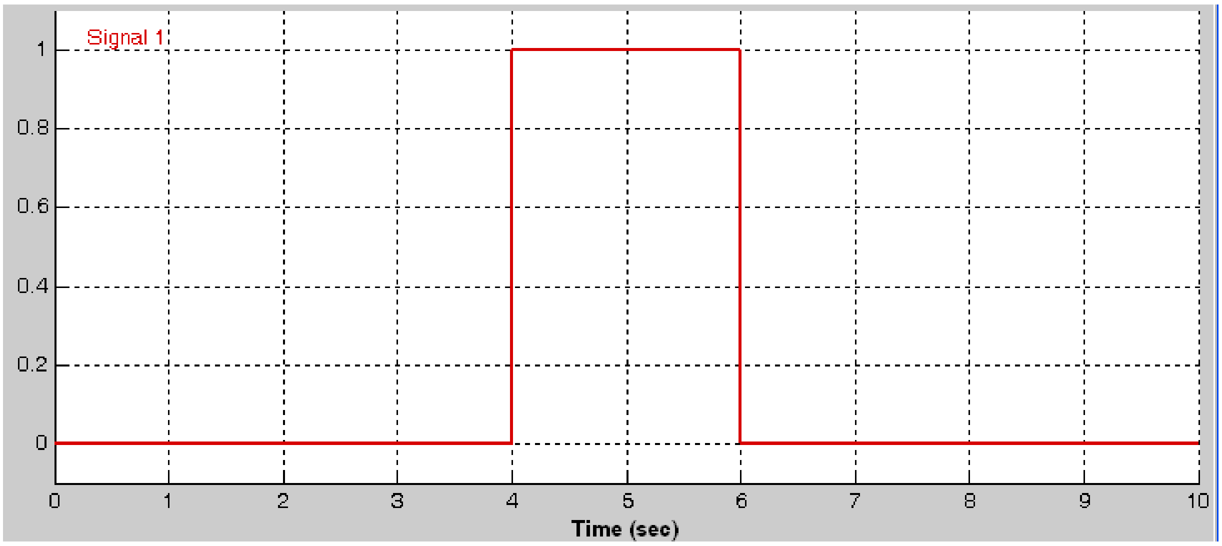


Figure 19.44. Input waveform to the Auto Correlator block in Figure 19.43

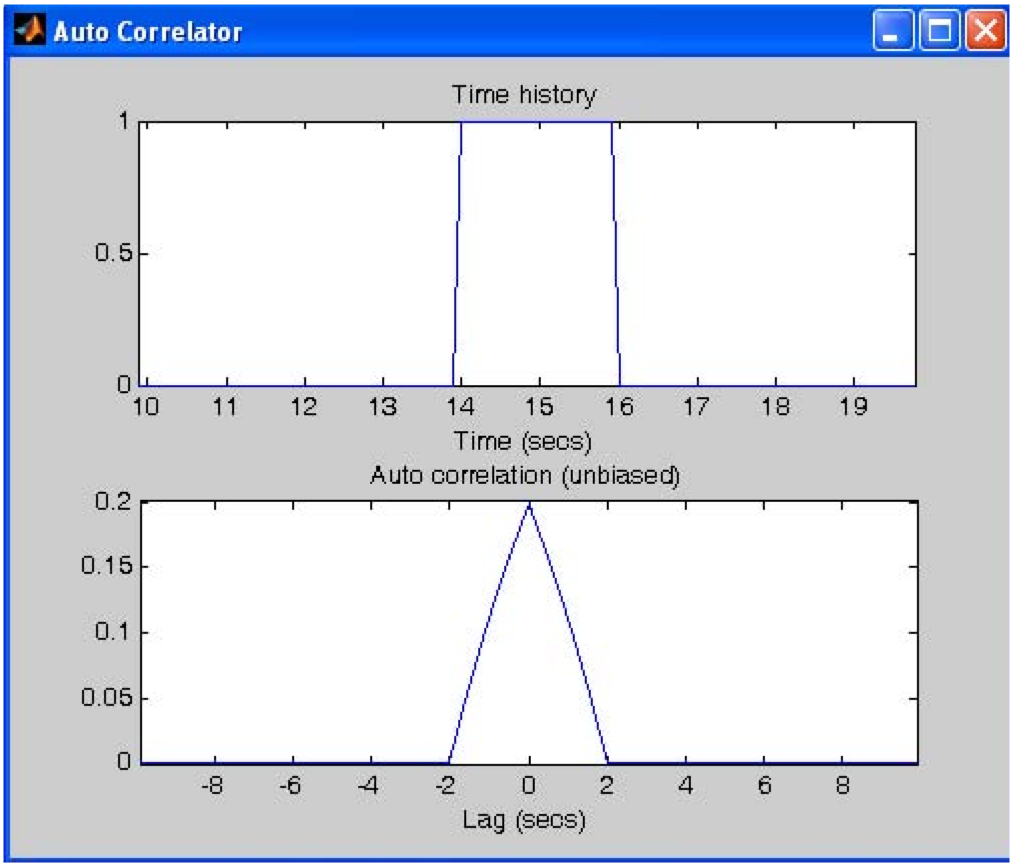


Figure 19.45. Output waveforms from the Auto Correlator block in Figure 19.43

The **Signal Builder 2** block in Figure 19.43 is configured to output the triangular waveform shown in Figure 19.46, and the **Power Spectral Density** block produces the $K(\sin x/x)^2$ waveform shown in Figure 19.47.

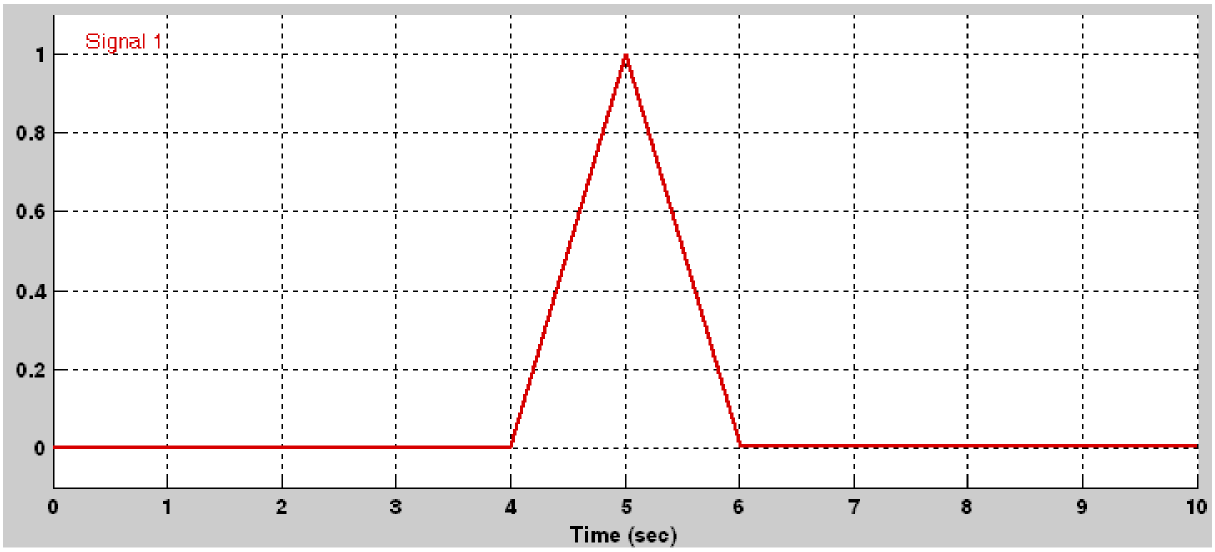


Figure 19.46. Input waveform to the Power Spectral Density block in Figure 19.43

As stated above, the power spectral density is the Fourier transform of the auto correlation function and we can prove* that the Fourier transform of a triangular pulse centered at the origin with amplitude K has the form $K(\sin x/x)^2$ and this signal has the waveform shown below in Figure 19.48.

* *The proof is provided in Signals and Systems with* MATLAB *Computing and Simulink Modeling, ISBN 978–0–9744239–9–9, Chapter 8, Exercise 6.*

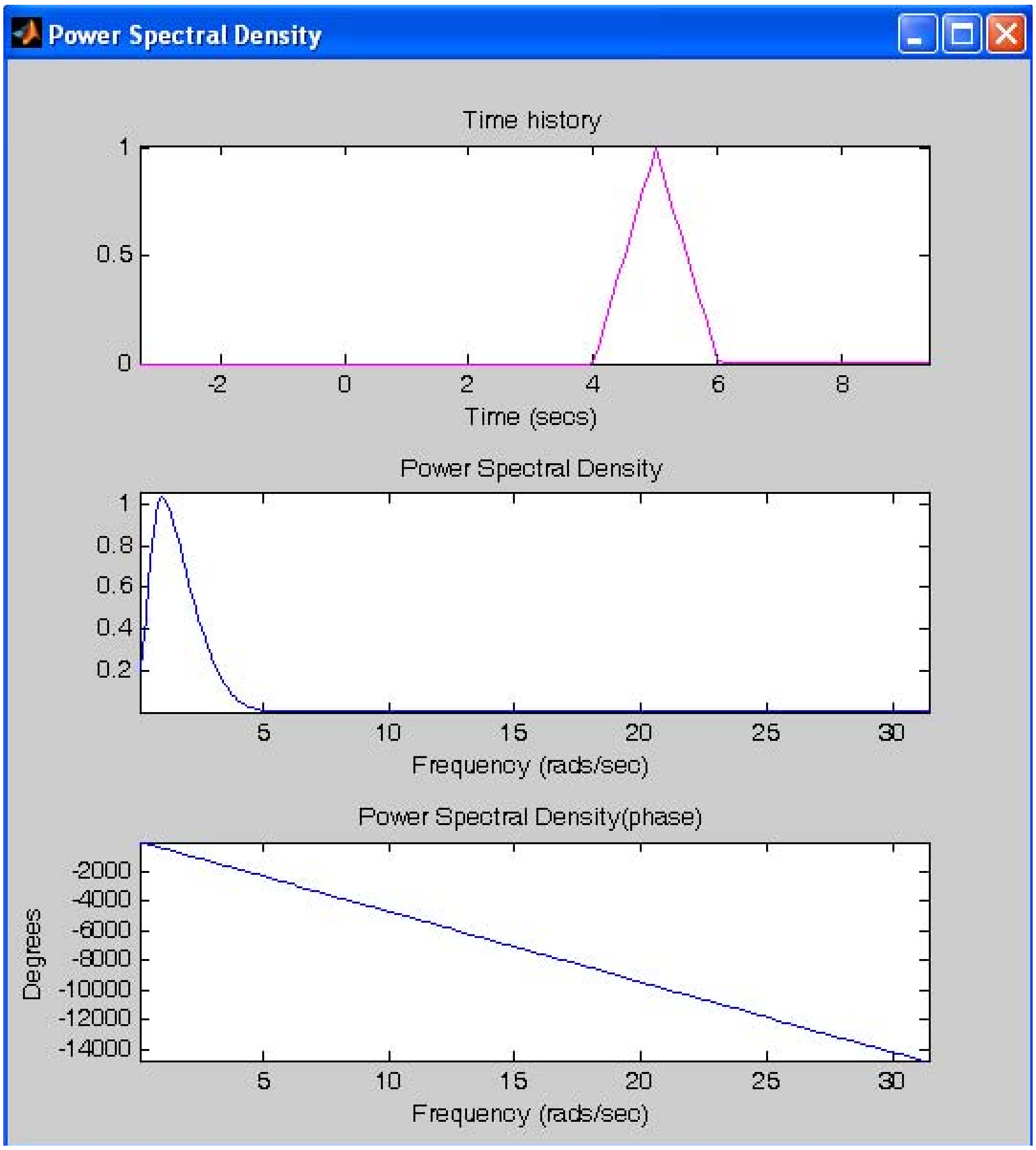


Figure 19.47. Waveforms displayed by the Power Spectral Density block in Figure 19.43

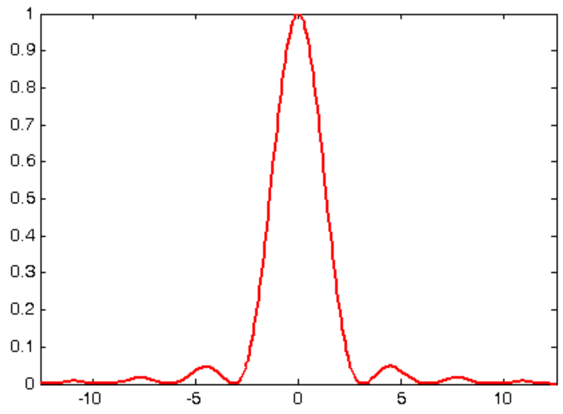


Figure 19.48. The Fourier transform of a triangular waveform centered at the origin

We observe from the power spectral density in Figure 19.48 is the same waveform as that in Figure 19.47 for $\omega > 0$.

19.3.2 The Averaging Power Spectral Density Block

The Simulink documentation describes this block as follows:

This block when hooked to the output of a system displays the frequency content of the buffer in the graph window. For more see the m–file sfunpsd.

The **Averaging Power Spectral Density** block displays the Fourier transform of the auto correlation function described in Subsection 19.3.6 below.

Example 19.14

This example is the same as Example 19.13 except that the **Power Spectral Density** block has been replaced with the **Averaging Power Spectral Density** block shown in Figure 19.49.

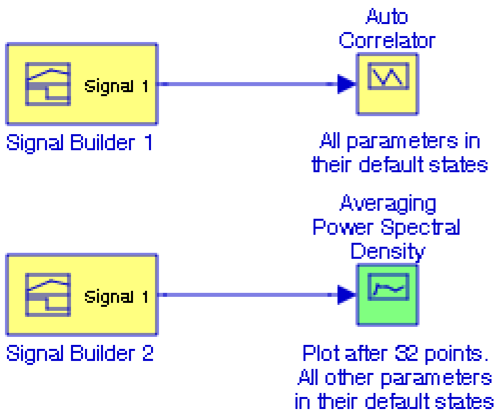
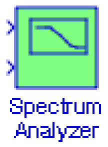

Signal 1
Signal Builder 1
Auto Correlator
All parameters in their default states
Signal 1
Signal Builder 2
Averaging Power Spectral Density
Plot after 32 points. All other parameters in their default states

Figure 19.49. Model for Example 19.14

The waveform displayed by the **Averaging Power Spectral Density** block is shown in Figure 19.50 below.

19.3.3 The Spectrum Analyzer Block



The Simulink documentation describes this block as follows:

Hook the system's input to the first port of this block and the system's output to second port. Results are displayed as the frequency response of this system. Use signals with high harmonic content for best results.

Example 19.15

The Spectrum Analyzer block in the model in Figure 19.51 displays the waveforms shown in Figure 19.52.

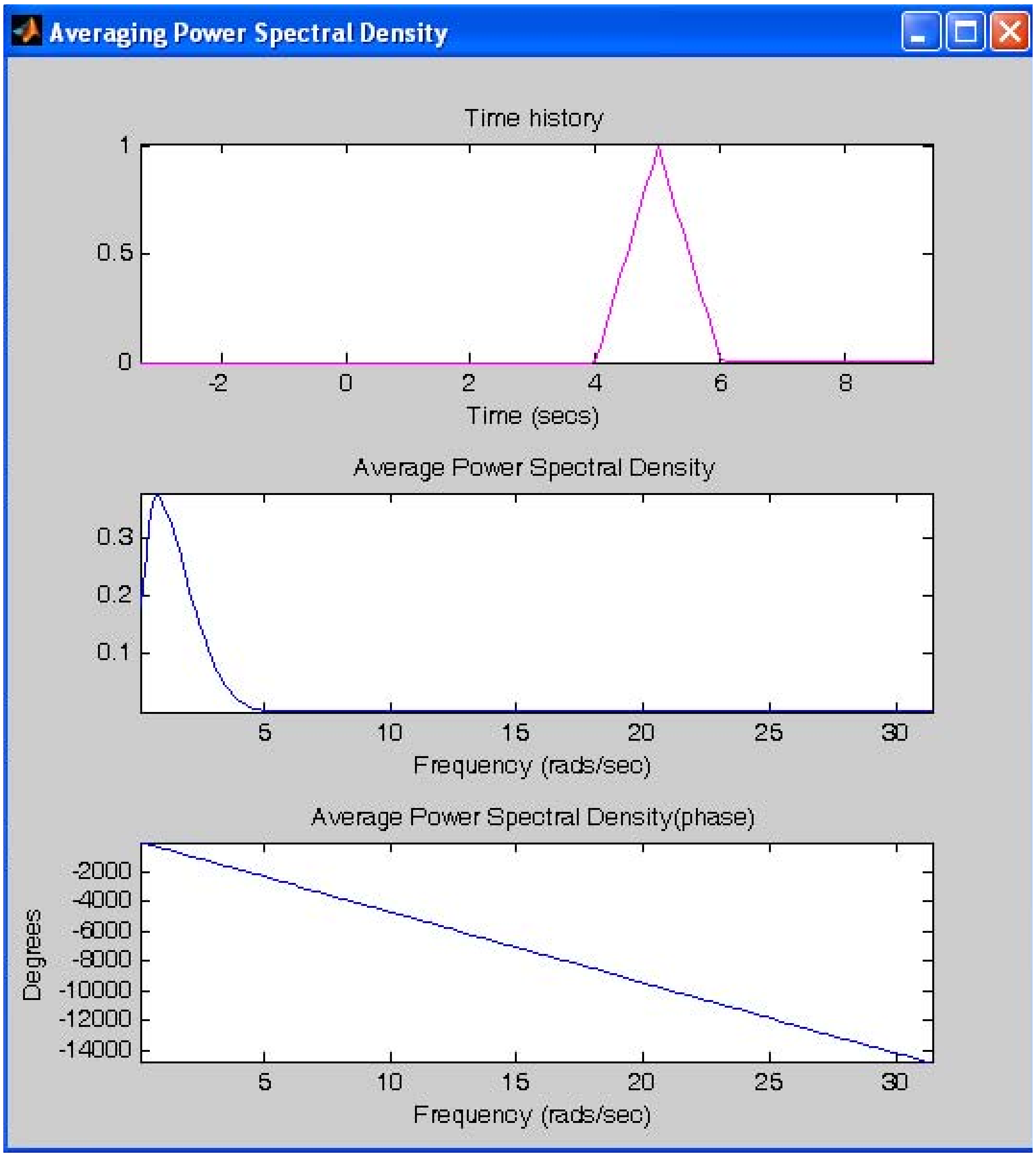

Averaging Power Spectral Density
Time history
1
0.5
0
-2
0
2
4
6
8
Time (secs)
Average Power Spectral Density
0.3
0.2
0.1
5
10
15
20
25
30
Frequency (rads/sec)
Average Power Spectral Density(phase)
Degrees
-2000
-4000
-6000
-8000
-10000
-12000
-14000
5
10
15
20
25
30
Frequency (rads/sec)

Figure 19.50.

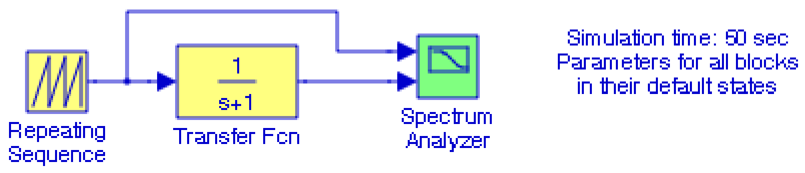


Figure 19.51. Model for Example 19.15

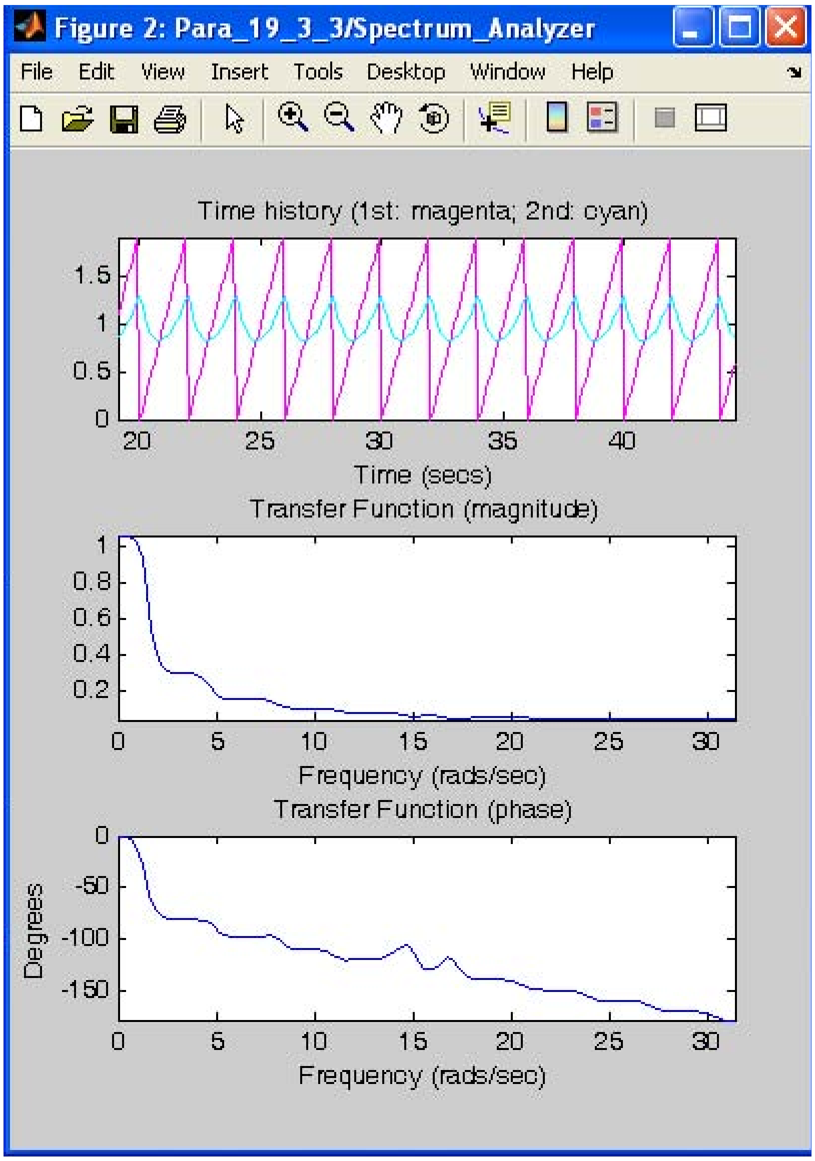
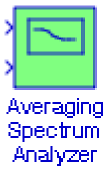


Figure 2: Para_19_3_3/Spectrum_Analyzer
File Edit View Insert Tools Desktop Window Help
Time history (1st: magenta; 2nd: cyan)
1.5
1
0.5
0
20
25
30
35
40
Time (secs)
Transfer Function (magnitude)
1
0.8
0.6
0.4
0.2
0
5
10
15
20
25
30
Frequency (rads/sec)
Transfer Function (phase)
0
-50
-100
-150
Degrees
0
5
10
15
20
25
30
Frequency (rads/sec)

Figure 19.52. Waveforms displayed by the Spectrum Analyzer block in Figure 19.51

19.3.4 The Averaging Spectrum Analyzer Block



The Simulink documentation describes this block as follows:

Hook the system's input to the first port of this block and the system's output to second port. Results are displayed as the frequency response of this system. Use signals with high harmonic content for best results.

Example 19.16

The model in Figure 19.53 produces the waveforms shown in Figure 19.54.

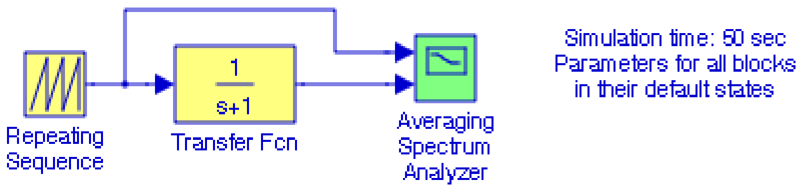


Figure 19.53. Model for Example 19.16

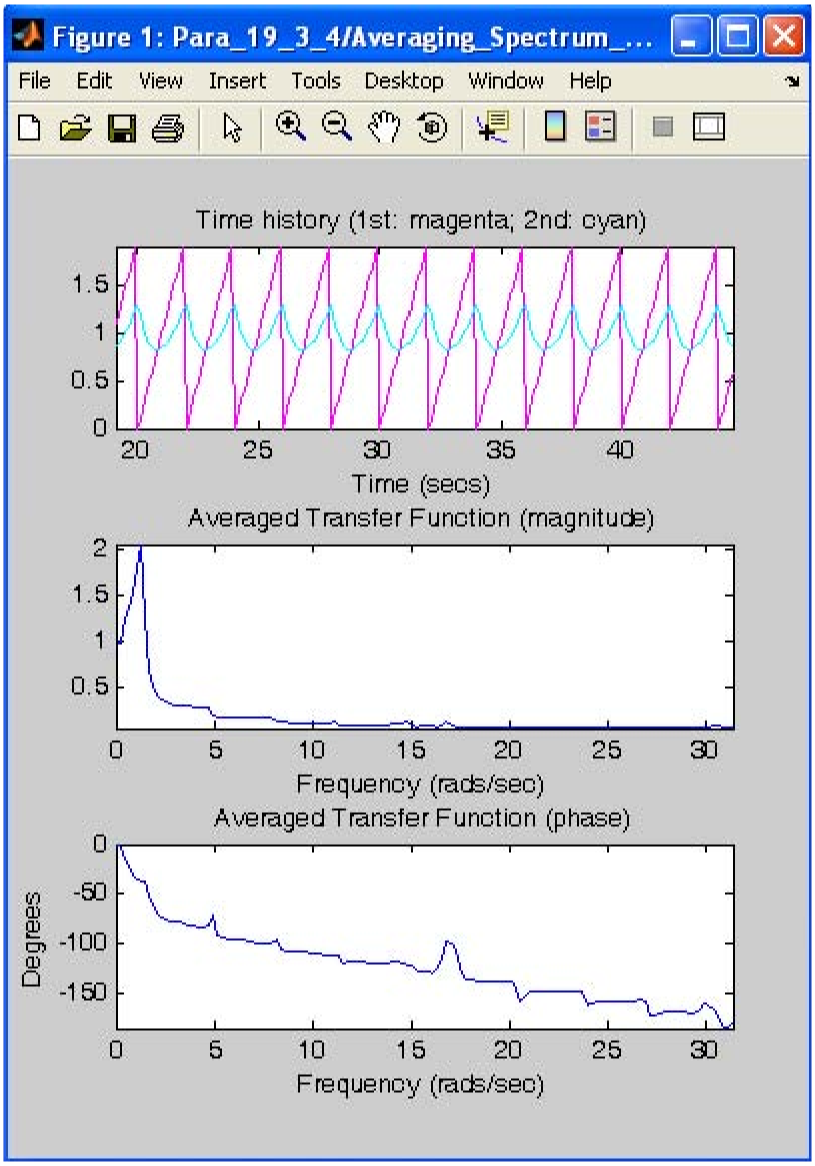
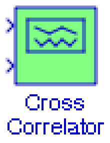


Figure 1: Para_19_3_4/Averaging_Spectrum_...
File Edit View Insert Tools Desktop Window Help
Time history (1st: magenta; 2nd: cyan)
Time (secs)
Averaged Transfer Function (magnitude)
Frequency (rads/sec)
Averaged Transfer Function (phase)
Degrees
Frequency (rads/sec)

Figure 19.54. Waveforms displayed by the Averaging Spectrum Analyzer block in Figure 19.53

19.3.5 The Cross Correlator Block



The Simulink documentation describes this block as follows:

This block when hooked to the outputs of a system displays the cross correlation of the buffer in the graph window. For more see the m–file sfuncorr.

The cross correlation function and the auto correlation function play a critical role in the design of linear methods for analyzing and processing random signals. The cross–correlation is similar in nature to the convolution* of two functions. Whereas convolution involves reversing a signal, then shifting it and multiplying by another signal, correlation only involves shifting it and multiplying.

Example 19.17

The cross correlator block in the model in Figure 19.55 displays the waveforms shown in Figure 19.56.

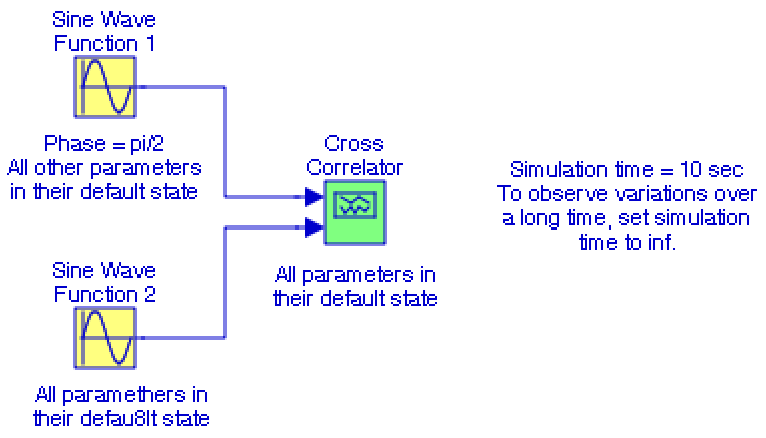


Figure 19.55. Model for Example 19.17

* *Convolution is discussed in Signals and Systems with MATLAB Computing and Simulink Modeling, ISBN 978–0–9744239–9–9, Chapter 6.*

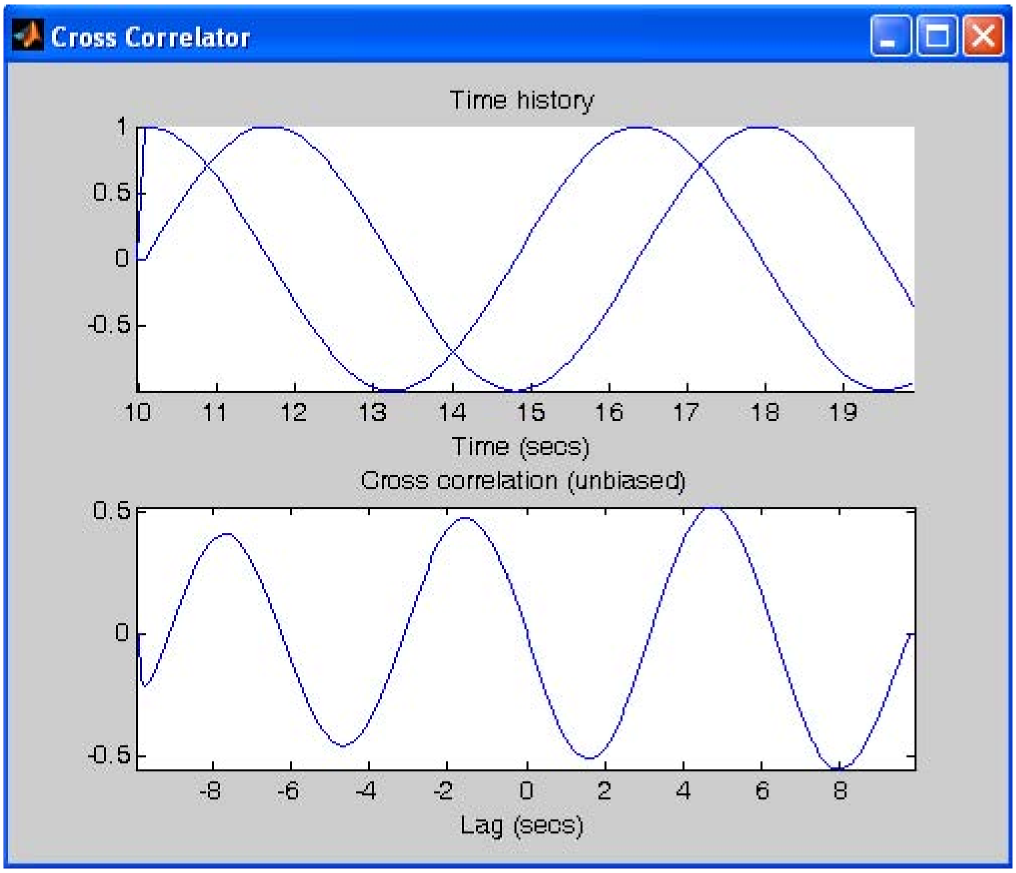


Figure 19.56. Waveforms displayed by the Cross Correlation block in Figure 19.55

The cross correlation of two signals x and y denoted as $R_{xy}(\tau)$ where τ represents a time delay is defined as

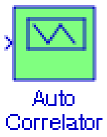
$$R_{xy}(\tau) = \lim_{t_p \to \infty} \frac{1}{t_p}\int_0^{t_p} x(t)y(t-\tau)dt \tag{19.1}$$

The cross correlation $R_{xy}(\tau)$ is an indication of how well the signals x and y are correlated for a particular value of the delay τ. If the cross correlation function peaks for a particular value of τ, this would indicate a very good correlation, which means that the two signals match each other very well. Conversely, a very small or zero value of the cross correlation function would indicate little or no correlation.

In probability and statistics, the cross–correlation is also referred to as the **covariance** cov(X, Y)* between two random vectors X and Y.

* *For a detailed discussion on covariance, please refer to Mathematics for Business, Science, and Technology, ISBN 978–1–934404–01–0.*

19.3.6 The Auto Correlator Block



The Simulink documentation describes this block as follows:

This block when hooked to the output of a system displays the auto correlation of the buffer in the graph window. For more see the m–file sfuncorr.

Auto correlation is a time–domain function that is a measure of how much a signal shape, or waveform, resembles a delayed version of itself. It is closely related to the *cepstrum*.* The value of auto correlation can vary between zero and one. A periodic signal, such as a sine wave has an auto correlation which is equal to one at zero time delay, zero at a time delay of one–half the period of the wave, and one at a time delay of one period; in other words, it is a sinusoidal wave form itself. Random noise has an auto correlation of one at zero delay, but is essentially zero at all other delays. Auto correlation is sometimes used to extract periodic signals from noise.

The auto correlation of a signal x denoted as $R_{xx}(\tau)$ where τ represents a time delay is a special case of the cross correlation function defined in relation (19.1) above with $y(t) = x(t)$, and it is defined as

$$R_{xx}(\tau) = \lim_{t_p \to \infty} \frac{1}{t_p}\int_0^{t_p} x(t)x(t-\tau)dt \qquad (19.2)$$

and this relation states that the auto correlation is the average of the product of the signal and a delayed version of the signal as a function of the delay.

Example 19.18

The Auto Correlator block in Figure 19.57 displays the waveforms in Figure 19.58.

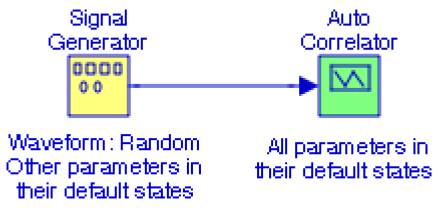


Figure 19.57. Model for Example 19.18

* *The Fourier transform of the log–magnitude spectrum.*

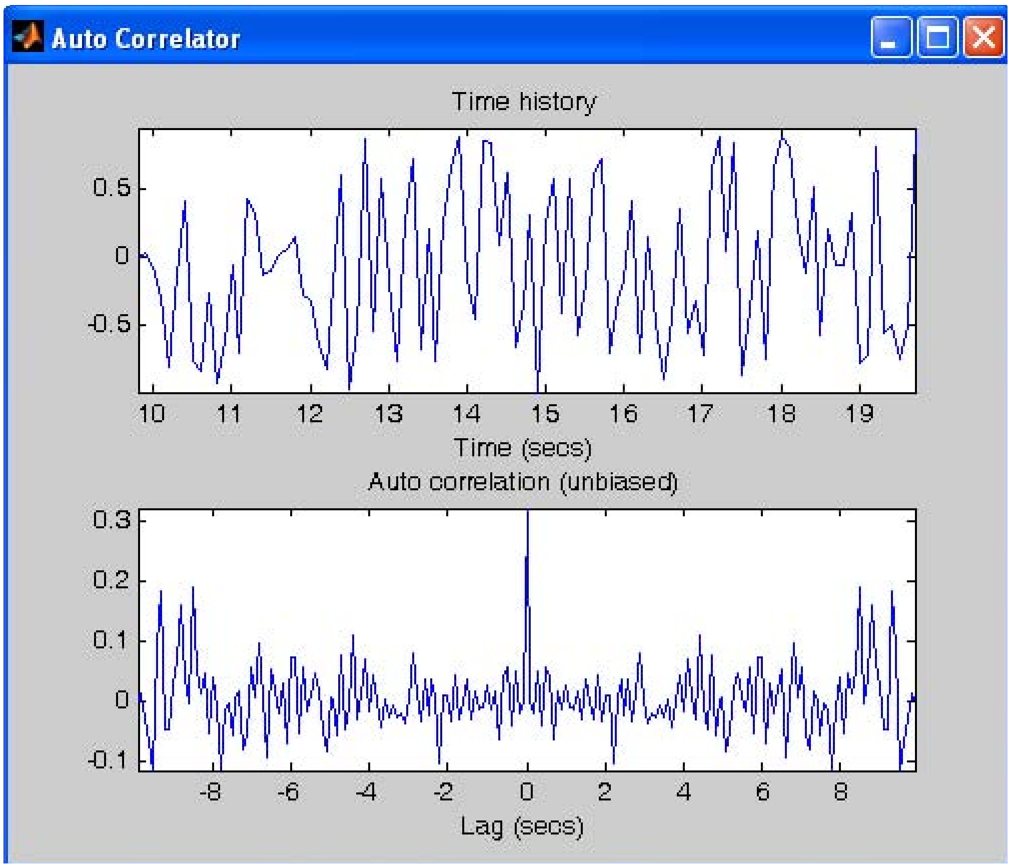


Figure 19.58. Waveforms for the model in Figure 19.57

The auto correlation signal above justifies the following two properties of the auto correlation function:

1. The auto correlation function is an even function, i.e., $R_{xx}(-\tau) = R_{xx}(\tau)$

2. The auto correlation function is maximum at the origin, i.e., $R_{xx}(0) \geq |R_{xx}(\tau)|$.

19.3.7 The Floating Bar Plot Block

Floating Bar Plot

The Simulink documentation describes this block as follows:

Displays selected signal values (click on signal) as bar plot while the simulation is running. To select multiple signals use shift–click. Each signal (selected line) is displayed in it's own axes. The

1st Y–Limits pair is used for the 1st axes, the 2nd for the 2nd axes, etc. If there are more axes, than Y–Limits pairs, the last Y–Limits pair is used.

Example 19.19

The **Floating Bar Plot** block has no input and no output. Upon execution of the simulation command this block in the model in Figure 19.59 will display the values of the selected signal lines in bar plot form as shown in Figure 19.60.

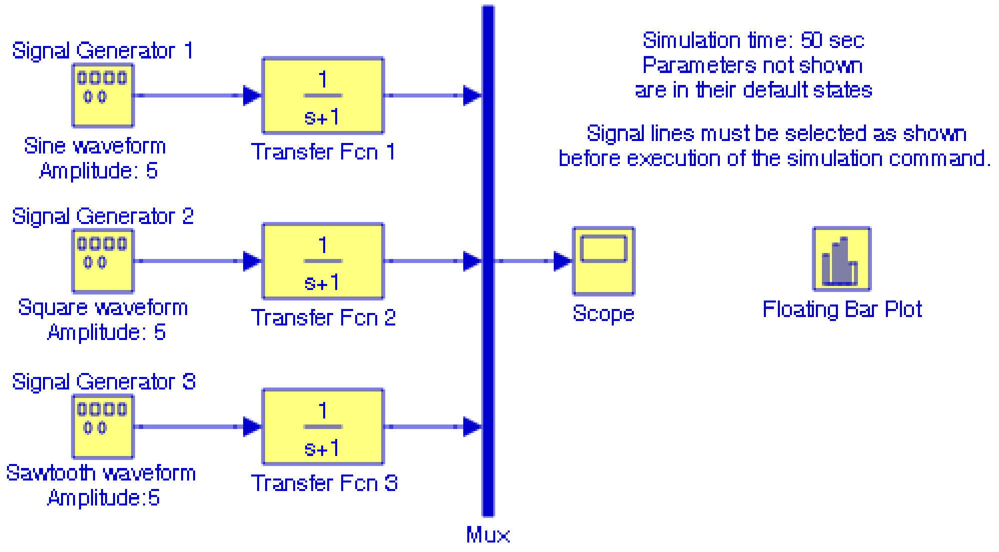


Figure 19.59. Model for Example 19.19

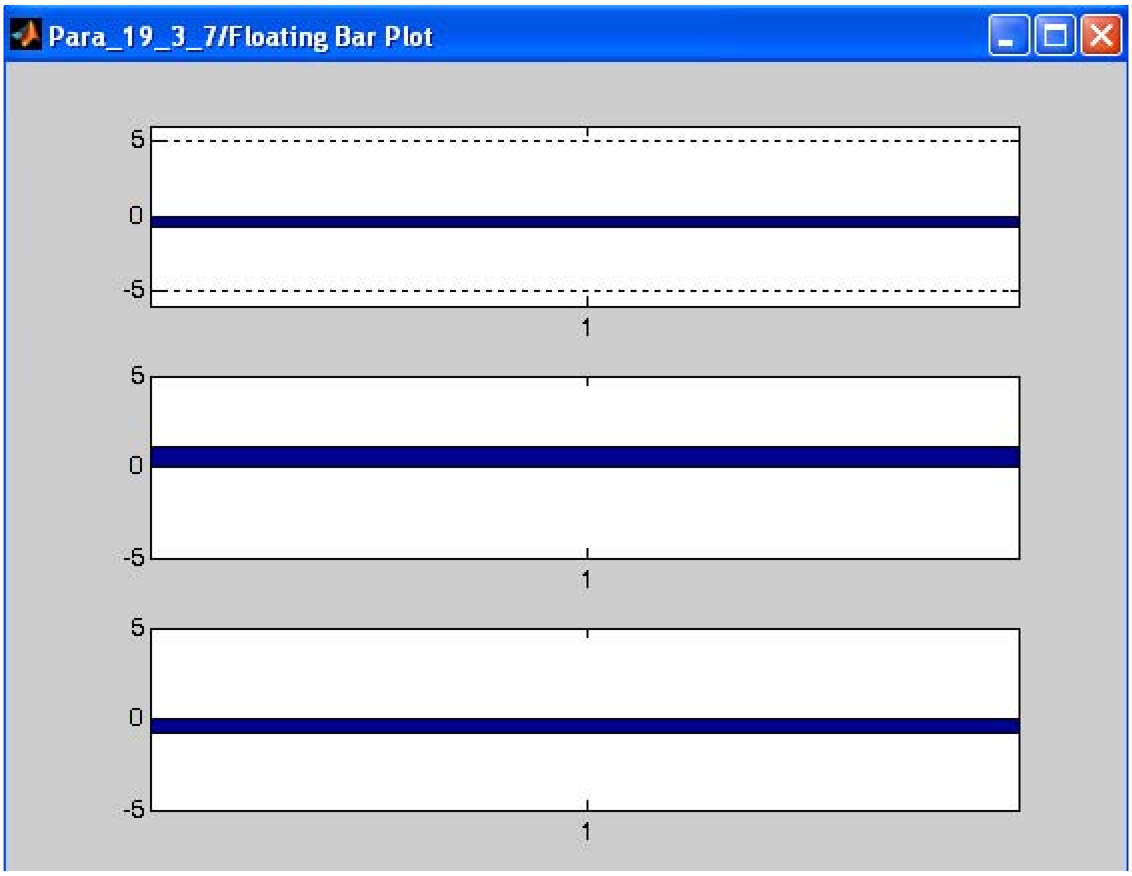
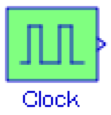


Figure 19.60. Waveforms displayed by the Floating Bar Plot in Figure 19.59

19.4 The Flip Flops Group

The **Flip Flop Group*** contains the blocks described in Subsections 19.4.1 through 19.4.5 below.

19.4.1 The Clock Block



The Simulink documentation describes this block as follows:

Digital clock for logic systems.

* *For a detailed discussion on Flip Flops, please refer to Digital Circuit Analysis and Design with Simulink Modeling and Introduction to CPLDs and FPGAs.*

Example 19.20

In Figure 19.61, the **Clock** block is a digital clock as displayed by the **Scope** block.

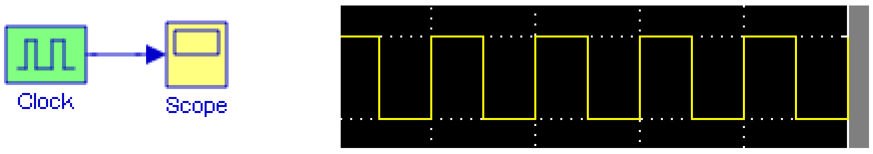
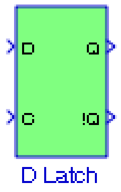


Figure 19.61. Model for Example 19.20

19.4.2 The D Latch Block



The Simulink documentation describes this block as follows:

The D latch flip flop block has the following characteristic table:

Q(t)	D(t)	Q(tnext)
0	0	0
0	1	1
1	0	0
1	1	1

The D latch transfers "data" into a memory element (flip flop). The D latch flip flop is sometimes called a gated D latch. The chip enable input signal, C, is sometimes given the designation G (for gate) to indicate that this input enables the gated latch allowing data entry into the flip flop.

Example 19.21

The model in Figure 19.62 verifies the characteristic table above.

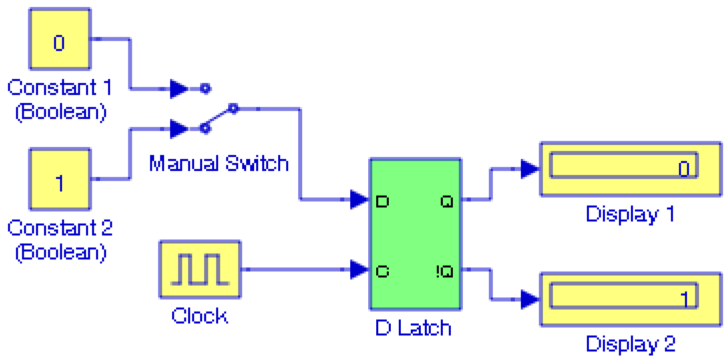
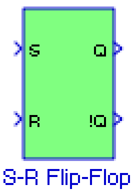


Figure 19.62. Model for Example 19.21

19.4.3 The S–R Flip Flop Block



The Simulink documentation describes this block as follows:

The S–R flip flop is also known as a set–reset flip flop. This implementation is modeled after an S–R flip flop constructed using NOR gates. The characteristic table for this block is:

S	R	Q	!Q	
1	0	1	0	
0	0	1	0	(after S == 1, R == 0)
0	1	0	1	
0	0	0	1	(after S == 0, R == 1)
1	1	0	0	

In an S–R flip flop that is implemented with NOR gates, when a 1 is applied to both the set and reset inputs, both outputs go to 0. Technically, this state is undefined and is usually avoided. Note, if the flip–flop is implemented with NAND gates, when a 0 is applied to both inputs, both outputs go to 0 and when a 1 is applied to both inputs, the output depends on the previous state of the flip–flop (previous value of Q).

Example 19.22

The model in Figure 19.63 illustrates the fact that when a logical 1 is applied to both S and R inputs, both outputs Q and $\bar{Q}$ go to logical 0, and this condition should be avoided.

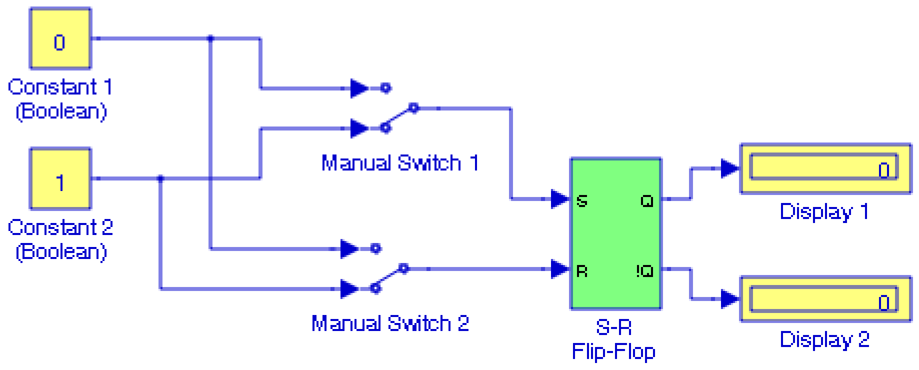
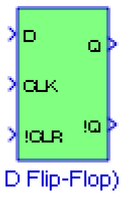


Figure 19.63. Model for Example 19.22

19.4.4 The D Flip Flop Block



The Simulink documentation describes this block as follows:

The D flip flop block has the following characteristic table:

Q(t)	D(t)	Q(tnext)
0	0	0
0	1	1
1	0	0
1	1	1

Q(tnext) refers to the output on a clock pulse (CLK) rising edge and when the chip is enabled (!CLR ~= 0).

The D flip flop transfers "data" into a memory element (flip flop) on each clock pulse (CLK). The chip enable input signal, !CLR, is sometimes given the designation G (for gate) to indicate that this input enables the gated latch allowing data entry into the flip flop.

Example 19.23

The model in Figure 19.64 illustrates the operation of the D flip flop.

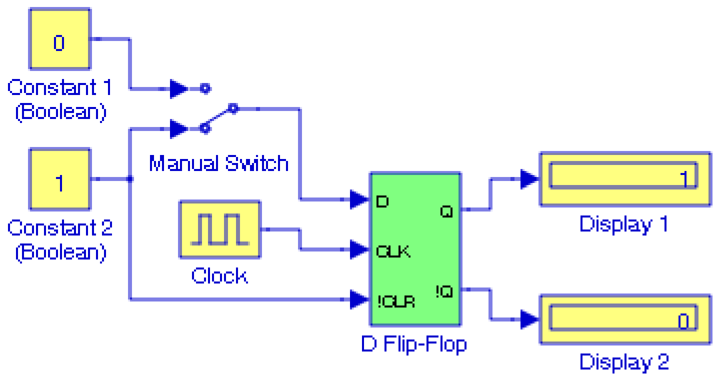
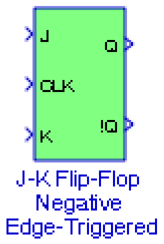


Figure 19.64. Model for Example 19.23

19.4.5 The J–K Flip Flop Block



The Simulink documentation describes this block as follows:

The J–K flip flop block has the following characteristic table:

```
Q(t)  J(t)  K(t)   Q(tnext)
---------------------------
  0     0     0        0
  0     0     1        0
  0     1     0        1
  0     1     1        1
  1     0     0        1
  1     0     1        0
  1     1     0        1
  1     1     1        0
```

The JK flip flop transfers "data" into a memory element (flip flop) on the negative edge of each clock pulse (CLK). Q(tnext) refers to the output on a clock pulse (CLK) falling (negative) edge.

Example 19.24

The model in Figure 19.65 illustrates the operation of the JK flip flop. For best results, we can set the simulation time to **inf** and observe that the flip flop toggles, that is, the outputs Q and $\overline{Q}$ alternate between logical 0 and logical 1.

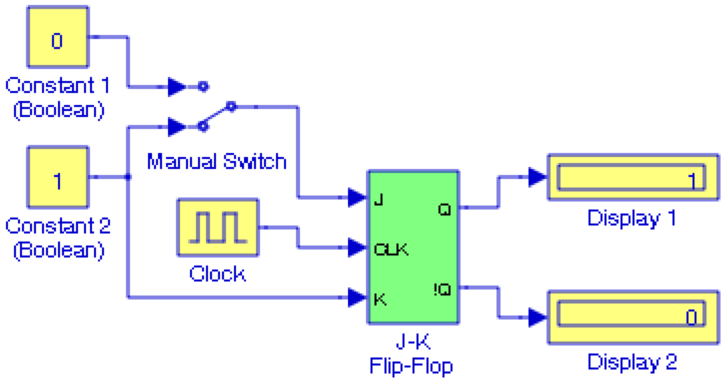
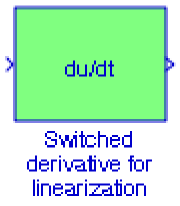


Figure 19.65. Model for Example 19.24

19.5 The Linearization Group

The **Linearization Group** contains the blocks described in Subsections 19.5.1 and 19.5.2 below.

19.5.1 The Switched Derivative for Linearization Block



The Simulink documentation describes this block as follows:

This block should be used in place of the derivative when you are linearizing the model. It approximates the derivative with a proper transfer function.

Example 19.25

Let us consider the model in Figure 19.66.

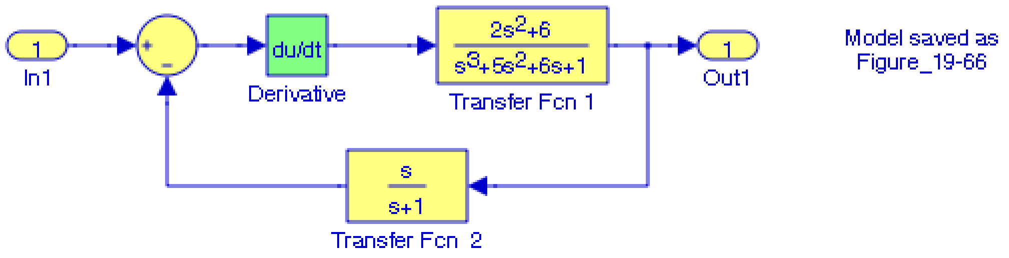


Figure 19.66. Model for Example 19.25

We can linearize this model with the MATLAB function **linmod('x')** as discussed in Chapter 3. At the MATLAB command prompt we enter:

```
[A B C D]=linmod('Figure_19_66') *
```

and MATLAB outputs the matrices A, B, C, and D as shown below.

```
A =
    -5     -6     -1      0
     1      0      0      0
     0      1      0      0
     2      0      6     -1
B =
     0
     0
     0
     0
C =
     2      0      6      0
D =
     0
```

Next, let us consider the model in Figure 19.67 where the derivative block in the previous model is replaced with switched derivative for linearization block.

* *The model must be open before we execute this statement.*

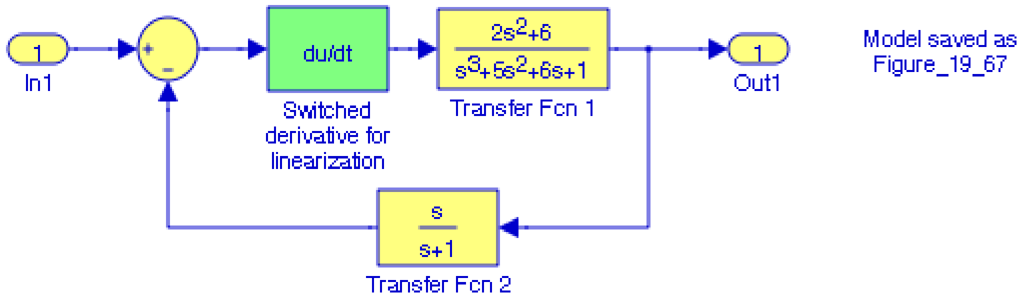

1
In1
+
-
du/dt
Switched derivative for linearization
$\frac{2s^2+6}{s^3+5s^2+6s+1}$
Transfer Fcn 1
1
Out1
Model saved as Figure_19_67
$\frac{s}{s+1}$
Transfer Fcn 2

Figure 19.67. Model for Example 19.25 with Switched derivative for linearization block

We can linearize this modified model with the following MATLAB function **linmod('x')** as shown below.

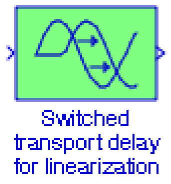
```
[A B C D]=linmod('Figure_19_67')
```

and MATLAB outputs the matrices and vectors below.

```
A =
               -5          -6          -1           0      -10000
                1           0           0           0           0
                0           1           0           0           0
                2           0           6          -1           0
                0           0           0           0        -100
B =
          0
          0
          0
          0
          0
C =
          2     0     6     0     0
D =
          0
```

We observe that the model in Figure 19.67 extracts a more precise linear model.

19.5.2 The Switched Transport Delay for Linearization Block



The Simulink documentation describes this block with the following six paragraphs:

1. The Transport Delay block delays the input by a specified amount of time. It can be used to simulate a time delay.At the start of the simulation, the block outputs the Initial output parameter until the simulation time exceeds the Time delay parameter, when the block begins generating the delayed input. The Time delay parameter must be nonnegative.The block stores input points and simulation times during a simulation in a buffer whose initial size is defined by the Initial buffer size parameter. If the number of points exceeds the buffer size, the block allocates additional memory and Simulink displays a message after the simulation that indicates the total buffer size needed.

2. Because allocating memory slows down the simulation, define this parameter value carefully if simulation speed is an issue. For long time delays, this block might use a large amount of memory, particularly for dimensionalized input.When output is required at a time that does not correspond to the times of the stored input values, the block interpolates linearly between points.

3. When the delay is smaller than the step size, the block extrapolates from the last output point, which can produce inaccurate results. Because the block does not have direct feedthrough, it cannot use the current input to calculate its output value. To illustrate this point, consider a fixed–step simulation with a step size of 1 and the current time at $t = 5$. If the delay is 0.5, the block needs to generate a point at $t = 4.5$. Because the most recent stored time value is at $t = 4$, the block performs forward extrapolation.

4. The Transport Delay block does not interpolate discrete signals. Instead, it returns the discrete value at the required time.

5. This block differs from the Unit Delay block, which delays and holds the output on sample hits only. Using linmod to linearize a model that contains a Transport Delay block can be troublesome.

6. For more information about ways to avoid the problem, see Linearizing Models.

Example 19.26

Let us consider the model in Figure 19.68.

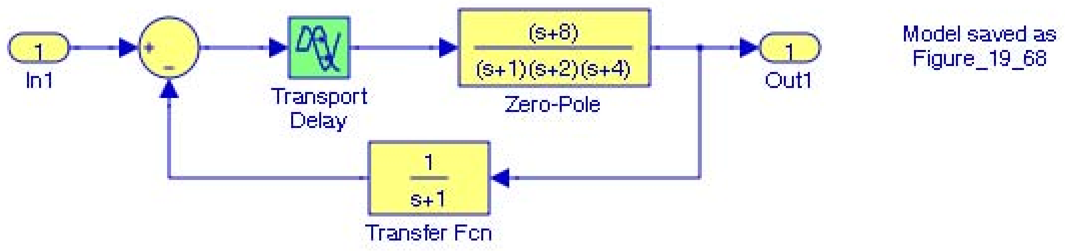


Figure 19.68. Model for Example 19.26

We can linearize this model with the MATLAB function **linmod('x')** as discussed in Chapter 3. At the MATLAB command prompt we enter:

```
[A B C D]=linmod('Figure_19_68')
```

and MATLAB outputs the matrices A, B, C, and D as shown below.

```
A =
   -1.0000         0         0   -1.0000
    7.0000   -6.0000   -2.8284   -1.0000
         0    2.8284         0         0
         0         0    0.3536   -1.0000
B =
     1
     1
     0
     0
C =
         0         0    0.3536         0
 D =
         0
```

Next, let us consider the model in Figure 19.69 where the transport delay block in the previous model is replaced with a Switched transport delay for linearization block.

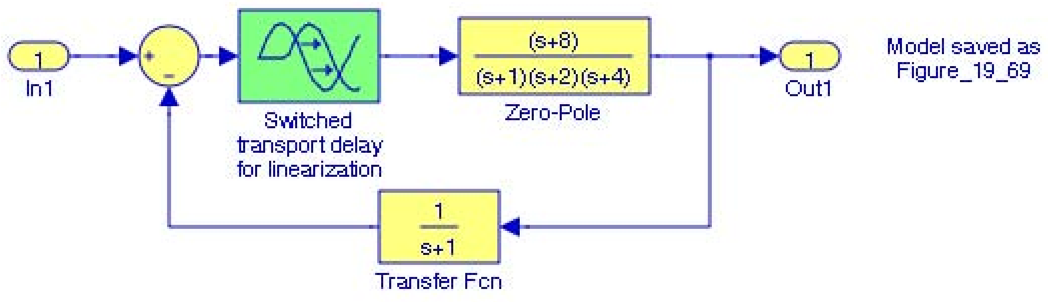

1
In1
+
-
Switched transport delay for linearization
(s+8)
(s+1)(s+2)(s+4)
Zero-Pole
1
Out1
Model saved as Figure_19_69
1
s+1
Transfer Fcn

Figure 19.69. Model for Example 19.26

We can linearize this modified model with the following MATLAB function **linmod('x')** as shown below.

```
[A B C D]=linmod('Figure_19_69')
```

and MATLAB outputs the matrices A, B, C, and D as shown below.

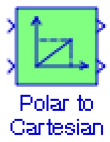
```
A =
   -1.0000         0         0   -1.0000   -6.0000         0
    7.0000   -6.0000   -2.8284   -1.0000   -6.0000         0
         0    2.8284         0         0         0         0
         0         0    0.3536   -1.0000         0         0
         0         0         0   -1.0000   -3.0000   -3.0000
         0         0         0         0    1.0000         0
B =
     1
     1
     0
     0
     1
     0
C =
         0         0    0.3536         0         0         0
D =
     0
```

We observe that the model in Figure 19.69 extracts a more precise linear model.

19.6 The Transformations Group

The **Transformations Group** contains the blocks described in Subsections 19.6.1 through 19.6.8 below.

19.6.1 The Polar to Cartesian Block



The **Polar to Cartesian** block performs the transformation $r\angle\theta = r\cos\theta + jr\sin\theta$ as shown in Figure 19.70 below, where the angle θ is in radians.

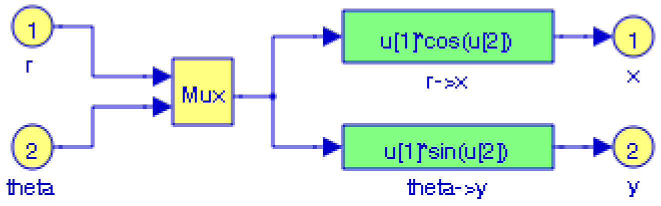


Figure 19.70. Model for Polar to Cartesian transformation

Example 19.27

The model in Figure 19.71 performs the transformation $5\angle 36.87° = 4 + j3$.

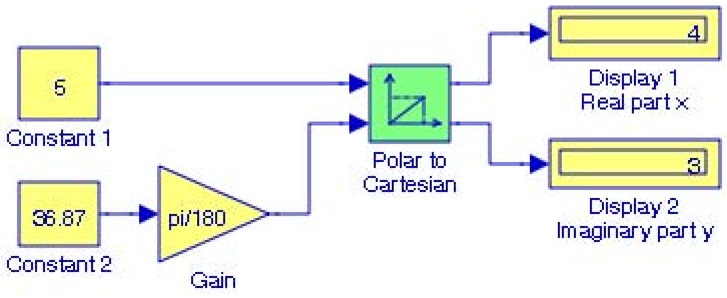


Figure 19.71. Model for Example 19.27

19.6.2 The Cartesian to Polar Block

The **Cartesian to Polar** block performs the transformation $r\cos\theta + jr\sin\theta = r\angle\theta$ as shown in Figure 19.72 below, where the angle θ is in radians.

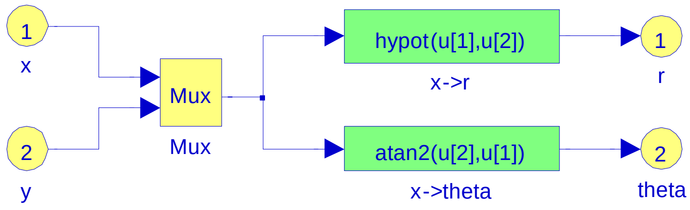


Figure 19.72. Model for Cartesian to Polar transformation

Example 19.28

The model in Figure 19.73 performs the transformation $4 + j3 = 5\angle 36.87°$.

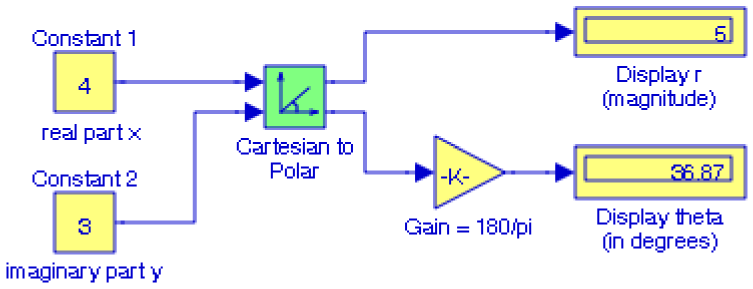
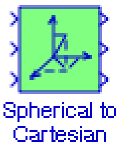


Figure 19.73. Model for Example 19.28

For two additional examples, see the **Radar Tracking Using Embedded MATLAB** demo by typing sldemo_radar_eml at the MATLAB command prompt, and **Missile Guidance System** demo by typing aero_guidance at the MATLAB command prompt.

19.6.3 The Spherical to Cartesian Block



If (ρ, θ, ϕ) are the spherical coordinates and (x, y, z) are the rectangular coordinates of the point P, shown in Figure 19.74, the **Spherical to Cartesian** block performs the transformation $x = \rho\cos\theta\sin\phi$, $y = \rho\sin\theta\sin\phi$, and $z = \rho\cos\phi$, where the angles θ and ϕ are in radians.

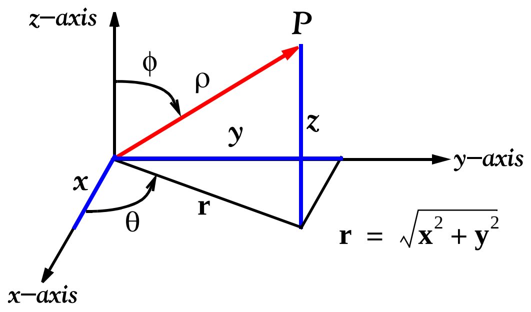


Figure 19.74. Relation between Cartesian and Spherical coordinates

The Simulink model for this transformation is shown in Figure 19.75 below.

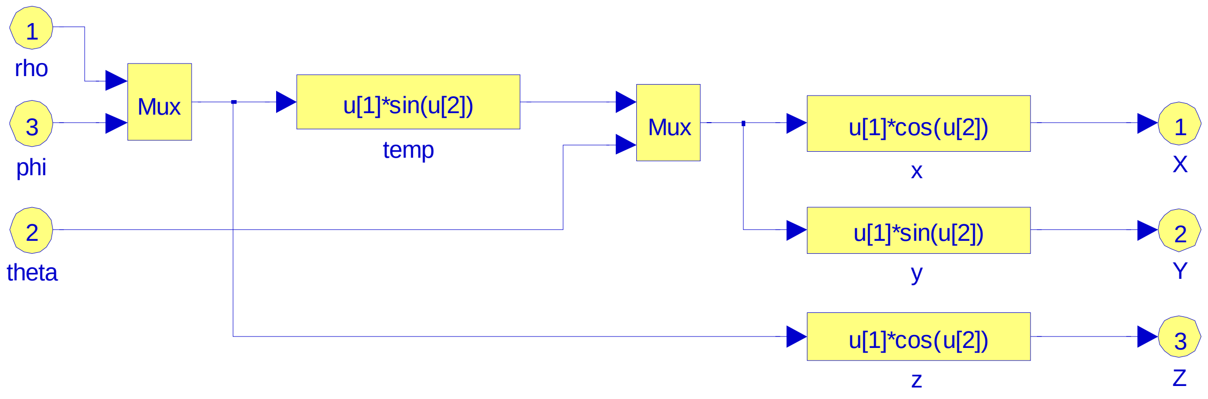


Figure 19.75. Model for Spherical to Cartesian transformation

Example 19.29

The model in Figure 19.76 below performs the Spherical to Cartesian transformation.

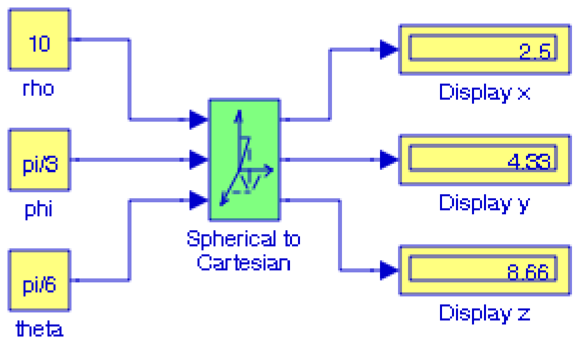


Figure 19.76. Model for Example 19.29

19.6.4 The Cartesian to Spherical Block

If (x, y, z) are the rectangular coordinates and (ρ, θ, ϕ) are the spherical coordinates of the point P, shown in Figure 19.74, above, the **Cartesian to Spherical** block performs the transformation $\rho = \sqrt{x^2+y^2+z^2}$, $\theta = \tan^{-1}(y/x)$, and $\phi = \tan^{-1}(z/(\sqrt{x^2+y^2+z^2}))$, where the angles θ and ϕ are in radians.

The Simulink model for this transformation is shown in Figure 19.77 below.

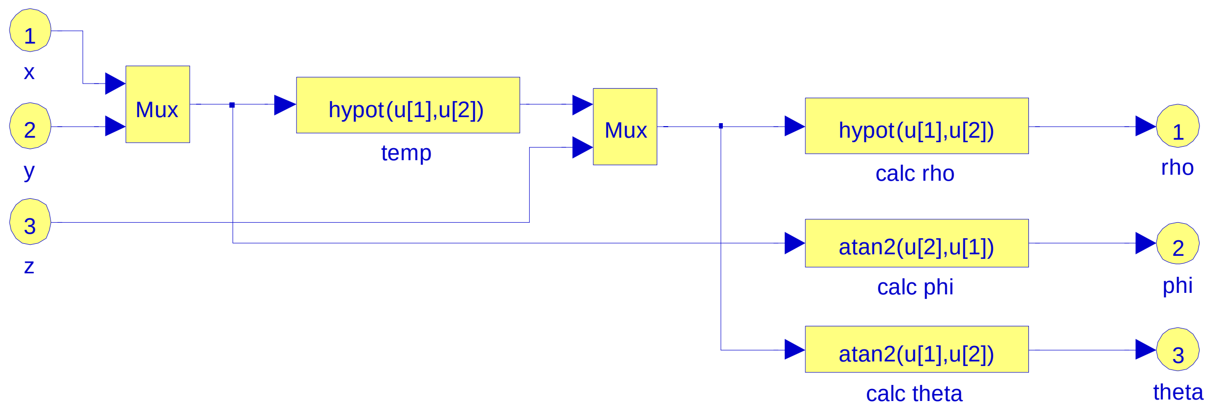


Figure 19.77. Model for Cartesian to Spherical transformation

Example 19.30

The model in Figure 19.78 below performs the Spherical to Cartesian transformation.

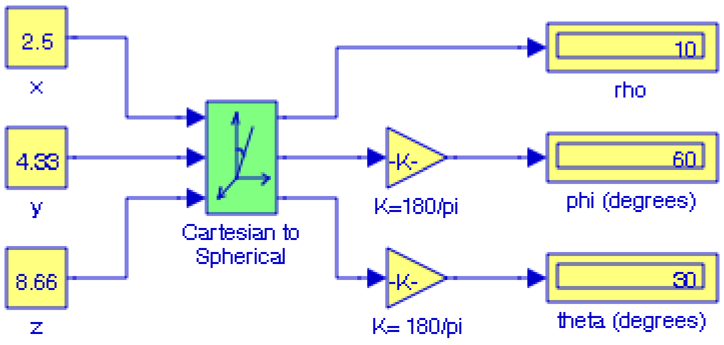
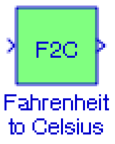


Figure 19.78. Model for Example 19.30

19.6.5 The Fahrenheit to Celsius Block



To convert degrees Fahrenheit (^0F) to degrees Celsius (^0C), we use the relation $^0C = \frac{5}{9}(^0F - 32)$. This block converts from degrees Fahrenheit to degrees Celsius.

The Simulink model for this transformation is shown in Figure 19.79 below.

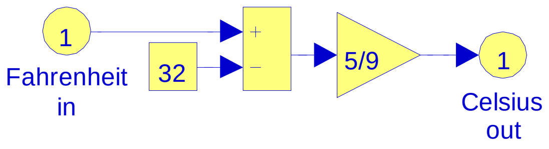


Figure 19.79. Model for degrees Fahrenheit to degrees Celsius transformation

Example 19.31

The model in Figure 19.80 performs the Fahrenheit (^0F) to degrees Celsius (^0C), transformation.

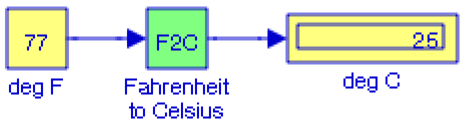
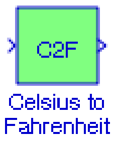


Figure 19.80. Model for Example 19.31

19.6.6 The Celsius to Fahrenheit Block



To convert degrees Celsius $({}^0\mathrm{C})$ to degrees Fahrenheit $({}^0\mathrm{F})$, we use the relation ${}^0\mathrm{F} = \frac{9}{5}({}^0\mathrm{F} + 32)$.

This block converts from degrees Celsius to degrees Fahrenheit.

The Simulink model for this transformation is shown in Figure 19.81 below.

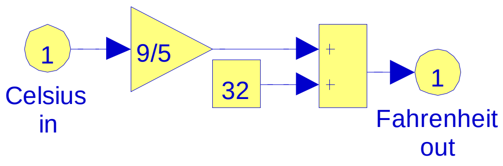


Figure 19.81. Model for degrees Celsius degrees to degrees Fahrenheit transformation

Example 19.32

The model in Figure 19.82 below performs the degrees Celsius $({}^0\mathrm{C})$ to degrees Fahrenheit $({}^0\mathrm{F})$, transformation.

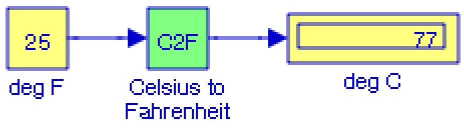
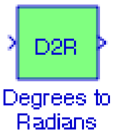


Figure 19.82. Model for Example 19.32

19.6.7 The Degrees to Radians Block



To convert degrees to radians we use the relation $\mathrm{rad} = \mathrm{deg} \times \frac{\pi}{180}$. This block converts from Degrees to Radians.

The Simulink model for this transformation is shown in Figure 19.83 below.

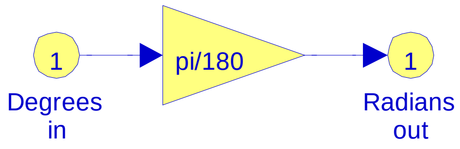


Figure 19.83. Model for degrees to radians block

Example 19.33

The model in Figure 19.84 below performs the degrees to radians transformation.

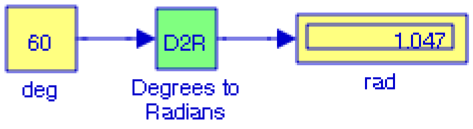
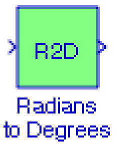


Figure 19.84. Model for Example 19.33

19.6.8 The Radians to Degrees Block



To convert radians to degrees we use the relation $\mathrm{deg} = \mathrm{rad} \times \frac{180}{\pi}$. This block converts from Radians to Degrees.

The Simulink model for this transformation is shown in Figure 19.85 below.

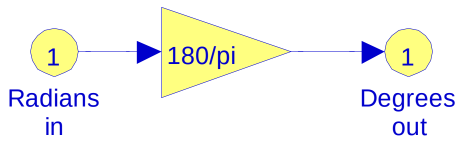


Figure 19.85. Model for radians to degrees block

Example 19.34

The model in Figure 19.86 below performs the radians to degrees transformation.

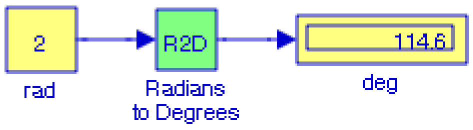


Figure 19.86. Model for Example 19.34

19.7 Summary

- When using the Discrete Transfer Fcn (with initial states) block, we specify the initial states for the transfer function. The state ordering is determined by the m–file `tf2ss`.
- When using the Discrete Transfer Fcn (with initial outputs) block, we specify the initial output for the transfer function. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved.
- When using the Discrete Zero–Pole (with initial states) block, we specify the initial states for the transfer function. The state ordering is determined by the m–file `zp2ss`.
- When using the Discrete Zero–Pole (with initial outputs) block, we specify the initial output for the zero–pole–gain system. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved.
- We use the Idealized ADC Quantizer block to model an ideal analog to digital converter.
- When using the Transfer Fcn (with initial states) block, we specify the initial states for the transfer function. The state ordering is determined by the m–file `tf2ss`.
- When using the Transfer Fcn (with initial outputs) block, we specify the initial output for the transfer function. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved.
- When using the Zero–Pole (with initial states) block, we specify the initial states for the transfer function. The state ordering is determined by the m–file `zp2ss`.
- When using the Zero–Pole (with initial outputs) block, we specify the initial output for the zero–pole–gain system. An optimization routine attempts to determine the appropriate initial states so that the specified initial output is achieved.
- When using the State–Space (with initial outputs) block, we specify an initial output. An optimization routine is used to attempt to find the steady state x values that satisfy the initial output. The block states will be initialized to these values.
- When using the PID Controller block, we specify the Proportional, Integral and Derivative terms.
- When using the PID Controller (with Approximate Derivative) block, we specify the Proportional, Integral and Derivative and divisor terms. The derivative term is implemented using an $s/(s/N+1)$ transfer function block.
- The Power Spectral Density block displays the Fourier transform of the auto correlation function.
- The Averaging Power Spectral Density block displays the average of the Fourier transform of the auto correlation function.

- The Spectrum Analyzer block displays the frequency content of a system.
- The Averaging Spectrum Analyzer block displays the average of the frequency content of a system.
- The Cross Correlator block displays the cross correlation of two signals x and y denoted as $R_{xy}(\tau)$ where τ represents a time delay is defined as

$$R_{xy}(\tau) = \lim_{t_p \to \infty} \frac{1}{t_p} \int_0^{t_p} x(t)y(t-\tau)dt$$

- The Auto Correlator block displays auto correlation of a signal denoted as $R_{xx}(\tau)$ where τ represents a time delay, and it is defined as

$$R_{xx}(\tau) = \lim_{t_p \to \infty} \frac{1}{t_p} \int_0^{t_p} x(t)x(t-\tau)dt$$

  that is, the auto correlation is the average of the product of the signal and a delayed version of the signal as a function of the delay.
- The Floating Bar Plot block has no input and no output. Upon execution of the simulation command, this block will display the values of selected signal lines in bar plot form
- The Clock block is a digital clock for logic systems such as flip flops.
- The D latch block transfers data into a memory element (flip flop) and has the following characteristic table:

Q(t)	D(t)	Q(tnext)
0	0	0
0	1	1
1	0	0
1	1	1

- The S–R flip flop block is modeled after an S–R flip–flop constructed using NOR gates. The characteristic table for this block is:

S	R	Q	!Q	
1	0	1	0	
0	0	1	0	(after S == 1, R == 0)
0	1	0	1	
0	0	0	1	(after S == 0, R == 1)
1	1	0	0	

- The D flip flop block has the following characteristic table:

Q(t)	D(t)	Q(tnext)
0	0	0
0	1	1
1	0	0
1	1	1

- The JK flip flop block has the following characteristic table:

Q(t)	J(t)	K(t)	Q(tnext)
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	0

- The Linearization Group in this library contains the Switched Derivative for Linearization and the Switched Transport Delay for Linearization blocks and both are for use with the MATLAB **linmod** function.

- The Transformations Group in this library contains the following eight blocks:

1. Polar to Cartesian coordinates block
2. Cartesian to Polar coordinates block
3. Spherical to Cartesian coordinates block
4. Cartesian to Spherical coordinates block
5. Farherheit degrees to Celsius degrees conversion
6. Celsius degrees to Farherheit degrees conversion
7. Degrees to Radians conversion
8. Radians to Degrees conversion

Chapter 20

Engineering Applications

This chapter is devoted to engineering applications with examples using appropriate Simulink blocks to illustrate the application of the blocks in the libraries which we described in Chapters 2 through 19. Most of these applications may be considered components or subsystems of large systems such as the demos provided by Simulink.

20.1 Applications to Differential Equations

We will present several applications to differential equations in Subsections 20.1.1 through 20.1.10 below, where in Subsections 20.1.1 through 20.1.6 we have derived the solutions as a brief review, and for convenience to the reader. In previous chapters we used Integrator blocks to display the waveforms of the solutions. In these subsections we have created models based on the solutions, to illustrate the applications of several Simulink blocks, and in some instances to verify the results with MATLAB statements.

It is also useful to remember that some analogies between mechanical and electrical components are as shown in Table 20.1 below.

TABLE 20.1 Analogies of mechanical and electrical components

Mechanical	Electrical
Mass m	Inductance L
Displacement X	Charge Q
Damping factor β	Resistance R
Spring constant k	Reciprocal of Capacitance, i.e., $1/C$
Force F	Electromotive force E (or V)

20.1.1 A Math Example

Figure 20.1 below shows a bouncing ball. The ball is dropped from a meters above a flat surface, and each time the ball hits the ground after falling a distance h it rebounds a distance rh, where r is a positive number less than one. We will derive an expression for the computation of the total distance s that the ball travels and we will create a Simulink model.

The distance is computed with the geometric series

$$s = a + 2ar + 2ar^2 + 2ar^3 + \dots \tag{20.1}$$

We can obtain a closed form for this series s we begin with the infinite series

$$x = 2(ar + ar^2 + ar^3 + \dots + ar^{n-1} + ar^n + \dots) \tag{20.2}$$

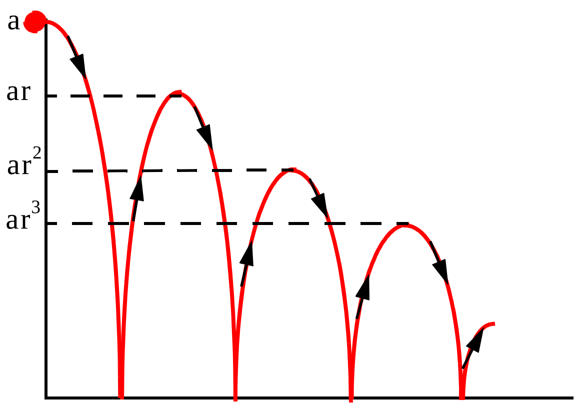


Figure 20.1. Sketch for bouncing ball

The sum of the first $n + 1$ terms in (20.2) is

$$x_n = 2(ar + ar^2 + \dots + ar^{n-1} + ar^n) \tag{20.3}$$

Multiplication of both sides of (20.3) by r yields

$$rx_n = 2(ar^2 + \dots + ar^{n-1} + ar^n + ar^{n+1}) \tag{20.4}$$

Subtraction of (20.4) from (20.3) results in the cancellation of many terms and we are left with

$$(1-r)x_n = 2ar - 2ar^{n+1} = 2ar(1-r^n) \tag{20.5}$$

and for $r \neq 1$, we obtain

$$x_n = \frac{2ar(1-r^n)}{(1-r)} \tag{20.6}$$

and since in our example $r < 1$, as $n \rightarrow \infty$, the term r^n approaches zero, that is,

$$\lim_{n \rightarrow \infty} x_n = \lim_{n \rightarrow \infty} \frac{2ar(1-r^n)}{(1-r)} = \frac{2ar}{1-r} \tag{20.7}$$

Therefore for our example, the total distance s traveled by the ball is

$$s = a + \frac{2ar}{1-r} = a \cdot \frac{1+r}{1-r} \tag{20.8}$$

Now, we can use Simulink to model the relation (20.8) with three Constant blocks and one each **Add**, **Subtract**, **Multiply**, and **Divide** blocks. The result can be displayed in a **Display** block. The model is shown in Figure 20.2 below where at the MATLAB command prompt we have entered:

```
a=6; r=0.1:0.1:0.9;
```

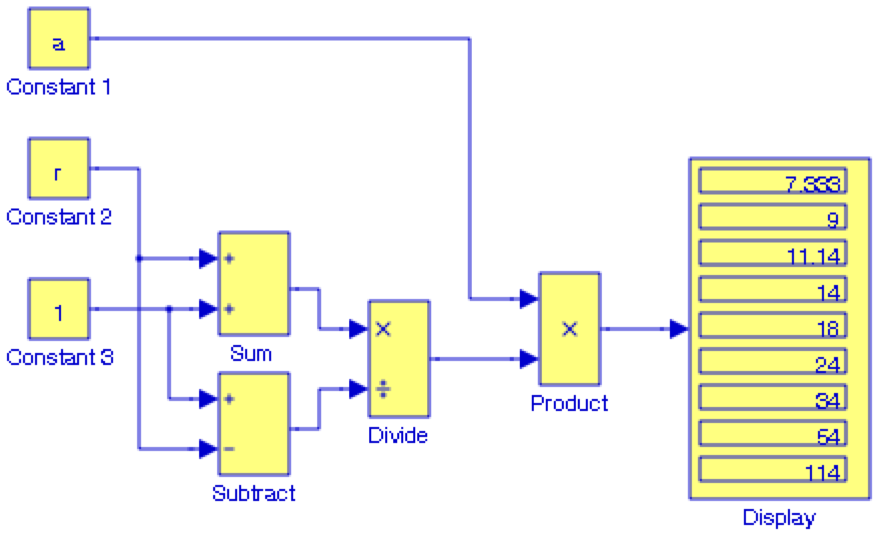


Figure 20.2. Model for the bouncing ball

The Simulink documentation includes the **Bouncing Ball with Zero Cross Detection** model. It can be accessed by typing

```
sldemo_bounce
```

at the MATLAB command prompt.

20.1.2 A Dynamics Example

Newton's Second Law states that the rate of change of momentum of a particle is proportional to the force acting on it, and it is in the same direction as the force, i.e.,

$$F = k\frac{d}{dt}(mv) = km\frac{dv}{dt} = kma$$

where a is the acceleration of the particle and k is a constant of proportionality depending upon the system of units employed. Thus, when cgs (centimeter–gram–second) units are used, if the mass is measured in grams, the acceleration in centimeters per second, and the force F in dynes, then $k = 1$. If the force F is in grams, then $k = 1/g$ where g is the gravitational constant, approximately equal to $980.5\ \mathrm{cm/sec}^2$.

When fps (foot–pound–second) units are used, if the mass is measured in pounds, the acceleration in feet per second, and the force F in poundals, then $k = 1$. If the force F is in pounds (lbs), then $k = 1/g$ where g is the gravitational constant, approximately equal to $32.7 \quad ft/sec^2$.

For this example, we will consider a mass m of 100 lbs being drawn on a rough surface and the force in the direction of motion is 30 lbs. The force of friction is 20 lbs, and there is an air resistance whose magnitude in pounds at any instance is twice the speed in feet per second. We will derive expressions for the velocity v and the displacement x as functions of time.

We assume that the force acting in the direction of motion is positive, and the forces opposing the motion are negative. Then, the net force F is

$$F = 30 - 20 - 2v = 10 - 2v = m \cdot \frac{1}{g} \cdot \frac{dv}{dt} = \frac{100}{g}\frac{dv}{dt}$$

or

$$5 - v = \frac{50}{g}\frac{dv}{dt} \tag{20.9}$$

and separation of variables yields

$$\frac{dv}{5-v} = \frac{g}{50}dt \tag{20.10}$$

Using the dummy variables σ for v and τ for t and integrating both sides of (20.10), we obtain

$$\int_0^v \frac{1}{5-\sigma}d\sigma = \frac{g}{50}\int_0^t d\tau \tag{20.11}$$

from which

$$-\ln(5-\sigma)\Big|_0^v = \frac{g}{50}\tau\Big|_0^t$$

$$\ln(5-\sigma)\Big|_0^v = -\frac{g}{50}\tau\Big|_0^t$$

$$\ln(5-v) - \ln 5 = -\frac{g}{50}t$$

$$\ln\frac{(5-v)}{5} = -\frac{g}{50}t$$

$$\frac{(5-v)}{5} = e^{-gt/50}$$

and thus the equation for the velocity is

$$v(t) = \frac{dx}{dt} = 5(1 - e^{-gt/50}) \text{ ft/sec} \tag{20.12}$$

To derive the equation for the displacement x we separate the variables in (20.12) as

$$dx = 5(1 - e^{-gt/50})dt$$

and integrating both sides, we obtain

$$\int_0^x d\chi = \int_0^t 5(1 - e^{-gt/50})dt$$

from which

$$x = 5\left(t + \frac{50}{g}e^{-gt/50} - \frac{50}{g}\right) \tag{20.13}$$

and the model is shown in Figure 20.3.

The velocity as a function of time is shown on the **Scope 1** block in Figure 20.4 where we observe that the velocity attains the maximum value at $v = 5$ ft/sec since

$$\lim_{t \to \infty} v = \lim_{t \to \infty} 5(1 - e^{-gt/50}) = 5$$

The displacement as a function of time is shown on the **Scope 2** block in Figure 20.5 where we observe that the displacement increases with increasing time.

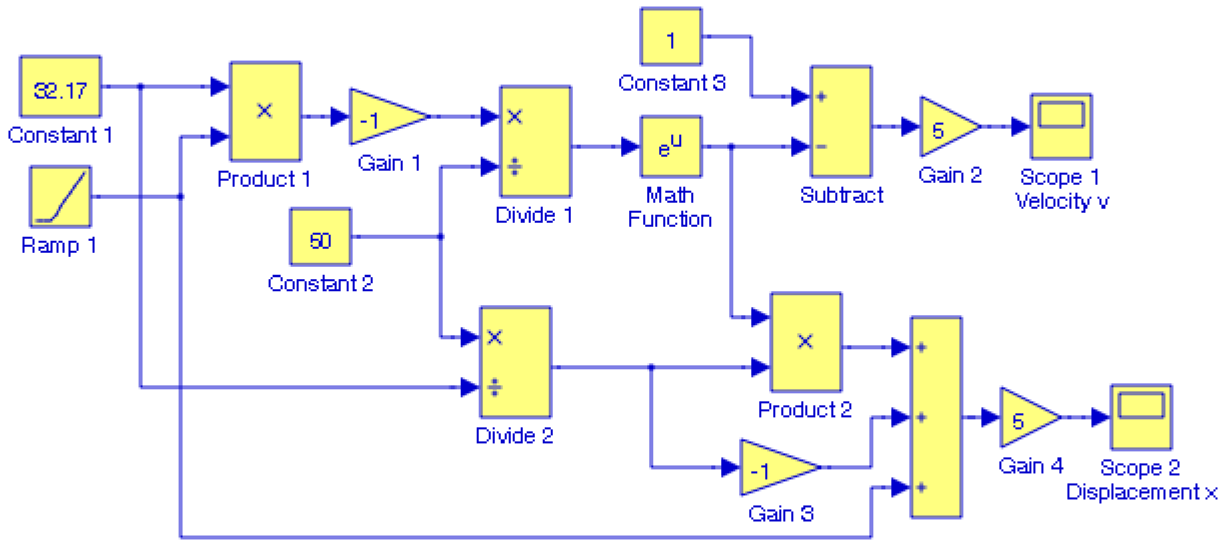


Figure 20.3. Model for the dynamics system example

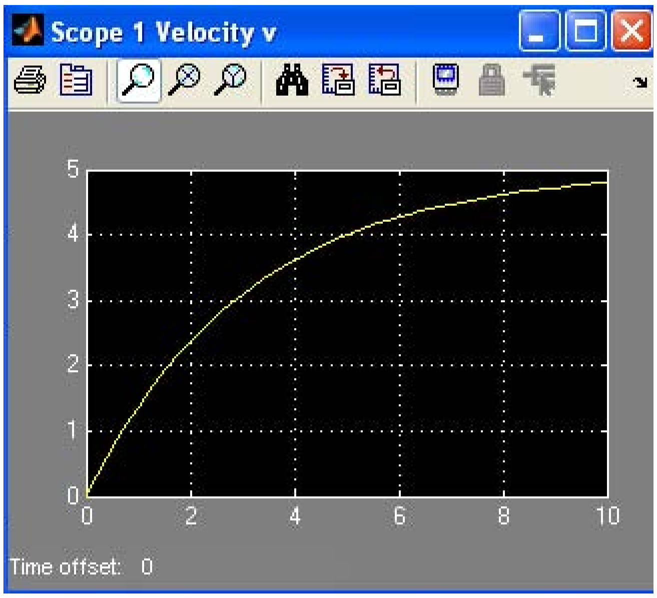


Figure 20.4. Velocity displayed by Scope 1 in Figure 20.3 as a function of time

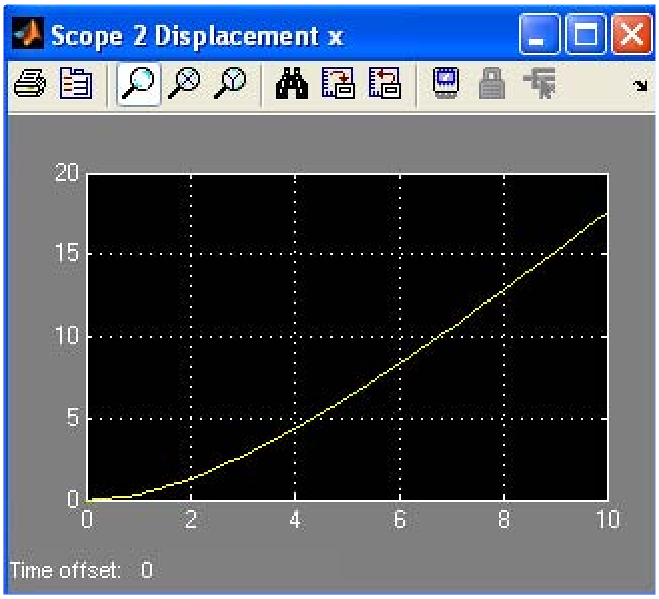


Figure 20.5. Displacement displayed by Scope 2 in Figure 20.3 as a function of time

20.1.3 Chemical Solutions Example

Let us consider a tank with 1000 gal capacity initially holding 100 gal. of a salt solution in which 50 lbs of salt are dissolved. Suppose that 3 gal. of brine, each containing 2 lbs of dissolved salt, are added to the tank per minute, and that the mixture, kept uniform by stirring, leaves the tank at the rate of 2 gal. per minute. We wish to compute the amount of salt in the tank at any time t.

Let Q be the number of lbs of salt present at the end of t minutes. Then, the rate at which the salt content is changing will be dQ/dt. The rate of gain will be

$$\text{Gain} = 3 \text{ gal/min} \times 2 \text{ lbs/gal} = 6 \text{ lbs/min} \tag{20.14}$$

Let C in gal/min denote the concentration; then and the rate of loss will be

$$\text{Loss} = 2 \text{ gal/min} \times C \text{ lbs/gal} = 2C \text{ lbs/min} \tag{20.15}$$

Since the original number of gallons in the tank is 100 and the net increase is 1 gal/min, at any time t the number of gallons of brine will be

$$\text{Number of gallons at time } t = 100 + t$$

and the concentration C will be

$$C = \frac{Q}{100+t}$$

and from (20.15), the concentration loss per minute will be

$$\text{Concentration loss} = \frac{2Q}{100+t}$$

The concentration gain from (20.14) is 6 lbs/min and therefore, dQ/dt, i.e., the rate at which the salt content is changing will be

$$\frac{dQ}{dt} = 6 - \frac{2Q}{100+t}$$

or

$$\frac{dQ}{dt} + \frac{2Q}{100+t} = 6 \tag{20.16}$$

This is linear differential equation of the first order* and it can be solved with the use of an integrating factor† which for this example the integrating factor is $(100+t)^2$, and integration yields the general solution

$$(100+t)^2 Q = 2(100+t)^3 + k \tag{20.17}$$

where k is a constant of integration, and using the initial condition $Q = 50$ when $t = 0$, we find that $k = -1.5 \times 10^6$, and thus

* *A differential equation of the first order is said to be linear when it is of the first degree in the dependent variable and its derivative.*

† *For a discussion on integrating factors, please refer to any text in differential equations*

$$Q = 2(100+t) - \frac{1.5 \times 10^6}{(100+t)^2} \qquad (20.18)$$

The model for equation (20.18) is shown in Figure 20.6, and the Scope block displays Q as an increasing function of time t in Figure 20.7.

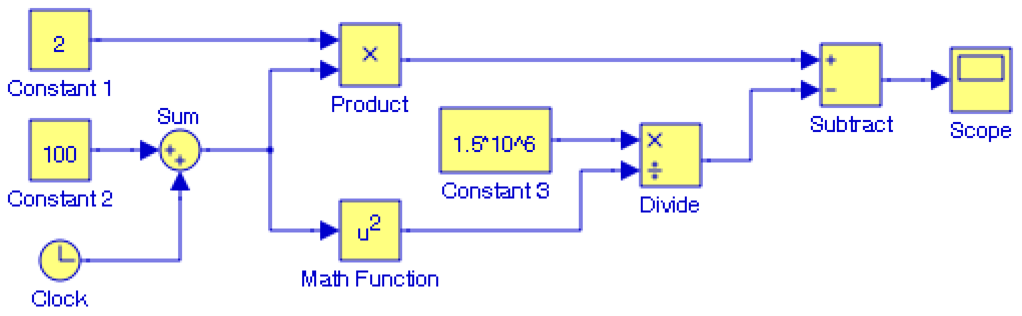


Figure 20.6. Model for the chemical solution example

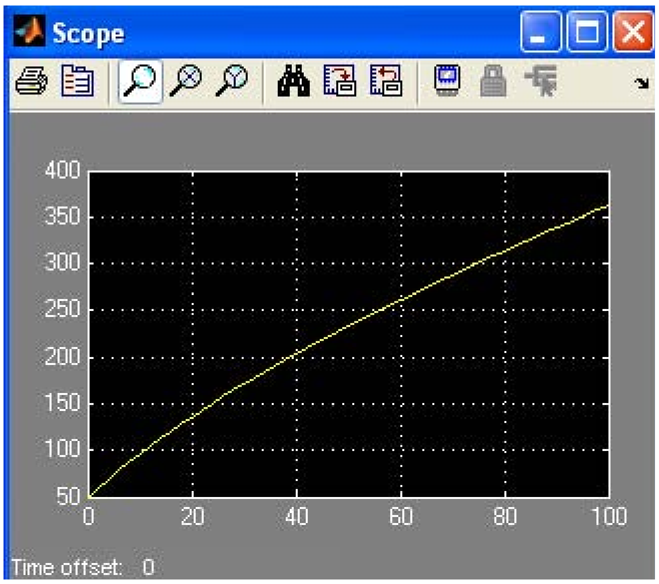


Figure 20.7. The value of Q as a function of time displayed on the Scope block in Figure 20.6

20.1.4 Heat Flow Example

Let q in cal/sec be the constant quantity of heat flowing through an area A in cm^2 perpendicular to the direction of flow per second, let u in ^{o}C be the temperature at a point P of the body, and let x in cm be the distance, taken as positive in the direction of flow, from some point chosen as origin to the point P. Then, the magnitude of q will be $(KA)(du/dx)$ where K is the thermal conductivity in $\mathrm{cal/(sec \cdot cm \cdot {}^oC)}$. Since the temperature decreases in the direction of flow, i.e., heat flows from a higher to a lower temperature, du/dx will be negative and thus

$$q = -KA\frac{du}{dx} \tag{20.19}$$

Let us consider a cylindrical pipe containing steam and covered with an insulating material of thermal conductivity K. Let the inner and outer radii of the insulating cylindrical shell be x_1 and x_2 respectively, and let the corresponding temperatures be u_1 and u_2 respectively. Under steady–state conditions,* heat will flow radially, and the area A perpendicular to the direction of flow will be the lateral surface of a cylinder of radius x where $x_1 \le x \le x_2$. For a pipe of length L in cm the area is $A = 2\pi xL$, and the differential equation in (20.19) is expressed as

$$q = -2\pi KLx\frac{du}{dx} \tag{20.20}$$

Separation of the variables and integration between limits yields

$$q\int_{x_1}^{x_2}\frac{dx}{x} = -2\pi KL\int_{u_1}^{u_2}du$$

from which

$$q\ln\frac{x_2}{x_1} = -2\pi KL(u_2 - u_1)$$

and

$$q = \frac{2\pi KL(u_1 - u_2)}{\ln(x_2/x_1)} \tag{20.21}$$

The model for equation (20.21) is shown in Figure 20.8, and the **Scope** block displays q as a function of the parameters of (20.21) in Figure 20.9, where at the MATLAB command prompt we have entered the following:

```
u1=25:0.1:100; L=30; K=0.92; u2=20; x1=0.8; x2=1;
```

* *The more general problem of heat flow at a rate varying with time results to the partial differential equation* $\partial u/\partial t = \alpha^2(\partial^2 u/\partial x^2)$ *where* α^2 *is known as the diffusivity.*

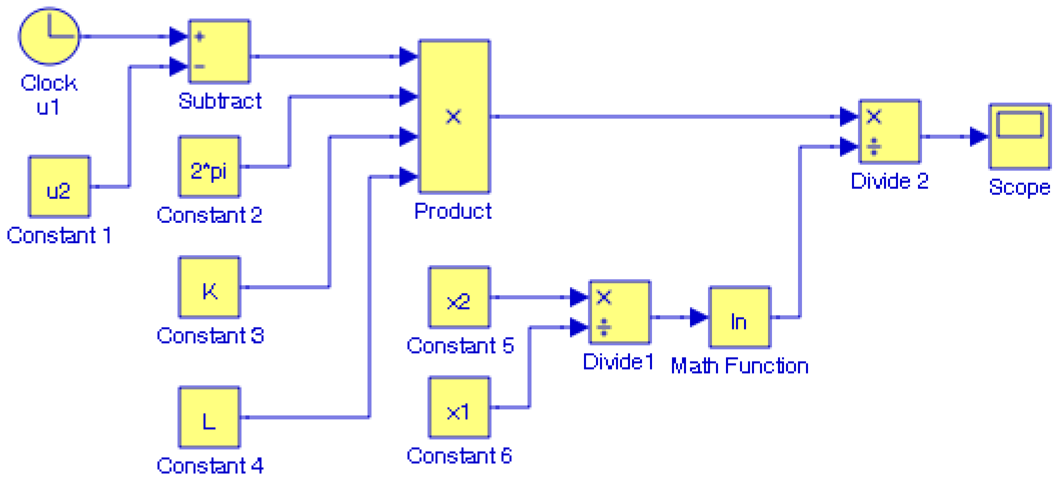


Figure 20.8. Model for the heat flow example

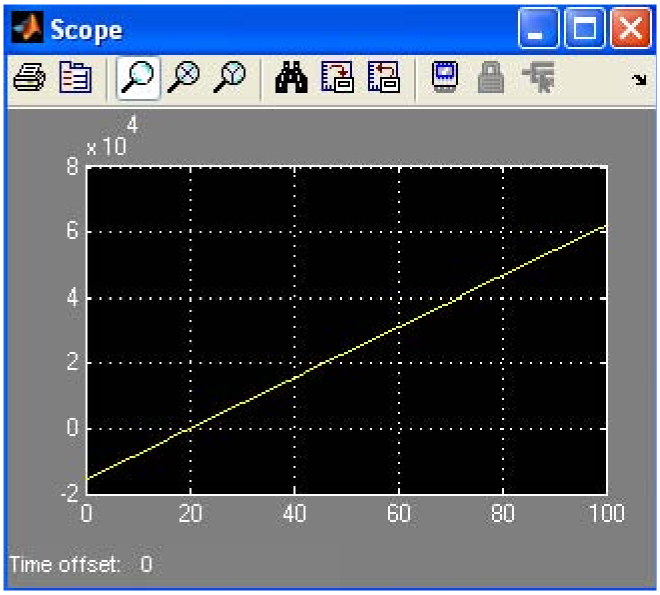


Figure 20.9. The value of q as a function of temperature u_1 *displayed on the Scope block in Figure 20.8*

20.1.5 Cantilever Beam Deflection Example

A cantilever beam of length L has one end built into a wall, while the other end is simply supported as shown in Figure 20.10. If the beam wights w Kg per unit length, the deflection y at distance x from the built–in end satisfies the equation

$$y = \frac{w}{48EI}(2x^4 - 5Lx^3 + 3L^2x^2) \tag{20.22}$$

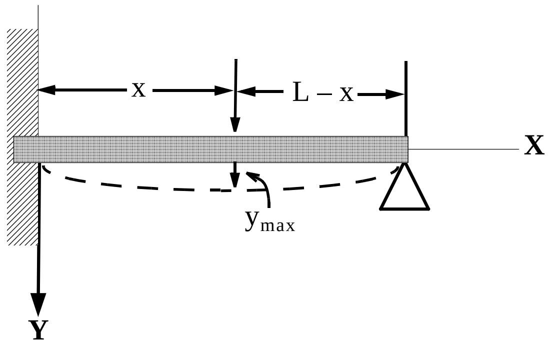
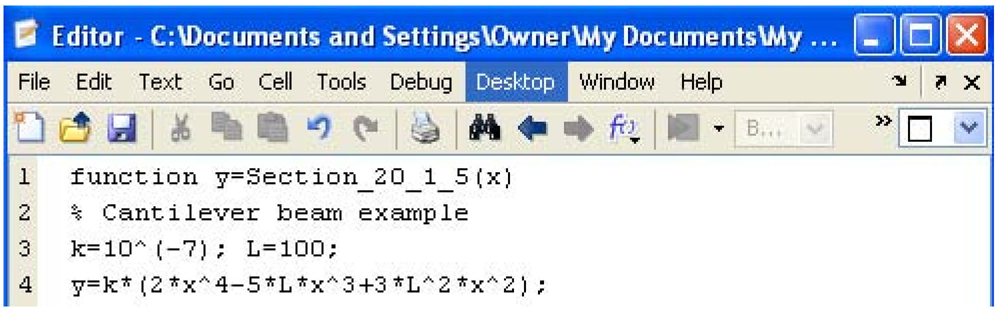


Figure 20.10. A cantilever beam deflected by its own weight

In (20.20) the quantity E is Young's modulus of elasticity* for the beam, and I is the moment of inertia.† In this example we wish to find how far from the built–in end the maximum deflection y_{max} occurs, given that $L = 100\ m$. For simplicity, we let $k = w/(48EI) = 10^{-7}$.

We begin with the new user–defined function Section_20_1_5 shown in the MATLAB Editor Window in Figure 20.11.


Editor - C:\Documents and Settings\Owner\My Documents\My ...
File Edit Text Go Cell Tools Debug Desktop Window Help

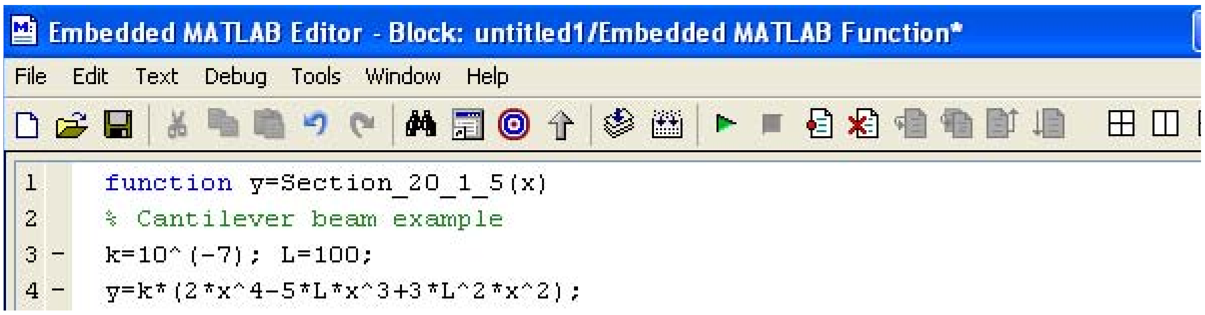
```
function y=Section_20_1_5(x)
% Cantilever beam example
k=10^(-7); L=100;
y=k*(2*x^4-5*L*x^3+3*L^2*x^2);
```

Figure 20.11. The user–defined function for the cantilever beam example

We create a new model and from the **User–Defined Functions** library we drag the **Embedded MATLAB Function** block, we double–click it, and in the **Embedded MATLAB Editor** window that pops up we erase its content and we paste the function file in Figure 20.11 as shown in Figure 20.12. The **Embedded MATLAB Function** block now appears as shown in Figure 20.13.

* $E = \dfrac{stress}{strain}$ *where* stress = force per unit area *and* strain = deformation caused by the action of stress

† $I = mr^2$ *where* m = mass *and* r = perpendicular distance of the mass to the axis of rotation


Embedded MATLAB Editor - Block: untitled1/Embedded MATLAB Function*
File Edit Text Debug Tools Window Help

```
function y=Section_20_1_5(x)
% Cantilever beam example
k=10^(-7); L=100;
y=k*(2*x^4-5*L*x^3+3*L^2*x^2);
```

Figure 20.12. The user–defined function as it appears in the Embedded MATLAB Editor window

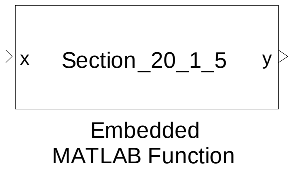


Figure 20.13. The Embedded MATLAB Function block with the user–defined function

To our model with add the **Clock** block from the **Sources** library, and the **XY Graph** block from the **Sinks** library. We connect then three blocks and the model is now as shown in Figure 20.14, and we execute the simulation command.

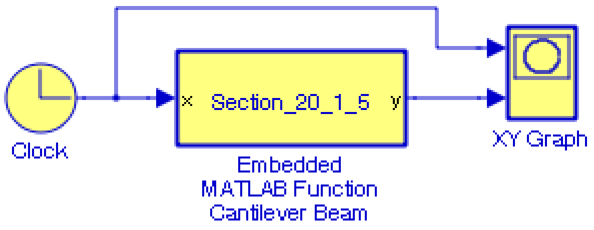


Figure 20.14. Model for the beam deflection example

The waveform displayed on the **XY Graph** block is shown in Figure 20.15 when the simulation time is set to 100 sec. The graph indicates the maximum deflection occurs when $x \approx 0.58L$. The exact result is obtained by taking the first derivative of the given function and setting it equal to zero as shown below.

$$dy/dx = 8x^3 - 15Lx^2 + 6L^2x = x(8x^2 - 15Lx + 6L^2) = 0$$

Since $x = 0$ is not a viable solution, with $L = 100$, we obtain

$$8x^2 - 1500x + 60000 = 0$$

$$x^2 - 187.5x + 7500 = 0$$

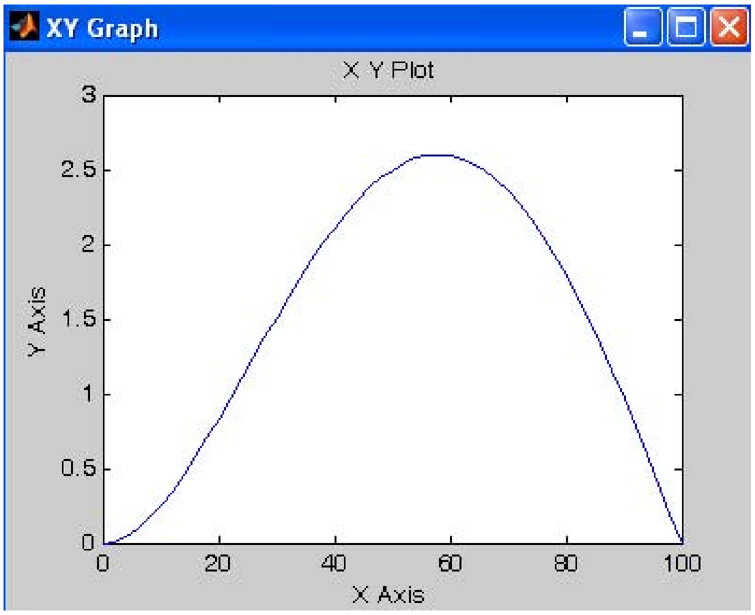


Figure 20.15. Waveform displayed on the XY Graph block in Figure 20.14 with simulation time = 100

and

```
syms x  y; y=solve('x^2–187.5*x+7500')
```

yields $x = 57.85$

20.1.6 Tractrix Curve Example

A heavy object P is dragged along a rough horizontal plane by a string PQ of length a as shown in Figure 20.16 below.

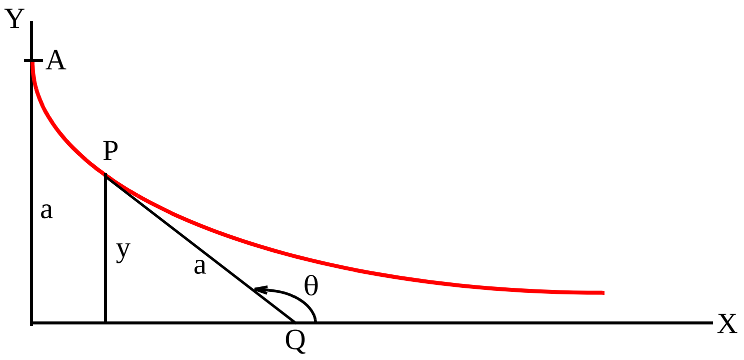


Figure 20.16. A tractrix curve

We wish to find the path of P if Q moves along the $x-\text{axis}$ starting at the origin when P is on the $y-\text{axis}$ at a distance a from the origin. The curve generated by the path of point P is called the *tractrix*.

From Figure 20.16,

$$\frac{dy}{dx} = \tan\theta = -\frac{y}{\sqrt{a^2-y^2}} \tag{20.23}$$

Separation of the variables yields

$$dx = -\frac{\sqrt{a^2-y^2}}{y}dy \tag{20.24}$$

and from tables of integrals

$$x = -\sqrt{a^2-y^2} + a \cdot \operatorname{asech}\left(\frac{y}{a}\right) + c$$

When $x = 0$, $y = a$, and thus $c = 0$. Therefore, the equation for the tractrix is

$$x = -\sqrt{a^2-y^2} + a \cdot \operatorname{acosh}\left(\frac{y}{a}\right) \tag{20.25}$$

Denoting the length of the arc AP by s positive in the direction AP, recalling that in general, the length of an arc is computed as $(ds)^2 = (dx)^2 + (dy)^2$, and observing that s increases as y decreases, we obtain

$$ds = -\sqrt{1+\left(\frac{dx}{dy}\right)^2}dy = -\sqrt{1+\frac{a^2-y^2}{y}}dy = -\frac{a}{y}dy \tag{20.26}$$

Thus, for the length AP we have

$$s = -a\int_a^y \frac{dy}{y} = a\ln\frac{a}{y} \tag{20.27}$$

and the model for the equation of (20.27) is shown in Figure 20.17 below, where at the MATLAB command prompt we have entered

```
a=1;
```

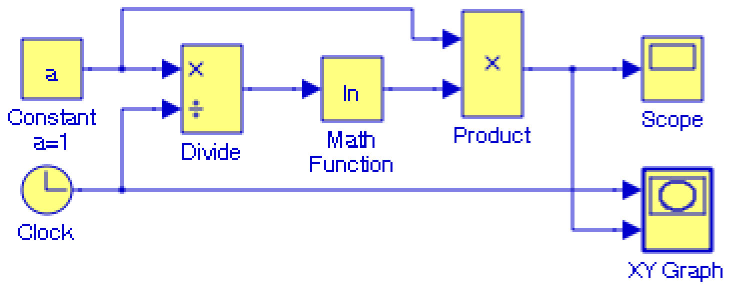


Figure 20.17. Model for the tractrix curve example

The waveform displayed on the **Scope** block in Figure 20.17 is shown in Figure 20.18. The **XY Graph** block displays the same waveform.

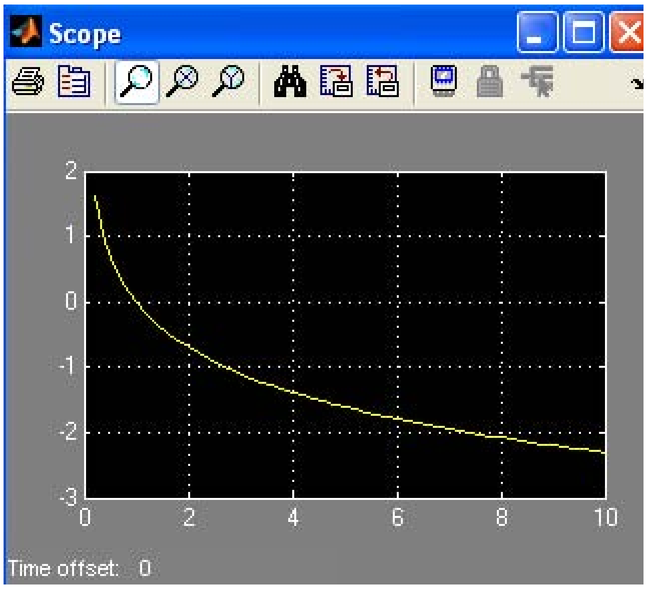


Figure 20.18. Waveform displayed on the Scope block for the model in Figure 20.17

20.1.7 Bessel Differential Equation Example

The *Bessel functions*,* denoted as $J_n(x)$, are used in engineering, acoustics, aeronautics, thermodynamics, theory of elasticity and others. For instance, in the electrical engineering field, they are used in frequency modulation, transmission lines, and telephone equations.

Bessel functions are solutions of the differential equation

$$x^2\frac{d^2y}{dx^2}+x\frac{dy}{dx}+(x^2-n^2)y = 0 \qquad (20.28)$$

where n can be any number, positive or negative integer, fractional, or even a complex number. Then, the form of the general solution of (20.31) depends on the value of n.

Differential equations with variable coefficients, such as (20.28), cannot be solved in terms of familiar functions as those which we encountered in ordinary differential equations with constant coefficients. The usual procedure is to derive solutions in the form of infinite series, and the most common are the *Method of Frobenius* and the *Method of Picard*.

The model in Figure 20.19, displays the waveform for y as the solution of the differential equation

* *For a more detailed discussion on Bessel functions please refer to Numerical Analysis Using MATLAB and Excel, ISBN 978–1–934404–03–4.*

$$\frac{d^2y}{dx^2} = -\frac{1}{x} \cdot \frac{dy}{dx} - (x^2 - y^2)y \tag{20.29}$$

where at the MATLAB command we have entered a value for n and the initial conditions $x1_0$ and $x2_0$ for the Integrator 1 and Integrator 2 blocks respectively.

```
n=2; x10=1; x20=–2;
```

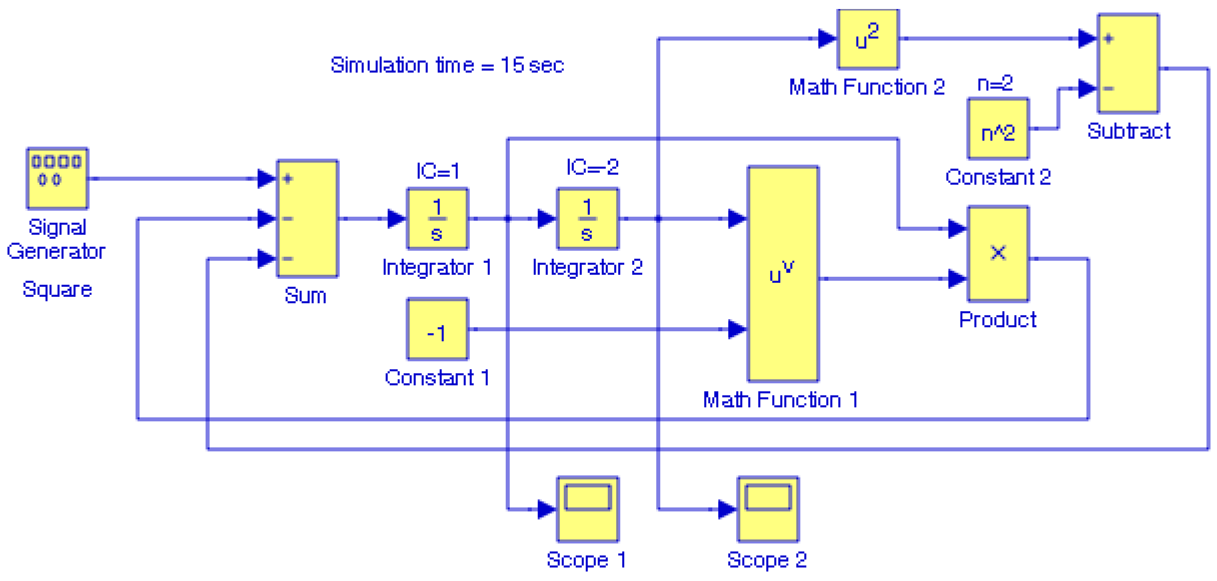


Figure 20.19. Model for the Bessel differential equation

The waveforms displayed on the **Scope** blocks are shown in Figures 20.20 and 20.21 below.

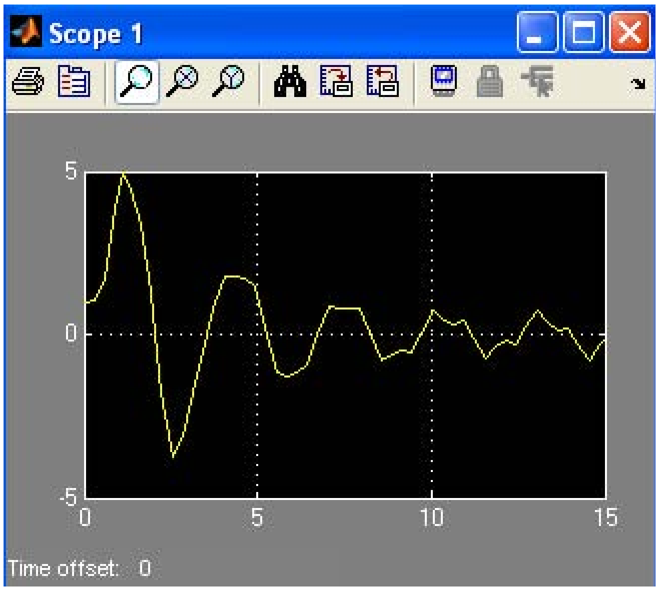


Figure 20.20. Waveform displayed by the Scope 1 block in the model of Figure 20.18

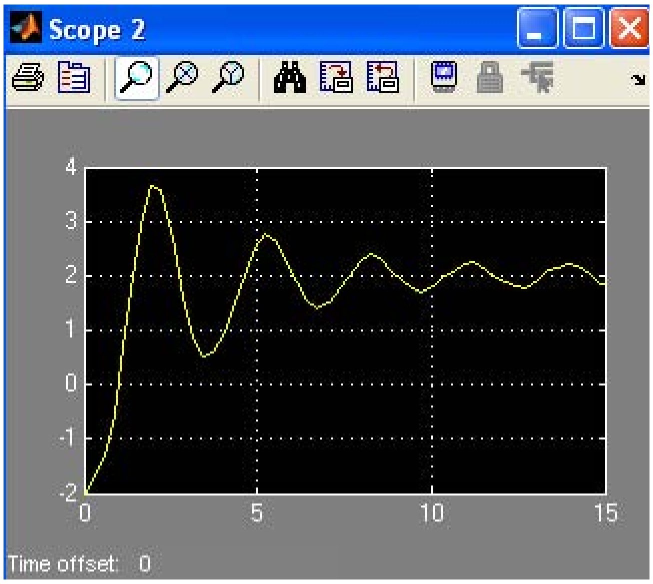


Figure 20.21. Waveform displayed by the Scope 2 block in the model of Figure 20.18

Another second–order differential equation with variable coefficients is the equation

$$(1-x^2)\frac{d^2y}{dx^2} - 2x\frac{dy}{dx} + n(n+1)y = 0 \qquad (15.30)$$

known as *Legendre's equation*, and it can be modeled by a similar procedure.

20.1.8 Van der Pol Differential Equation Example

Another interesting differential equation with variable coefficients is the *Van der Pol equation*

$$\frac{d^2x}{dt^2} - \mu(1-x^2)\frac{dx}{dt} + x = 0 \tag{20.31}$$

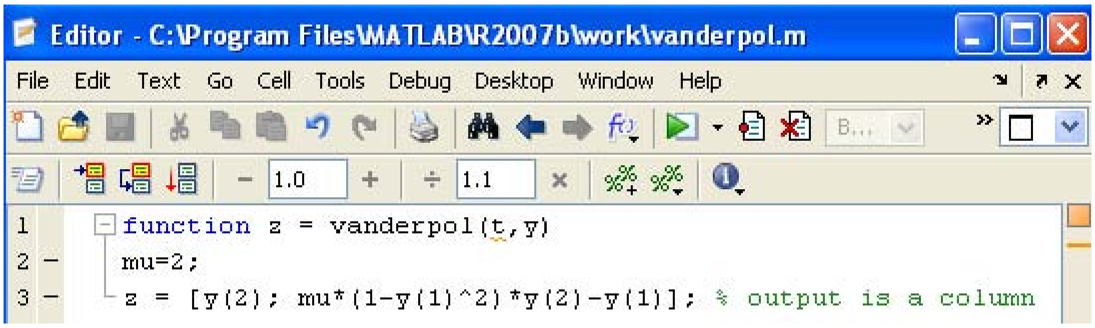
where μ is a scalar quantity and normally $\mu > 0$[*] indicating the degree of the non–linear damping. It is also known as *Van der Pol oscillator.* We will generate time plots of the solution with the MATLAB **ode45** function[†] and with Simulink. We begin by expressing (20.31) is state–space form as follows:

We let $x = y_1$ and $dx/dt = y_2$. Then $dy_1/dt = y_2 = dx/dt$ and thus we can have the second–order differential equation in (20.31) expressed as

$$\begin{aligned} \frac{dy_1}{dt} &= y_2 \\ \frac{dy_2}{dt} &= \mu(1-y_1^{\ 2})y_2 - y_1 \end{aligned} \tag{20.32}$$

Next, in the MATLAB script we let y1 represent the first derivative and y2 the second derivative. The value of μ will be defined at the MATLAB command prompt as mu. The initial conditions y0 = [y01;y02] and tspan = [first last] will also be defined as the MATLAB command prompt.

Now, we define a function m–file named vanderpol in the MATLAB Editor window as shown in Figure 20.22, where it is noted that the function vanderpol accepts the arguments t and y, it does not use t in its computations.


Editor - C:\Program Files\MATLAB\R2007b\work\vanderpol.m
File Edit Text Go Cell Tools Debug Desktop Window Help
1.0
1.1

```
function z = vanderpol(t,y)
mu=2;
z = [y(2); mu*(1-y(1)^2)*y(2)-y(1)]; % output is a column
```

Figure 20.22. The user–defined function for the Van der Pol differential equation example

* *If* $\mu < 0$ *the equation results in damped motion and if* $\mu = 0$ *there is no damping and the equation reduces to* $d^2x/dt^2 + x = 0$.

† *To see the solution of this equation under different conditions and a plot, we type* odedemo *at the MATLAB command prompt.*

The MATLAB script that produces the plots for $y_1 = x$ and $y_2 = dx/dt$ versus time t is shown below, and the plots are shown in Figure 20.23, where we also observe their initial conditions.

```
tspan=[0 20]; y0=[2; 0]; [t,y]=ode45('vanderpol', tspan, y0); plot(t,y(:,1),'r', t,y(:,2),'b'); grid;...
title('Solution of Van der Pol Differential Equation, \mu=2');...
xlabel('Time t'); ylabel('Solution y'); legend('y_1','y_2')
```

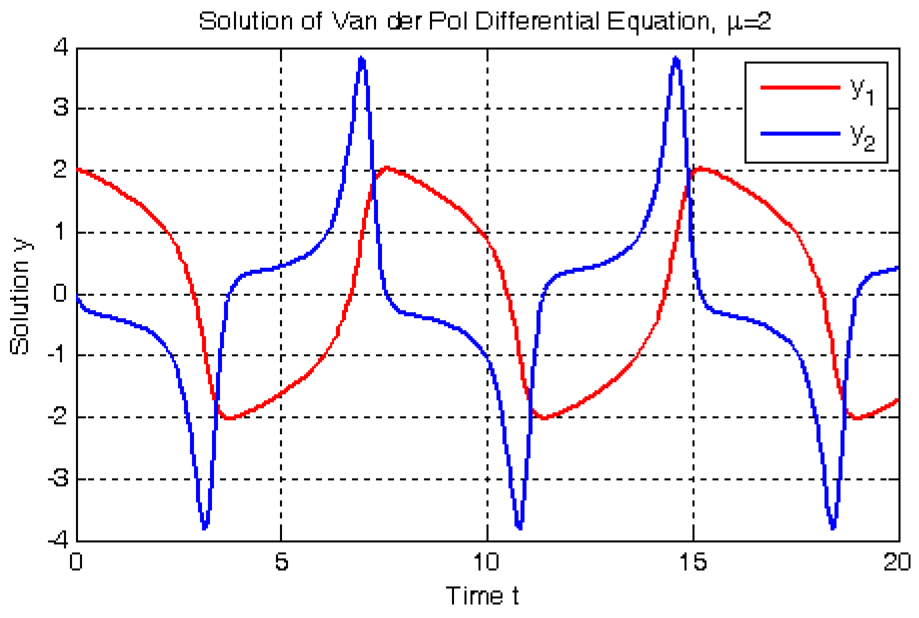


Figure 20.23. Plots for y_1 *and* y_2 *versus time* t *for the Van der Pol equation with* $\mu = 2$

We can also plot y_2 versus y_1 with the MATLAB script below and the plot is shown in Figure 20.24.

```
plot(y(:,1), y(:,2)); grid; xlabel('y(1)'); ylabel('y(2)'); ...
title('y(2) versus y(1), \mu=2')
```

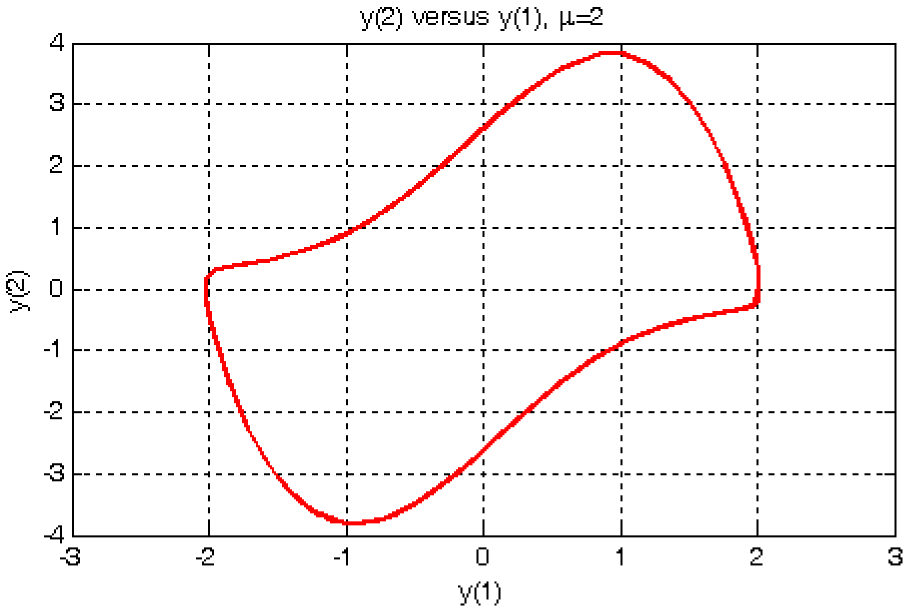


Figure 20.24.

The Simulink equivalent model for the Van der Pol differential equation is shown in Figure 20.25 where the **Function Block Parameters** are as shown in the model, and the value of μ is entered at the MATLAB command prompt.

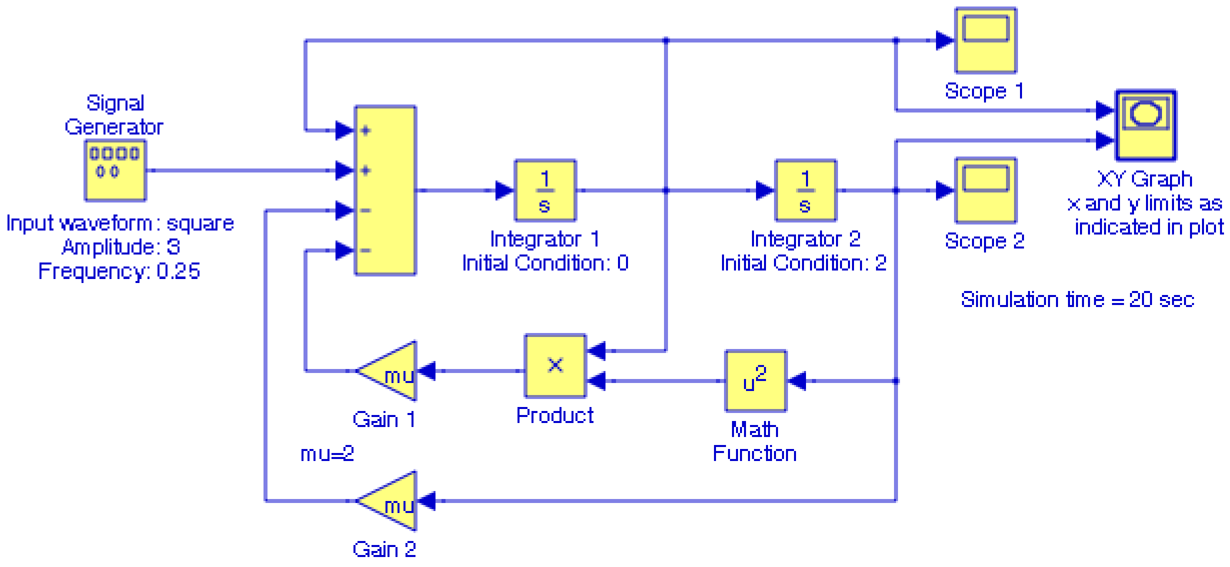


Figure 20.25. Simulink model for the Van der Pol differential equation

The waveforms displayed by the **Scope 1**, **Scope 2**, and **XY Graph** blocks are shown below in Figures 20.26, 20.27, and 20.28 respectively.

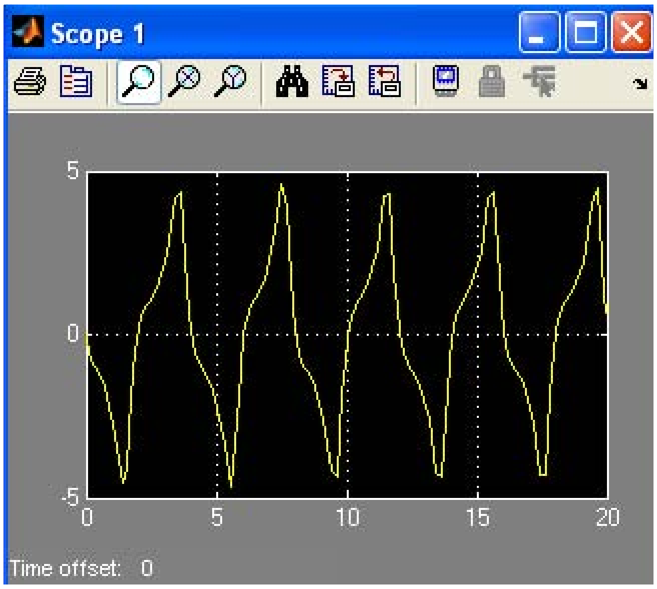


Figure 20.26. Waveform displayed by the Scope 1 block in Figure 20.25

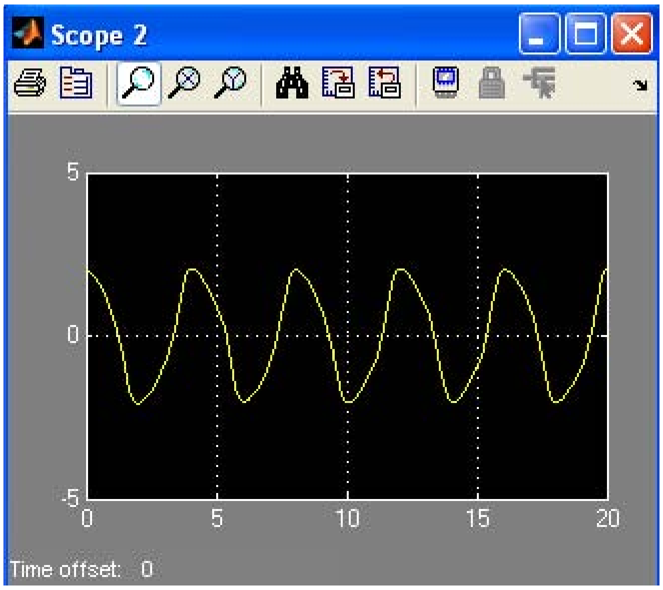


Figure 20.27. Waveform displayed by the Scope 2 block in Figure 20.25

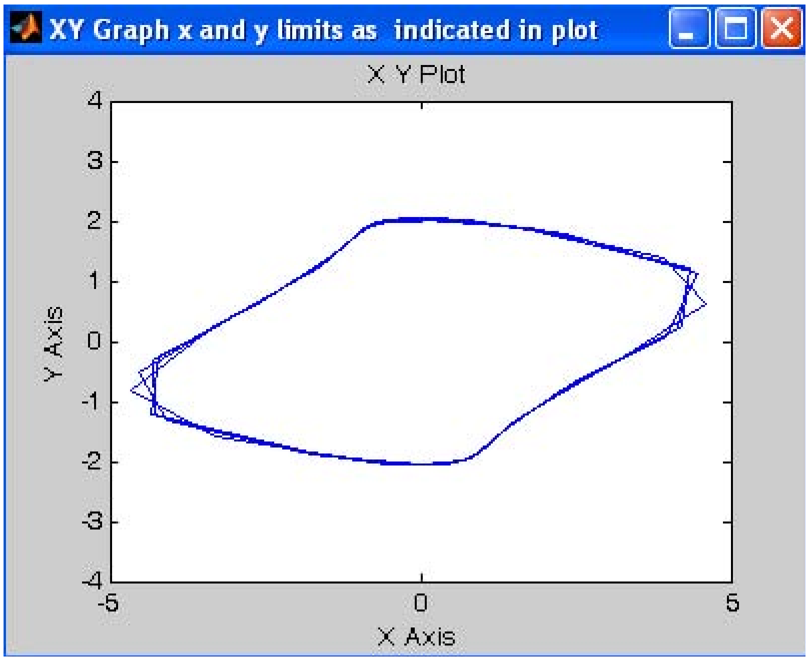


Figure 20.28. Waveform displayed by the XY Graph block in Figure 20.25

20.1.9 The Simple Pendulum Example

The *simple pendulum* is a classical example in physics and it is described in many Advanced Calculus and Advanced Mathematics for Engineers texts. We will not discuss the details, i.e., the differential equation that describes it, and its solution. It will suffice to say that the period T can be expressed as a function of an elliptic integral of the first kind, or in the form of a differential equation.

The Simulink documentation includes a simple pendulum model whose solution is based on Newton's Second Law of rotational motion and on the assumption that the friction force is a linear function of the angular velocity. It is described by the second–order differential equation

$$M = J\frac{d^2\theta}{dt^2} + c\frac{d\theta}{dt} + mgL\sin\theta \qquad (20.33)$$

or

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(M - c\frac{d\theta}{dt} - mgL\sin\theta\right)$$

where

M = applied moment (torque)

J = moment of inertia

θ = angle by which the pendulum is displaced from the vertical

c = viscous friction coefficient

m = concentrated mass at point of distance L from the pivot point

g = gravitational constant = $9.81\ \mathrm{m/sec^2}$

L = length of a weightless, inextensible string

To access this model we type

```
simppend
```

at the MATLAB command prompt and the model appears as shown in Figure 20.29.

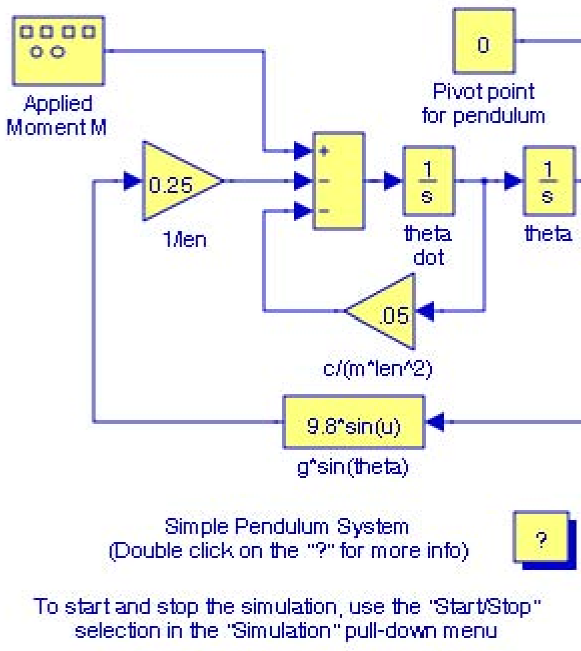

Applied Moment M
0
Pivot point for pendulum
0.25
1/len
1/s
theta dot
1/s
theta
x & theta
Animation Function
.05
c/(m*len^2)
9.8*sin(u)
g*sin(theta)
Simple Pendulum System (Double click on the "?" for more info)
?
To start and stop the simulation, use the "Start/Stop" selection in the "Simulation" pull-down menu

Figure 20.29. Demo model for the simple pendulum provided by the Simulink documentation

For this demo, the applied moment (torque) is a square waveform with unity amplitude and frequency $0.1\ \mathrm{rad/sec}$, $c = 0.8$, $m = 1$, $L(len) = 4$, and the **Animation Function** block shows the pendulum swing when the simulation command is executed.

The model in Figure 20.29 has no **Scope** blocks to indicate the changes in angle θ and changes in angular velocity ω. Figure 20.30 shows the simple pendulum demo with two **Scope** blocks and an **XY Graph** block to indicate changes in θ and changes in ω, and the changes in ω as θ changes.

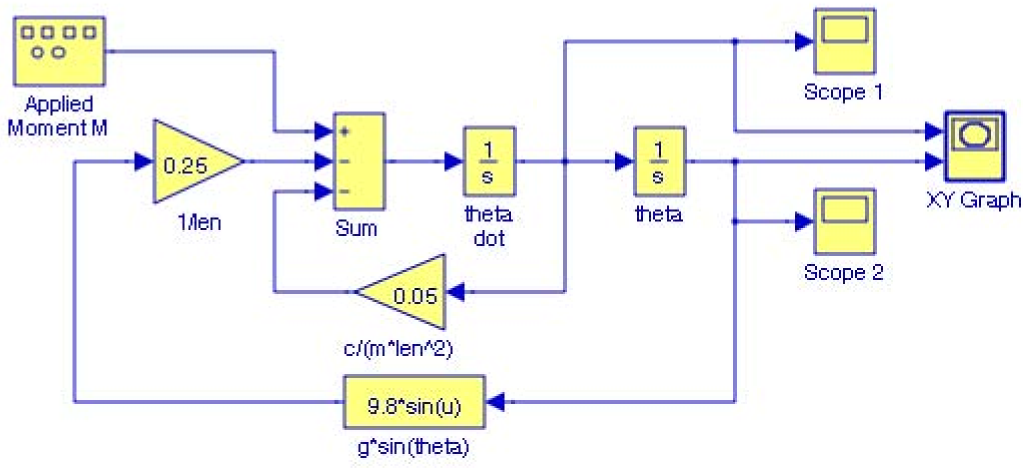


Figure 20.30. The model in Figure 20.29 with added Scope and XY Graph blocks

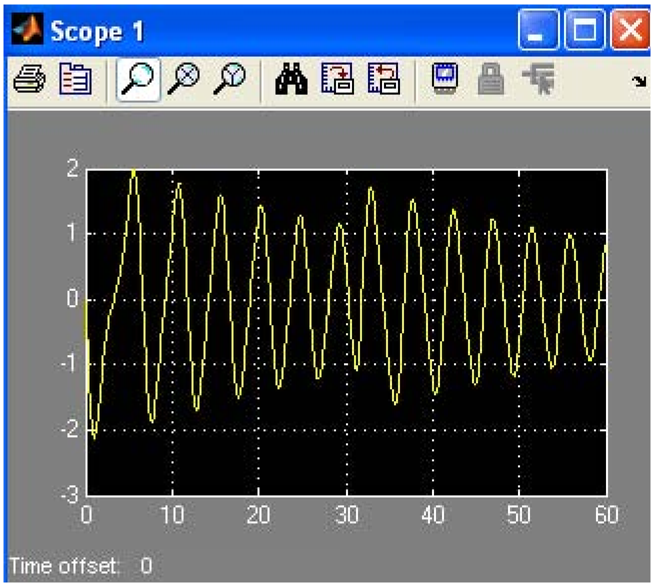


Figure 20.31. Waveform for $d\theta/dt$ *for the model in Figure 20.30*

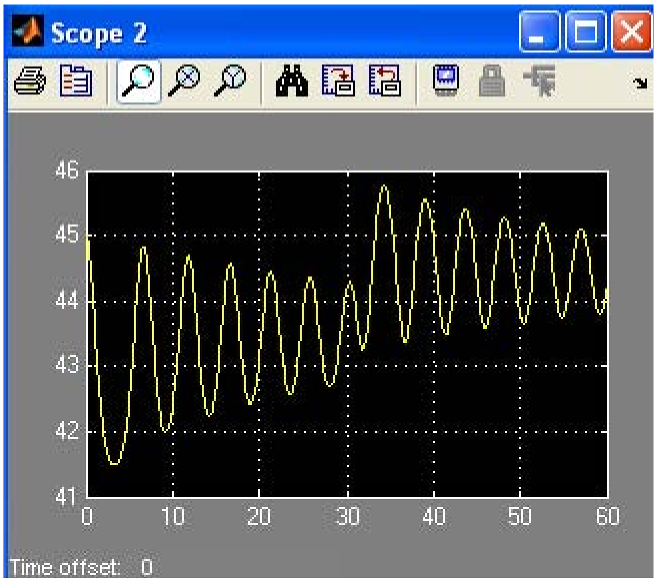


Figure 20.32. Waveform for θ *for the model in Figure 20.30*

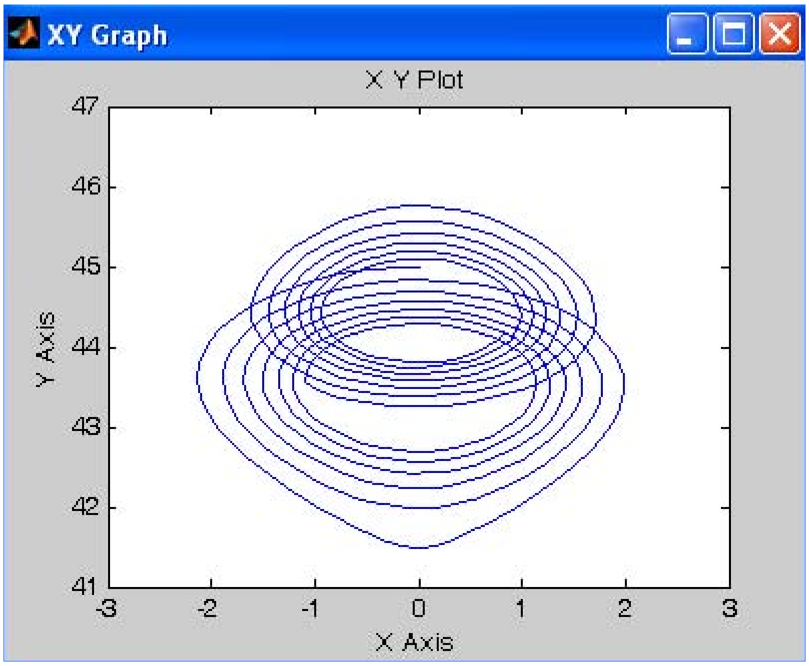


Figure 20.33. Waveform for $d\theta/dt$ *versus* θ *for the model in Figure 20.30*

The Simulink documentation includes two more demo models on pendulums, one is the **Inverted Pendulum on Cart with Animation** which can be accessed by typing

```
penddemo
```

at the MATLAB command prompt, and the other is the **Foucault Pendulum** which can be accessed by typing

```
sldemo_foucault
```

at the MATLAB command prompt.

20.1.10 A Simple Oscillator Example

Let us consider the differential equation

$$\frac{d^2y}{dt^2} + a\frac{dy}{dt} + by = 0 \tag{20.34}$$

or

$$\frac{d^2y}{dt^2} = -a\frac{dy}{dt} - by \tag{20.35}$$

The model for (20.35) is shown in Figure 20.34 below.

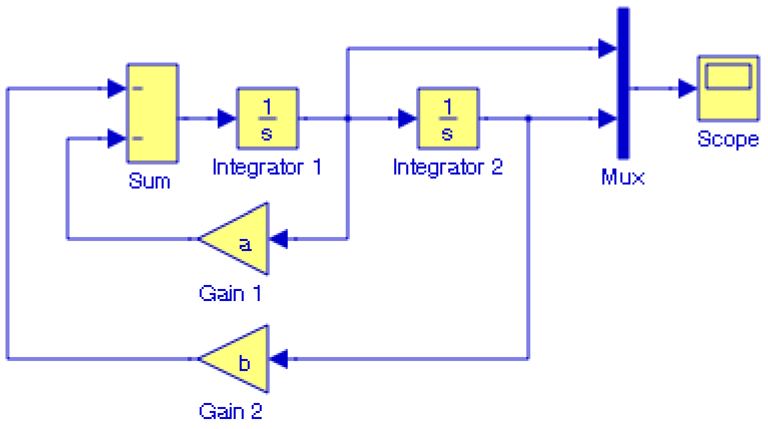


Figure 20.34. Model for the differential equation of (20.35)

At the MATLAB command prompt we type the values

```
a=0.1; b=3;
```

For the **Integrator 1** block we specify the initial condition 3 and for the **Integrator 2** block we specify the Initial condition -1. We also specify the simulation time as $20\ sec$, and under these conditions the **Scope** block displays the waveforms shown in Figure 20.35.

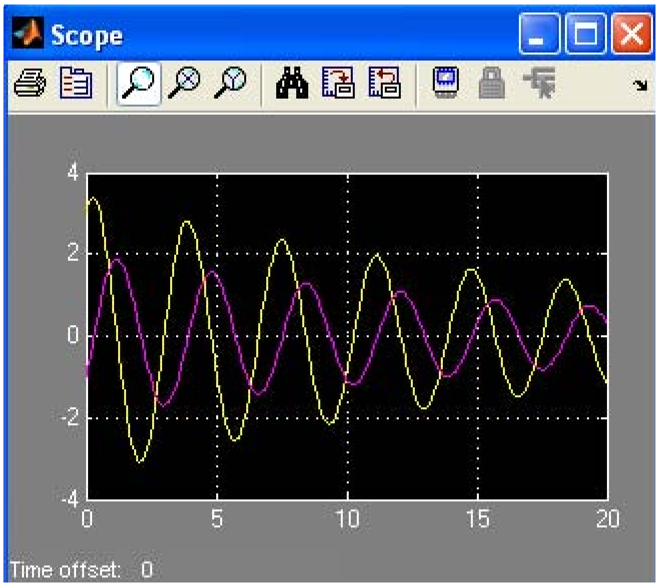


Figure 20.35. Waveforms displayed by the Scope block in Figure 20.34

Next, we let $a \rightarrow 0$ by specifying this value as 10^{-12} at the MATLAB command prompt and leave all other values unchanged. Upon execution of the simulation command, the **Scope** block displays the waveforms shown in Figure 20.36.

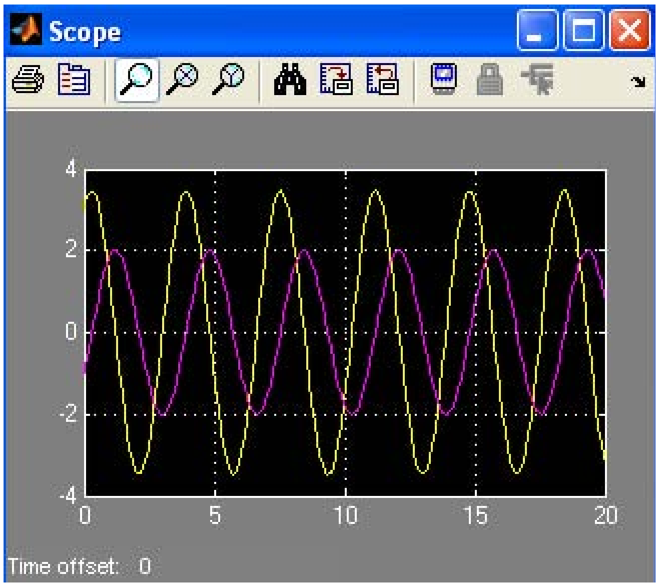


Figure 20.36. Waveforms when $a = 10^{-12}$ in differential equation (20.34)

The model in Figure 20.34 now behaves as a sinusoidal oscillator, and this is to be expected since with $a \to 0$, the differential equation of (20.34) reduces to the differential equation in (20.36) below

$$\frac{d^2y}{dt^2} + by = 0 \tag{20.36}$$

whose solution is

$$y = b(\sin\theta + \cos\theta)$$

20.2 The Zero–Order Hold and First–Order Hold as Reconstructors

Suppose that a continuous–time signal $x(t)$ is bandlimited with bandwidth B, and its Fourier transform $|X(\omega)|$ is zero for $\omega > B$. The Sampling Theorem states that if the sampling frequency ω_S is equal or greater than $2B$, the signal $x(t)$ can be recover entirely from the sampled signal $x_S(t)$ by applying $x_S(t)$ to an ideal lowpass filter with bandwidth B. Another method for recovering the continuous–time signal $x(t)$ from the sampled signal $x_S(t)$ is to use a holding circuit that holds the value of the sampled signal at time nT until it receives the next value at time $nT + T$. A Zero–Order Hold circuit behaves like a low–pass filter and thus can be used as a holding circuit to recover the continuous–time signal $x(t)$ from the sampled signal $x_S(t)$.

The model in Figure 20.37 shows the output of a **Zero–Order Hold** block specified at a low sampling frequency, and Figure 20.38 shows the input and output waveforms.

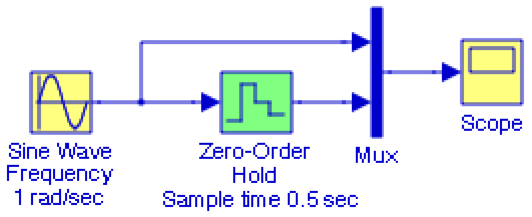


Figure 20.37. Model producing a piecewise constant waveform when the sampling frequency is low

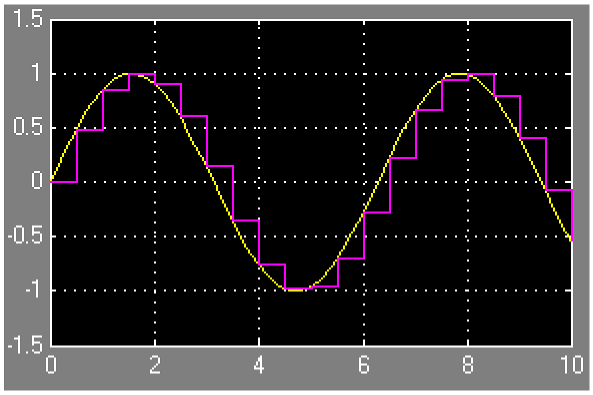


Figure 20.38. Input and output waveforms for the model in Figure 20.37

Whereas the **Zero–Order Hold** circuit generates a continuous input signal u(t) by holding each sample value u[k] constant over one sample period, a **First–Order Hold** circuit uses linear interpolation between samples as shown by the model of Figure 20.39 and the waveforms in Figure 20.40.

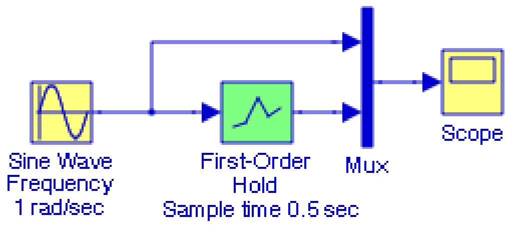


Figure 20.39. The model in Figure 20.37 with a First–Order Hold block

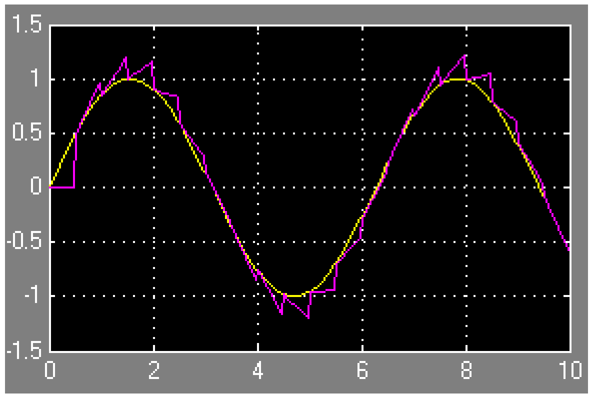


Figure 20.40. Input and output waveforms for the model in Figure 20.39

A comparison of the outputs produced by a **Zero–Order Hold** block and a **First–Order Hold** block with the same input, is shown in the model of Figure 20.41. The outputs are shown in Figure 20.42.

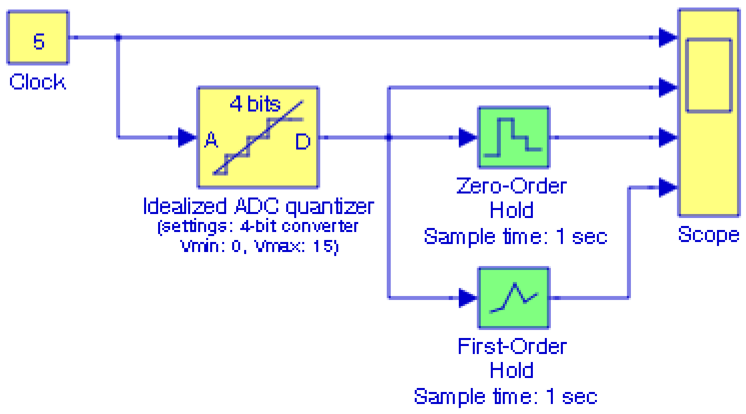


Figure 20.41. Model for comparison of a Zero–Order Hold and a First–Order Hold blocks with same input

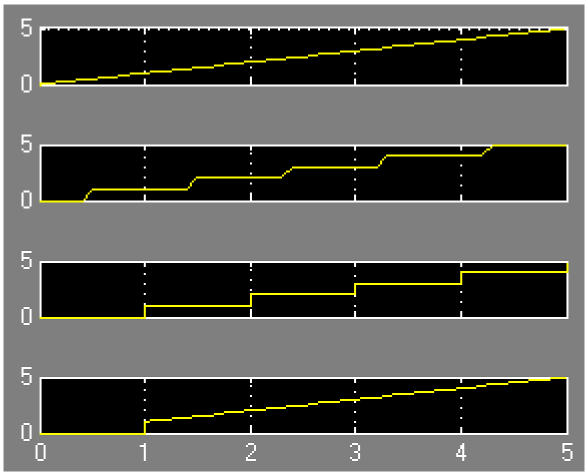


Figure 20.42. Waveforms for the model in Figure 20.41

20.3 Digital Filter Realization Forms

A given transfer function $H(z)$ of a digital filter can be realized in several forms, the most common being the **Direct Form I**, **Direct Form II**, **Cascade (Series)**, and **Parallel**. These are described in Subsections 20.3.1 through 20.3.4 below. Similar demo models can be displayed as indicated in these subsections.

20.3.1 The Direct Form I Realization of a Digital Filter

The **Direct Form I Realization** of a second–order digital filter is shown in Figure 20.43.

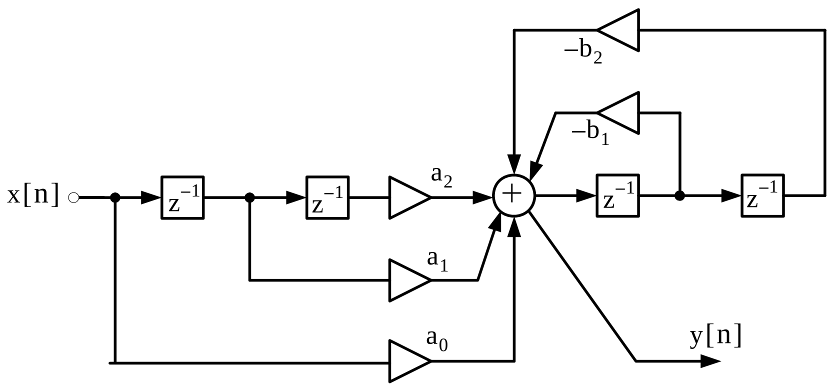


Figure 20.43. Direct Form I Realization of a second–order digital filter

At the summing junction of Figure 20.43 we obtain

$$a_0X(z) + a_1z^{-1}X(z) + a_2z^{-2}X(z) + (-b_1)z^{-1}Y(z) + (-b_2)z^{-1}Y(z) = Y(z)$$

$$X(z)(a_0 + a_1z^{-1} + a_2z^{-2}) = Y(z)(1 + b_1z^{-1} + b_2z^{-2})$$

and thus the transfer function of the **Direct Form I Realization** of the second–order digital filter of Figure 20.43 is

$$H(z) = \frac{Y(z)}{X(z)} = \frac{a_0 + a_1z^{-1} + a_2z^{-2}}{1 + b_1z^{-1} + b_2z^{-2}} \qquad (20.37)$$

A disadvantage of a Direct Form I Realization digital filter is that it requires $2k$ registers where k represents the order of the filter. We observe that the second–order $(k = 2)$ digital filter of Figure 20.27 requires 4 delay (register) elements denoted as z^{-1}. However, this form of realization has the advantage that there is no possibility of internal filter overflow.*

20.3.2 The Direct Form II Realization of a Digital Filter

Figure 20.28 shows the **Direct Form–II**† **Realization** of a second–order digital filter. The Simulink **Transfer Fcn Direct Form II** block implements the transfer function of this filter.

* *For a detailed discussion on overflow conditions please refer to Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–06–5, Section 10.5, Chapter 10.*

† *The Direct Form–II is also known as the* ***Canonical*** *Form.*

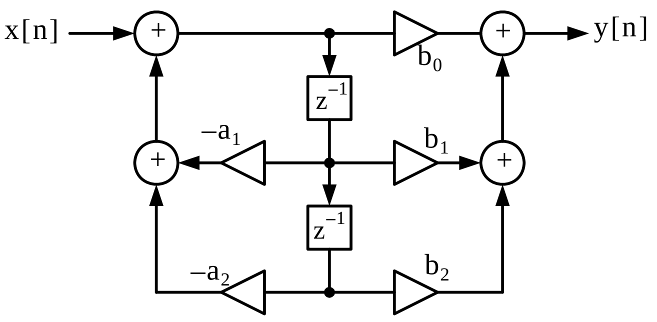


Figure 20.44. Direct Form–II Realization of a second–order digital filter

The transfer function for the Direct Form–II second–order digital filter of Figure 20.44 is the same as for a Direct Form–I second–order digital filter of Figure 20.27, that is,

$$H(z) = \frac{a_0 + a_1z^{-1} + a_2z^{-2}}{1 + b_1z^{-1} + b_2z^{-2}} \tag{20.38}$$

A comparison of Figures 20.43 and 20.44 shows that whereas a Direct Form–I second–order digital filter is requires $2k$ registers, where k represents the order of the filter, a Direct Form–II second–order digital filter requires only k register elements denoted as z^{-1}. This is because the register (z^{-1}) elements in a Direct Form–II realization are shared between the zero section and the pole section.

Example 20.1

Figure 20.45 shows a Direct Form–II second–order digital filter whose transfer function is

$$H(z) = \frac{1 + 1.5z^{-1} + 1.02z^{-2}}{1 - 0.25z^{-1} + 0.75z^{-2}} \tag{20.39}$$

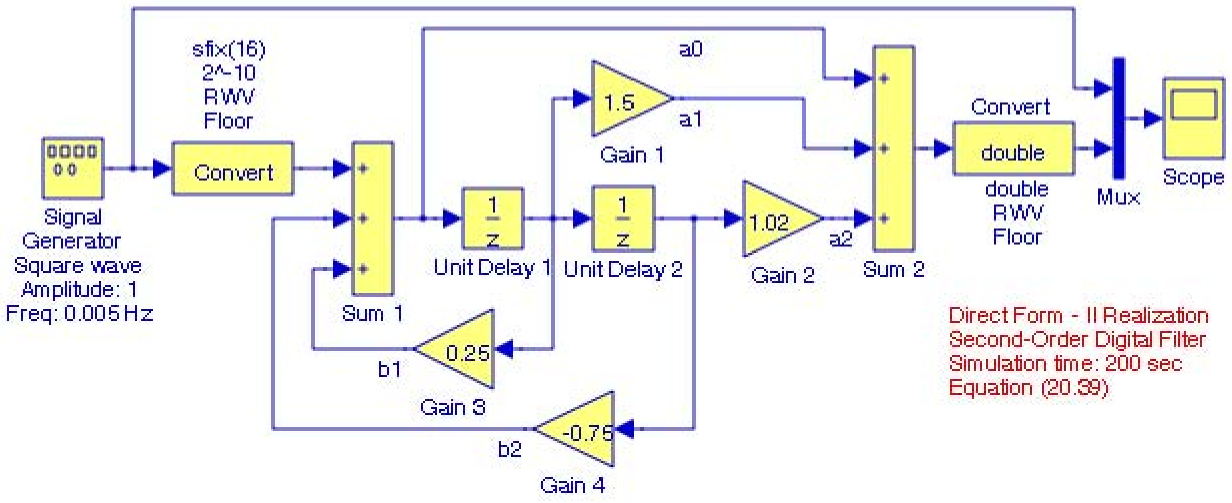


Figure 20.45. Model for Example 20.1

The input and output waveforms are shown in Figure 20.46.

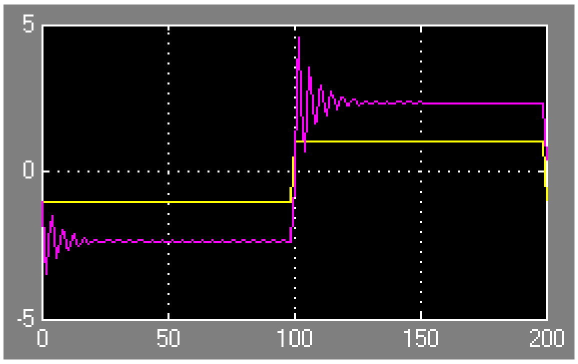


Figure 20.46. Input and output waveforms for the model in Figure 20.45

A demo model using fixed–point Simulink blocks can be displayed by typing

```
fxpdemo_direct_form2
```

at the MATLAB command prompt. This demo is an implementation of the third–order transfer function

$$H(z) = \frac{1 + 2.2z^{-1} + 1.85z^{-2} + 0.5z^{-3}}{1 - 0.5z^{-1} + 0.84z^{-2} + 0.09z^{-3}}$$

20.3.3 The Series Form Realization of a Digital Filter

For the Series* Form Realization, the transfer function is expressed as a product of first–order and second–order transfer functions as shown in relation (20.37) below.

$$H(z) = H_1(z) \cdot H_2((z) \ldots H_R(z)) \tag{20.40}$$

Relation (20.4) is implemented as the cascaded blocks shown in Figure 20.31.

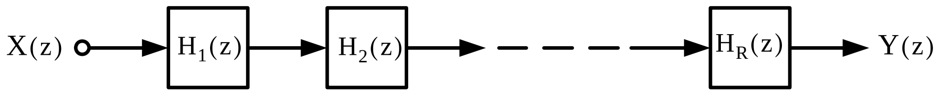


Figure 20.47. Series Form Realization

Figure 20.32 shows the Series–Form Realization of a second–order digital filter.

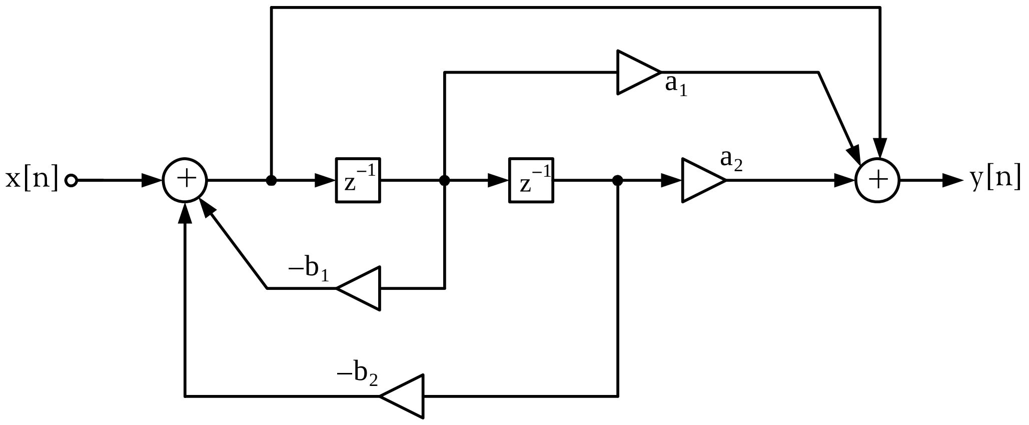


Figure 20.48. Series Form Realization of a second–order digital filter

The transfer function for the Series Form second–order digital filter of Figure 20.48 is

$$H(z) = \frac{1 + a_1 z^{-1} + a_2 z^{-2}}{1 + b_1 z^{-1} + b_2 z^{-2}} \tag{20.41}$$

Example 20.2

The transfer function of the Series Form Realization of a certain second–order digital filter is

$$H(z) = \frac{0.5(1-0.36z^{-2})}{1 + 0.1z^{-1} - 0.72z^{-2}}$$

* *The Series Form Realization is also known as the Cascade Form Realization*

To implement this filter, we factor the numerator and denominator polynomials as

$$H(z) = \frac{0.5(1+0.6z^{-1})(1-0.6z^{-1})}{(1+0.9z^{-1})(1-0.8z^{-1})}* \qquad (20.42)$$

The model is shown in Figure 20.49, and the input and output waveforms are shown in Figure 20.50.

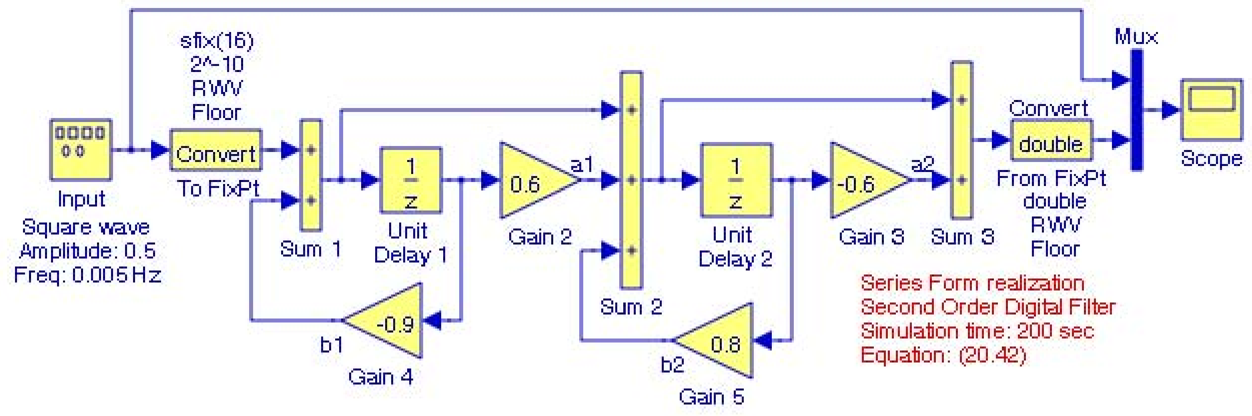


Figure 20.49. Model for Example 20.2

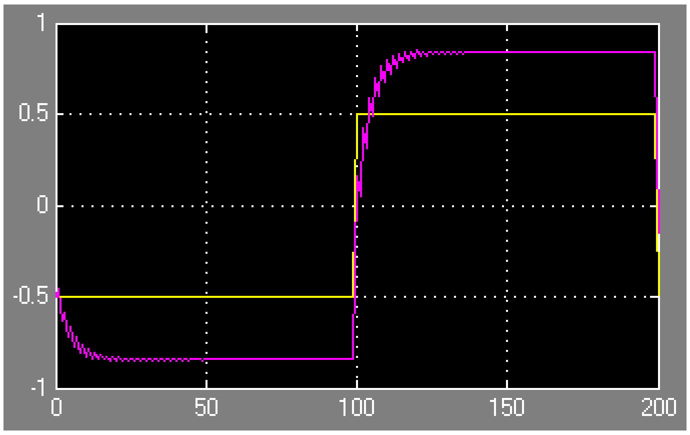


Figure 20.50. Input and output waveforms for the model in Figure 20.49

A demo model using fixed−point Simulink blocks can be displayed by typing fxpdemo_series_cascade_form at the MATLAB command prompt.

* *The combination of the of factors in parentheses is immaterial. For instance, we can group the factors as* $\frac{(1+0.6z^{-1})}{(1+0.9z^{-1})}$ *and* $\frac{(1-0.6z^{-1})}{(1-0.8z^{-1})}$ *or as* $\frac{(1+0.6z^{-1})}{(1-0.8z^{-1})}$ *and* $\frac{(1-0.6z^{-1})}{(1+0.9z^{-1})}$

at the MATLAB command prompt. This demo is an implementation of the third–order transfer function

$$H(z) = \frac{(1+0.5z^{-1})(1+1.7z^{-1}+z^{-2})}{(1+0.1z^{-1})(1-0.6z^{-1}+0.9z^{-2})}$$

20.3.4 The Parallel Form Realization of a Digital Filter

The general form of the transfer function of a Parallel Form Realization is

$$H(z) = K + H_1(z) + H_2(z) + \ldots + H_R(z) \tag{20.43}$$

Relation (20.40) is implemented as the parallel blocks shown in Figure 20.35.

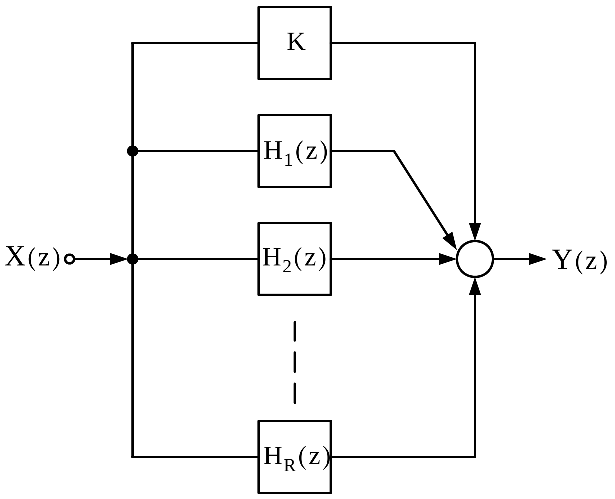


Figure 20.51. Parallel Form Realization

As with the Series Form Realization, the ordering of the individual filters in Figure 20.35 is immaterial. But because of the presence of the constant K, we can simplify the transfer function expression by performing partial fraction expansion after we express the transfer function in the form $H(z)/z$.

Figure 20.35 shows the Parallel Form Realization of a second–order digital filter. The transfer function for the Parallel Form second–order digital filter of Figure 20.35 is

$$H(z) = \frac{a_1 + a_2z^{-2}}{1 + b_1z^{-1} + b_2z^{-2}} \tag{20.44}$$

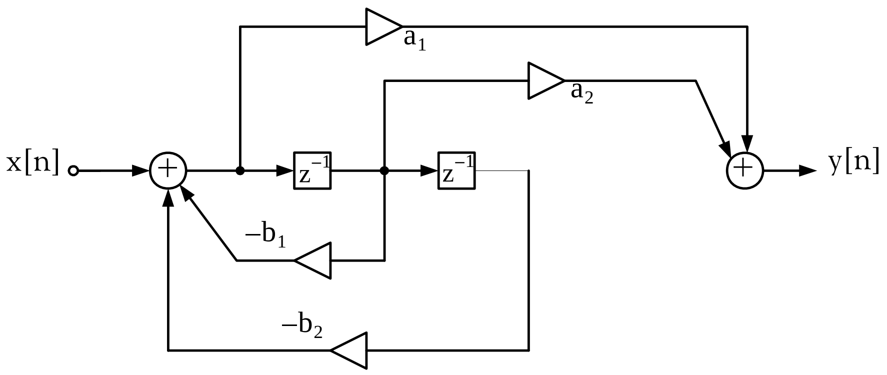


Figure 20.52. Parallel Form Realization of a second–order digital filter

Example 20.3

The transfer function of the Parallel Form Realization of a certain second–order digital filter is

$$H(z) = \frac{0.5(1-0.36z^{-2})}{1+0.1z^{-1}-0.72z^{-2}}$$

To implement this filter, we first express the transfer function as

$$\frac{H(z)}{z} = \frac{0.5(z+0.6)(z-0.6)}{z(z+0.9)(z-0.8)}$$

Next, we perform partial fraction expansion.

$$\frac{0.5(z+0.6)(z-0.6)}{z(z+0.9)(z-0.8)} = \frac{r_1}{z} + \frac{r_2}{(z+0.9)} + \frac{r_3}{(z-0.8)}$$

$$r_1 = \left.\frac{0.5(z+0.6)(z-0.6)}{(z+0.9)(z-0.8)}\right|_{z=0} = 0.25$$

$$r_2 = \left.\frac{0.5(z+0.6)(z-0.6)}{z(z-0.8)}\right|_{z=-0.9} = 0.147$$

$$r_3 = \left.\frac{0.5(z+0.6)(z-0.6)}{z(z+0.9)}\right|_{z=0.8} = 0.103$$

Therefore,

$$\frac{H(z)}{z} = \frac{0.25}{z} + \frac{0.147}{z+0.9} + \frac{0.103}{z-0.8}$$

$$H(z) = 0.25 + \frac{0.147z}{z+0.9} + \frac{0.103z}{z-0.8}$$

$$H(z) = 0.25 + \frac{0.147}{1 + 0.9z^{-1}} + \frac{0.103}{z - 0.8z^{-1}} \qquad (20.45)$$

The model is shown in Figure 20.53, and the input and output waveforms are shown in Figure 20.54.

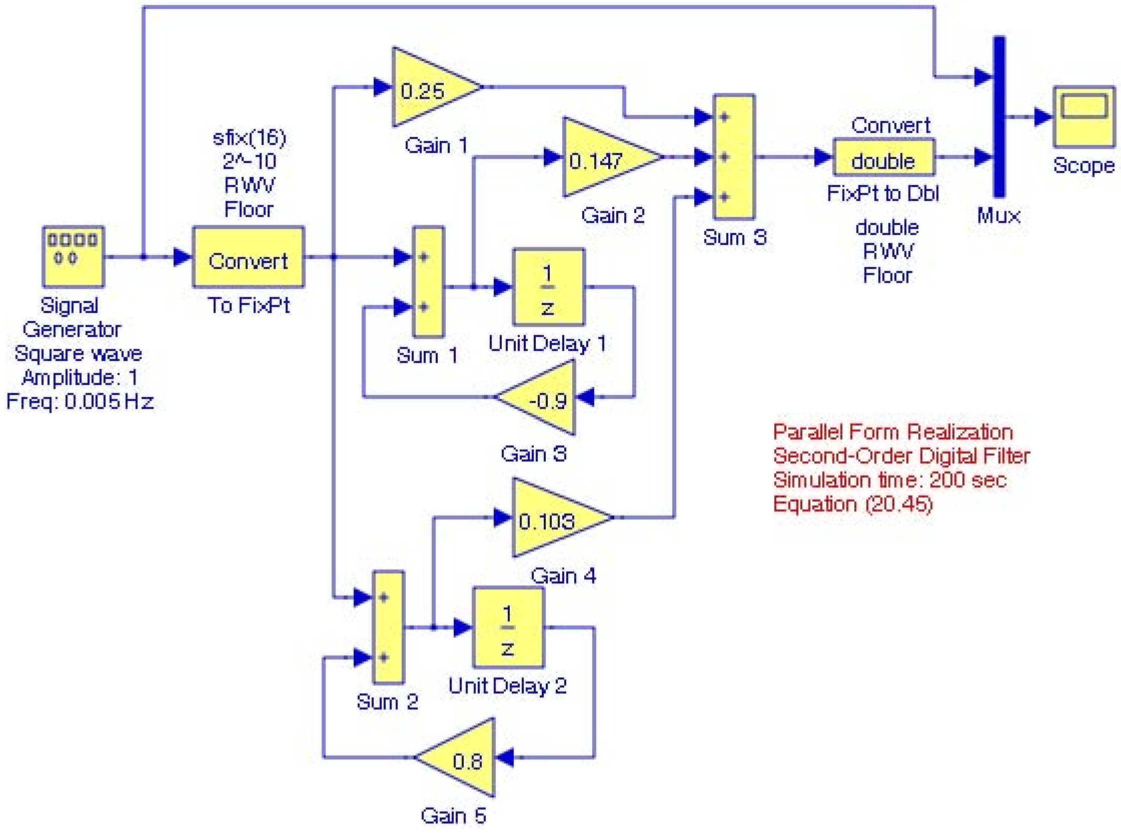


Figure 20.53. Model for Example 20.3

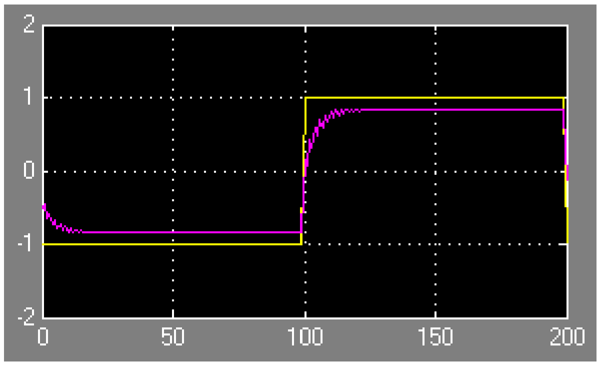


Figure 20.54. Input and output waveforms for the model in Figure 20.53

A demo model using fixed–point Simulink blocks can be displayed by typing

```
fxpdemo_parallel_form
```

at the MATLAB command prompt. This demo is an implementation of the third–order transfer function

$$H(z) = 5.5556 - \frac{3.4639}{(1+0.1z^{-1})} + \frac{-1.0916 + 3.0086z^{-1}}{1 - 0.6z^{-1} + 0.9z^{-2}}$$

20.4 Models for Binary Counters

In this section we will draw two models for binary counters.* Subsection 20.4.1 presents a 3–bit up / down counter, and Subsection 20.4.2 presents a 4–bit Johnson counter.

20.4.1 Model for a 3–bit Up / Down Counter

A model for the operation of a 3–bit counter with three D Flip Flop blocks, six NAND gate blocks, a NOT gate (Inverter) block, and a Clock block is shown in Figure 20.55. The D Flip–Flop and Clock blocks are described in Chapter 19 (**Simulink Extras**), and the NAND and NOT gates are in the **Logic and Bit Operations Library**. The D Flip–Flop CLK (clock) inputs are Negative Edge Triggered. The Clock waveform and the D Flip–Flops output waveforms when the **Manual Switch** block is the Count up position, are shown in Figure 20.56.

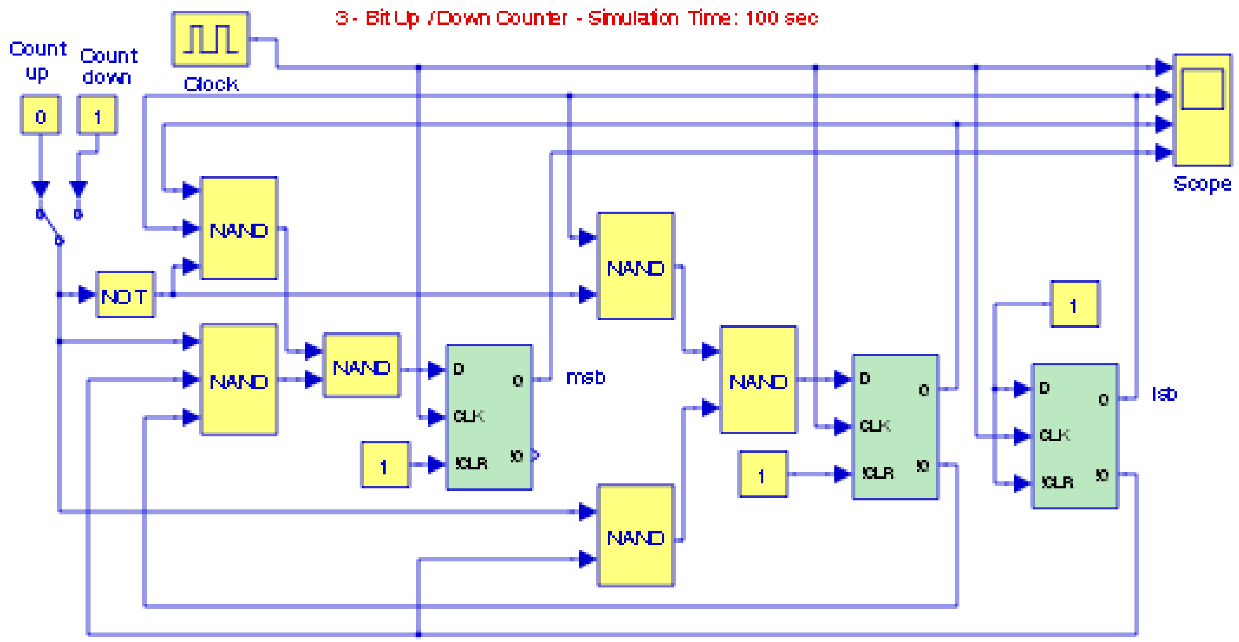


Figure 20.55. Model for a 3–bit Up / Down binary counter

* For a detailed discussion on the analysis and design of binary counters, refer to Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, ISBN 978–1–934404–05–8.

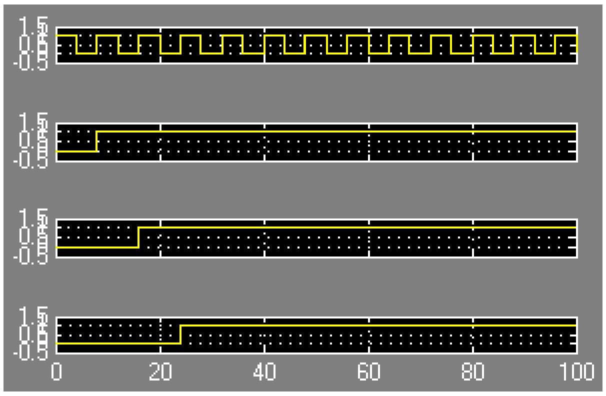


Figure 20.56. Waveforms for the model in Figure 20.55

For another example, refer to the **Modulo–4 Counter Using Flip Flops Demo** model by typing sldemo_flipflops at the MATLAB command prompt.

20.4.2 Model for a 4–bit Ring Counter

The model of Figure 20.57 implements a 4–bit binary counter known as **Johnson counter**. The D Flip–Flop and Clock blocks are discussed in Chapter 19 (**Simulink Extras**). The waveforms for this model are shown in Figure 20.58.

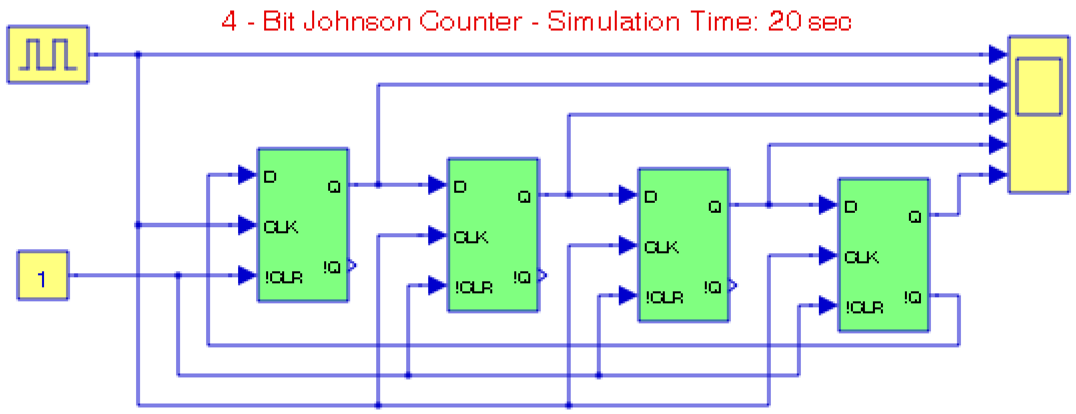


Figure 20.57. Model for a 4–bit Johnson counter

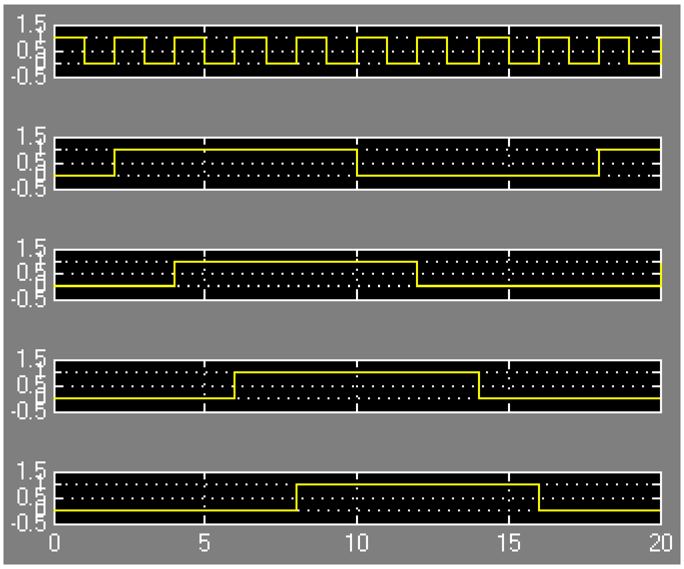


Figure 20.58. Waveforms for the model in Figure 20.57

20.5 Models for Mechanical Systems

In this section we will create three models for mechanical systems. Subsection 20.5.1 presents a Block–Spring–Dashpot system, Subsection 20.5.2 presents a system with two mass blocks and two springs, and Subsection 20.5.3 is a simple mechanical accelerometer system

20.5.1 Model for a Mass–Spring–Dashpot

Figure 20.59 shows a system consisting of a block, a dashpot, and a spring. It is shown in feedback and control systems textbooks that this system is described by the second–order differential equation

$$m\frac{d^2}{dt^2}x(t) + p\frac{d}{dt}x(t) + kx(t) = F(t) \tag{20.46}$$

where m represents the mass of the block, p is a positive constant of proportionality of the force that the dashpot exerts on the block, and k is also a positive constant of proportionality of the force that the spring exerts on the block, known as **Hooke's law**.

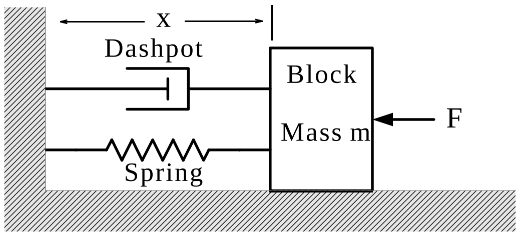


Figure 20.59. Mechanical system with a block, spring, and dashpot

The mass of the dashpot and the mass of the spring are small and are neglected. Friction is also neglected. For the system of Figure 20.59, the input is the applied force F and the output is the change in distance x.

Let us express the differential equation of (20.46) with numerical coefficients as

$$\frac{d^2}{dt^2}x(t) + 2\frac{d}{dt}x(t) + 3x(t) = (20\sin t)u_0(t) \tag{20.47}$$

where $u_0(t)$ is the unit step function, and the initial conditions are $x(0) = 4$, and $dx/dt = 0$. For convenience, we denote these are denoted as $x1_0$ and $x2_0$ respectively.

For the solution of (20.47) we will use the **State−Space** block found in the Continuous Library, and thus our model is as shown in Figure 20.60.

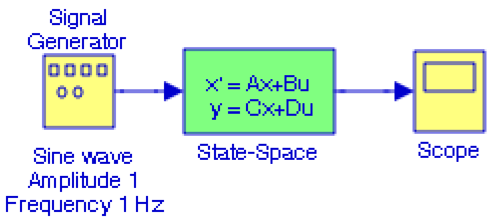


Figure 20.60. Model for Figure 20.59

The state equations are defined as

$$x_1(t) = x(t) \tag{20.48}$$

and

$$x_2(t) = \frac{d}{dt}x_1(t) \tag{20.49}$$

Then,

$$\frac{d}{dt}x_2(t) = \frac{d^2}{dt^2}x_1(t) = \frac{d^2}{dt^2}x(t) \tag{20.50}$$

From (20.45), (20.46), and (20.47) we obtain the system of state equations

$$\begin{aligned} \frac{d}{dt}x_1(t) &= x_2(t) \\ \frac{d}{dt}x_2(t) &= -3x_1(t) - 2x_2(t) + (20\sin t)u_0(t) \end{aligned} \tag{20.51}$$

and in matrix form,

$$\begin{bmatrix} \frac{d}{dt}x_1(t) \\ \frac{d}{dt}x_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -3 & -2 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 20\sin t \end{bmatrix} u_0(t) \tag{20.52}$$

The output state equation is

$$y = Cx + Du$$

or

$$y(t) = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}$$

Therefore, for the model of Figure 20.44, the coefficients A, B, C, and D are

$$A = \begin{bmatrix} 0 & 1 \\ -3 & -2 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 5 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 \end{bmatrix} \qquad D = 0 \tag{20.53}$$

The initial conditions $x1_0$ and $x2_0$ are denoted by the matrix

$$\begin{bmatrix} x1_0 \\ x2_0 \end{bmatrix} = \begin{bmatrix} 4 \\ 0 \end{bmatrix} \tag{20.54}$$

The values in (20.53) and (20.54) are entered in the **Block parameters** dialog box* for the **State–Space** block, and after the simulation command is issued, the **Scope** block displays the waveform of Figure 20.61.

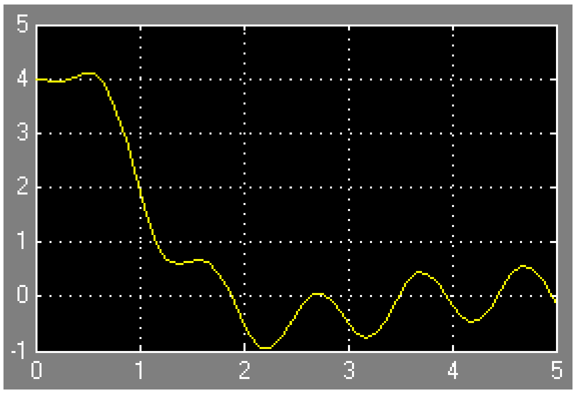


Figure 20.61. Waveform for the model of Figure 20.60

20.5.2 Model for a Cascaded Mass–Spring System

Figure 20.62 shows a a cascaded mass–spring system where F is the applied force, M is the mass, k is the spring constant, f is the friction, and X is the displacement. It is shown in feedback and control systems textbooks that the transfer function $G(s) = X_1/F$ is

* *The initial conditions $x1_0$ and $x2_0$ are entered as* x10 *and* x20 *respectively.*

$$G(s) = \frac{k_1}{(M_1s^2 + f_1s + k_1)(M_2s^2 + f_2s + k_1 + k_2) - k_1^2} \tag{20.55}$$

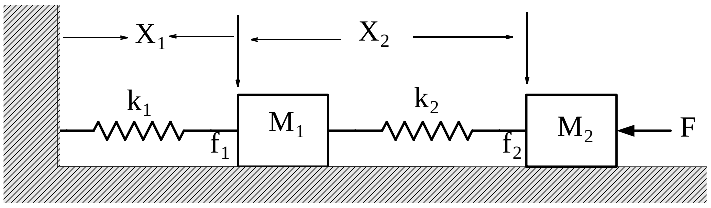


Figure 20.62. Cascaded mass−spring system

For simplicity, let us assume that the constants and conditions are such that after substitution into (20.55), this relation reduces to

$$G(s) = \frac{12}{s^4 + 10s^3 + 36s^2 + 56s + 32} \tag{20.56}$$

and the force applied at $50\sin t$. The model under those conditions is shown in Figure 20.63, and the input and output waveforms are shown in Figure 20.64.

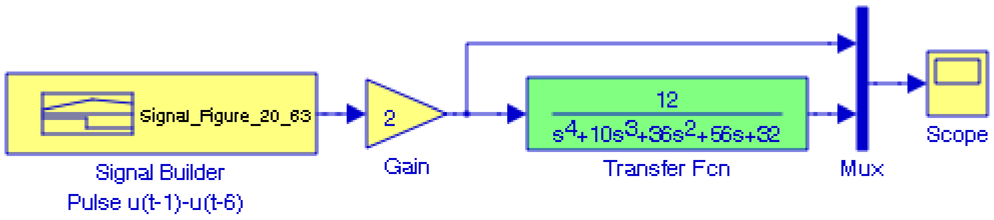


Figure 20.63. Model for the system in Figure 20.62

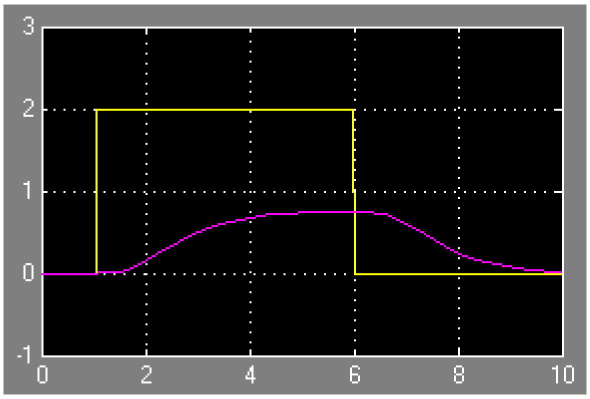


Figure 20.64. Input and output waveforms for the model in Figure 20.63

20.5.3 Model for a Mechanical Accelerometer

A simple mechanical accelerometer system consisting of a block, a dashpot, and a spring is connected as shown in Figure 20.65.

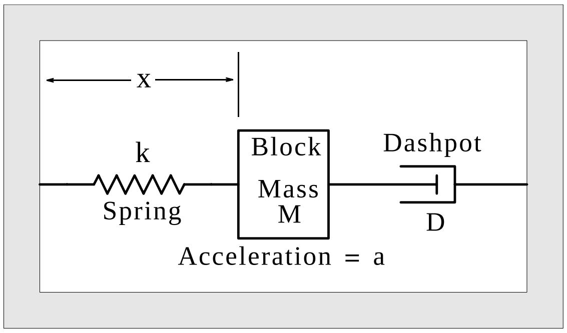


Figure 20.65. A simple mechanical accelerometer

It is shown in feedback and control systems textbooks that the transfer function $G(s) = x/a$ is

$$G(s) = \frac{1}{s^2 + (D/M)s + k/M} \qquad (20.57)$$

For simplicity, let us assume that the constants and conditions are such that after substitution into (20.54), this relation reduces to

$$G(s) = \frac{1}{s^2 + 0.1s + 0.2} \qquad (20.58)$$

and the force applied is $0.8u_0(t)$ where $u_0(t)$ is the unit step function. The model under those conditions is shown in Figure 20.66, and the input and output waveforms are shown in Figure 20.67.

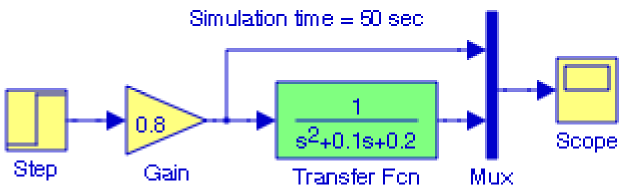


Figure 20.66. Model for the system in Figure 20.65

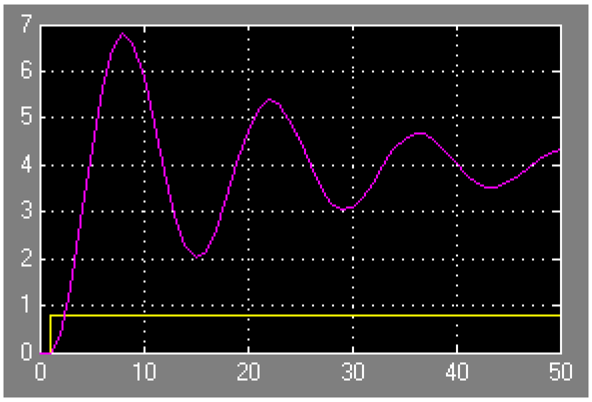


Figure 20.67. Input and output waveforms for the model in Figure 20.66

20.6 Feedback Control Systems

In our previous discussions in this chapter, we have used system components that are interconnected in series. These are referred to as **open–loop control systems**. An example of an open–loop system is a microwave oven which is controlled by a timer. However, most control systems are **closed–loop control systems** where the control action ia affected by the output. An example of a closed–loop system is the autopilot subsystem in an airplane which continuously measures the actual airplane direction and automatically adjusts other subsystems of the airplane to change the airplane heading to the desired direction. Feedback is the characteristic of a closed–loop control system which distinguishes it from open–loop systems. It is beyond the scope of this text to describe feedback control systems in detail. We will only describe some basics to aid the reader in understanding some of the advanced designs of the systems provided by the Simulink demos.

Figure 20.68 shows a simple feedback control system with two elements represented as blocks, the first of which is generally known as the **control element** or **controller**, and the second is known as the **plant**. The feedback (the line connecting the output to the summing point) is the same as the output and for this reason the entire system is referred to as **unity feedback system**. The path E represents the error, that is, the difference $E = X - Y$.

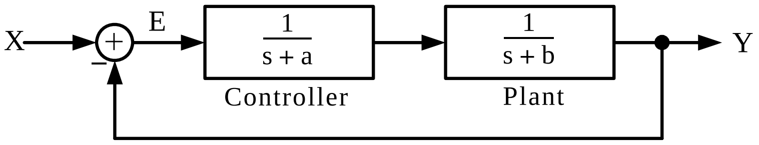


Figure 20.68. A unity feedback system

In Figure 20.52, the Controller and Plant blocks are in series and according to Feedback and Control Systems theory, can be replace by a single block whose transfer function is their product as shown in Figure 20.53.

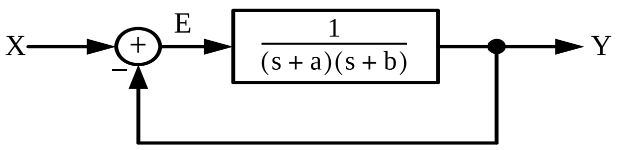


Figure 20.69. Simplified representation for the system of Figure 20.68

To find the overall transfer function $G(s) = Y/X$, observe that

$$Y = \frac{1}{(s+a)(s+b)}E = \frac{1}{(s+a)(s+b)}[X-Y]$$

or

$$Y + \frac{1}{(s+a)(s+b)}Y = \frac{1}{(s+a)(s+b)}X$$

$$Y\frac{(s+a)(s+b)}{(s+a)(s+b)} + \frac{1}{(s+a)(s+b)}Y = \frac{1}{(s+a)(s+b)}X$$

Dividing both sides by $(s+a)(s+b)$ we obtain

$$(s+a)(s+b)Y + Y = X$$

$$[(s+a)(s+b)+1]Y = X$$

and thus

$$G(s) = \frac{Y}{X} = \frac{1}{(s+a)(s+b)+1}$$

Therefore, the block diagram of Figure 20.69 can be replaced with only one block in an open–loop form as shown in Figure 20.54.

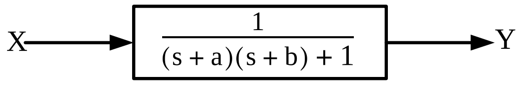


Figure 20.70. The system of Figure 20.69 in an open–loop form

A feedback control system in the form of the feedback path shown as in Figure 20.71 is referred to as a feedback control system in **canonical form**. For the system of Figure 20.71, the ratio Y/X is

$$\frac{Y}{X} = \frac{G}{1 \pm GH} \tag{20.59}$$

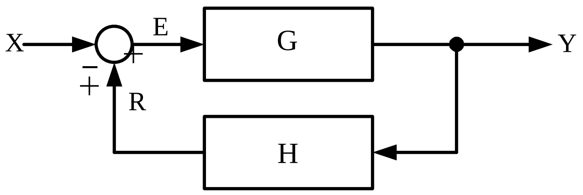


Figure 20.71. Canonical form of a feedback control system

More complicated block diagrams can be reduced by methods described in Feedback and Control Systems textbooks. For instance, the block diagram of Figure 20.72 below,

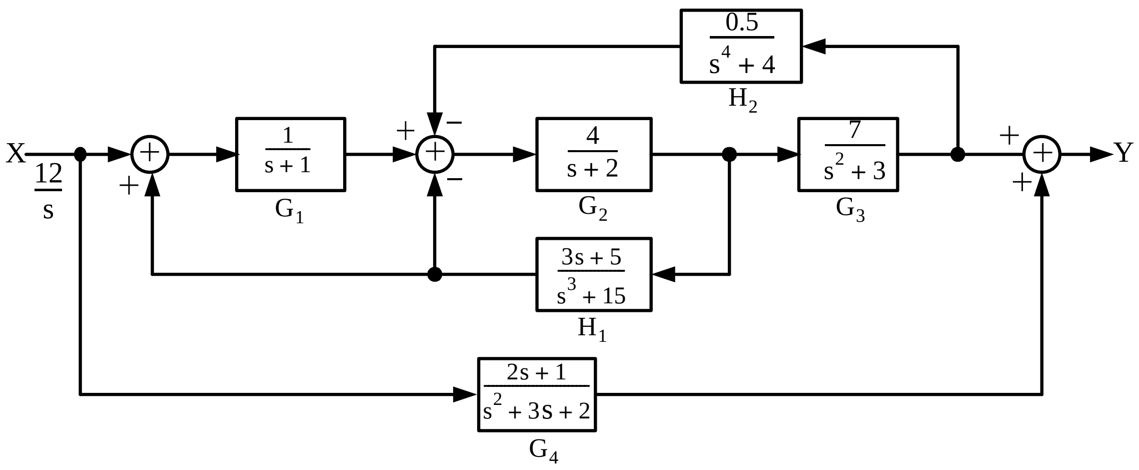


Figure 20.72. Feedback control system to be simplified to an open–loop system

can be replaced with the open–loop system of Figure 20.73.

$$X \longrightarrow \boxed{\frac{G_1G_2G_3 + G_4 - G_1G_2G_4H_1 + G_2G_4H_1 + G_2G_3G_4H_2}{1 - G_1G_2H_1 + G_2H_1 + G_2G_3H_2}} \longrightarrow Y$$

Figure 20.73. Open–loop equivalent control system for the closed–loop system of Figure 20.72

We can prove that the systems of Figures 20.72 and 20.73 are equivalent with Simulink blocks. The system in Figure 20.72 is represented by the model in Figure 20.74 and there is no need to represent it as an open–loop equivalent. Instead, we can represent it as the subsystem shown in Figure 20.75.

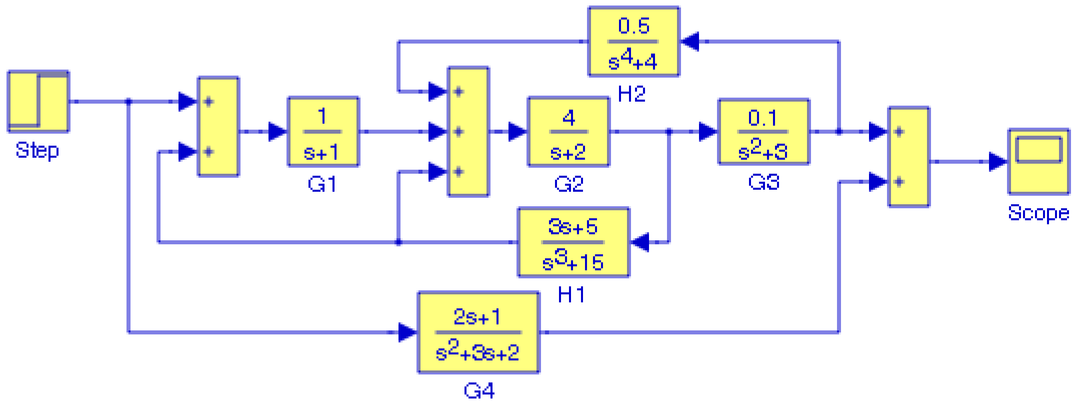


Figure 20.74. Model for the feedback control system of Figure 20.73

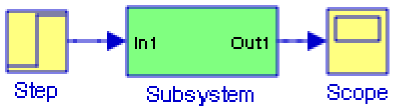


Figure 20.75. The model of Figure 20.74 replaced by a Subsystem block

20.7 Models for Electrical Systems

In this section we will draw two models for mechanical systems. Subsection 20.7.1 presents an electric circuit whose output voltage is determined by application of Thevenin's theorem, and Subsection 20.7.2 presents an electric circuit to be analyzed by application of the Superposition Principle.

20.7.1 Model for an Electric Circuit in Phasor* Form

By application of Thevenin's theorem, the electric circuit of Figure 20.76 can be simplified† to that shown in Figure 20.77.

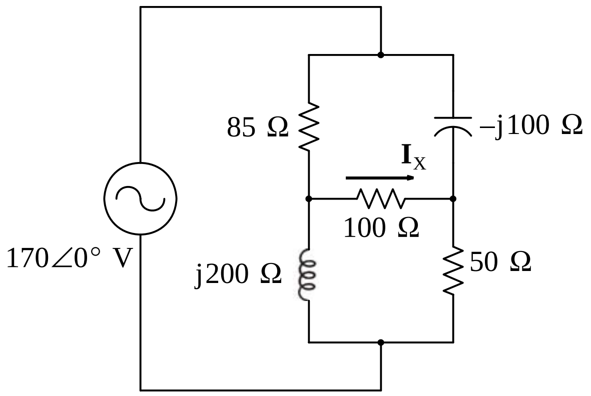


Figure 20.76. Electric circuit to be replaced by its Thevenin equivalent

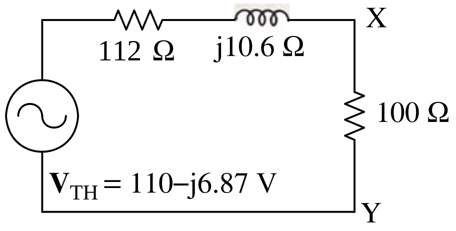


Figure 20.77. The circuit of Figure 20.60 replaced by its Thevenin equivalent

* *A phasor is a rotating vector. Phasors are used extensively in the analysis of AC electric circuits. For a thorough discussion on phasors, please refer to Circuit Analysis I with MATLAB Applications, ISBN 0−9709511−2−4.*

† *For a step−by−step procedure, please see same reference.*

Next, we let $V_{IN} = V_{TH}$, $V_{OUT} = V_{XY}$, $Z_1 = 112 + j10$, and $Z_2 = 100$. Application of the voltage division expression yields

$$V_{OUT} = \frac{Z_2}{Z_1 + Z_2} V_{IN} \tag{20.60}$$

Now, we use the model in Figure 20.78 to convert all quantities from the rectangular to the polar form, perform the addition and multiplication operations, display the output voltage in both polar and rectangular forms, and show the output voltage on a Scope block in Figure 20.79. The Simulink blocks used for the conversions are in the Math Operations library. We can also use the conversion blocks presented in Chapter 19, Simulink Extras.

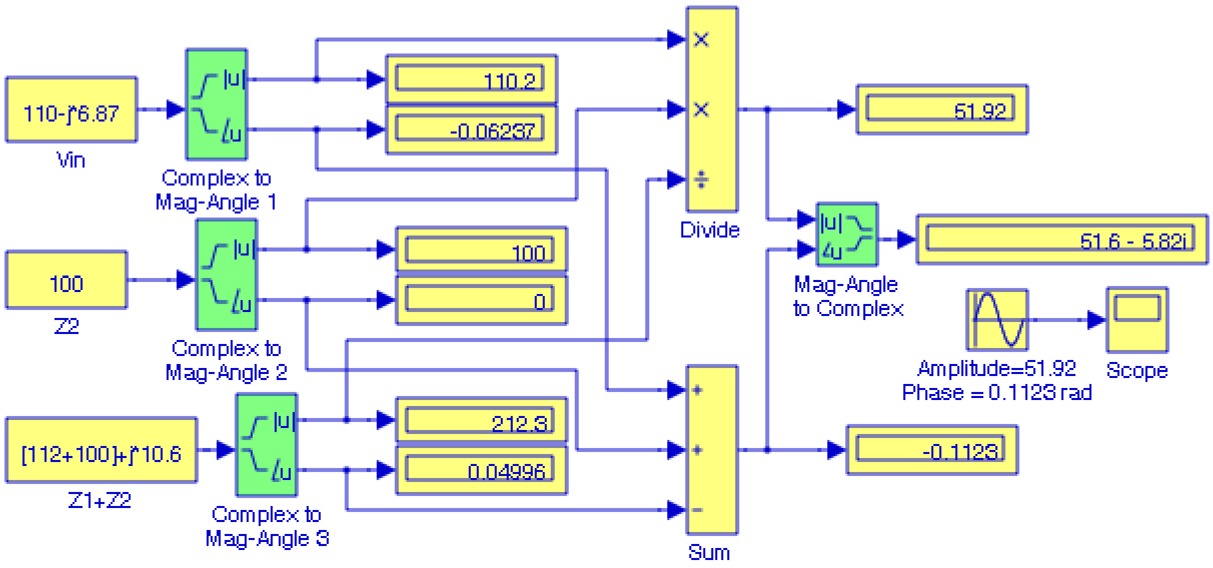


Figure 20.78. Model for the computation and display of the output voltage for the circuit in Figure 20.77

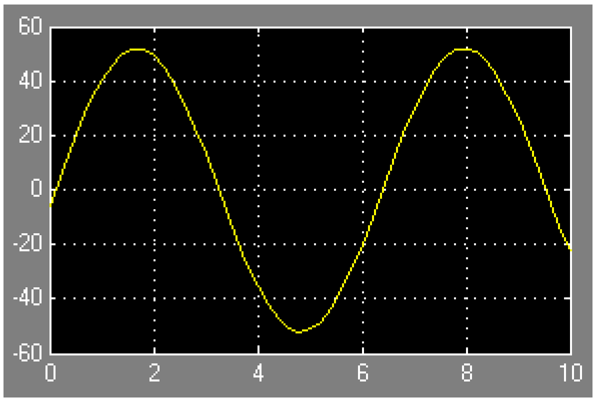


Figure 20.79. Waveform for the output voltage of model in Figure 20.78

20.7.2 Model for the Application of the Superposition Principle

We will create a model to illustrate the superposition principle by computing the phasor voltage across capacitor C_2 in the circuit of Figure 20.80.

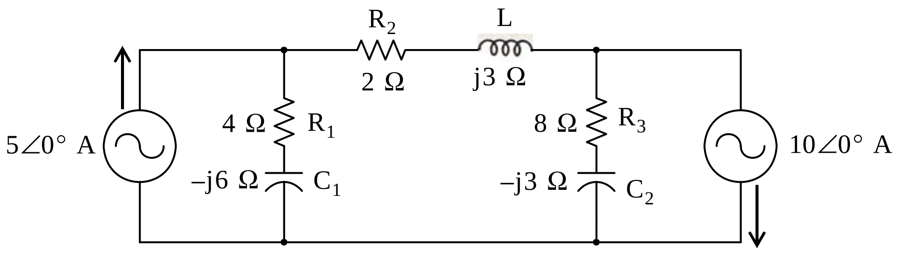


Figure 20.80. Electric circuit to illustrate the superposition principle

Let the phasor voltage across C_2 due to the $5\angle 0°\ A$ current source acting alone be denoted as $\mathbf{V}'_{C2}$, and that due to the $10\angle 0°\ A$ current source as $\mathbf{V}''_{C2}$. Then, by the superposition principle,

$$\mathbf{V}_{C2} = \mathbf{V}'_{C2} + \mathbf{V}''_{C2}$$

With the $5\angle 0°\ A$ current source acting alone, the circuit reduces to that shown in Figure 20.81.

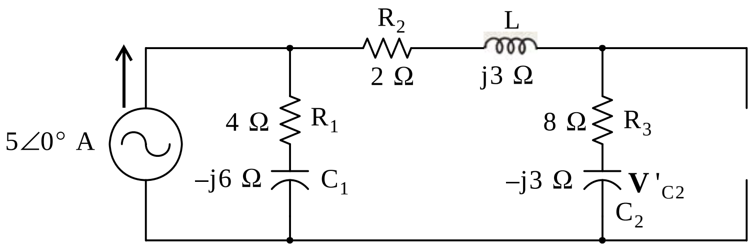


Figure 20.81. Circuit in Figure 20.80 with the $5\angle 0°\ A$ *current source acting alone*

By application of the current division expression, the current $\mathbf{I}'_{C2}$ through C_2 is

$$\mathbf{I}'_{C2} = \frac{4-j6}{4-j6+2+j3+8-j3}5\angle 0° = \frac{7.211\angle -56.3°}{15.232\angle -23.2°}5\angle 0° = 2.367\angle -33.1°$$

The voltage across C_2 with the $5\angle 0°$ current source acting alone is

$$\begin{aligned}\mathbf{V}'_{C2} &= (-j3)(2.367\angle -33.1°) = (3\angle -90°)(2.367\angle -33.1°)\\ &= 7.102\angle -123.1° = -3.878 - j5.949\end{aligned} \qquad (20.61)$$

Next, with the $10\angle 0°\ A$ current source acting alone, the circuit reduces to that shown in Figure 20.82.

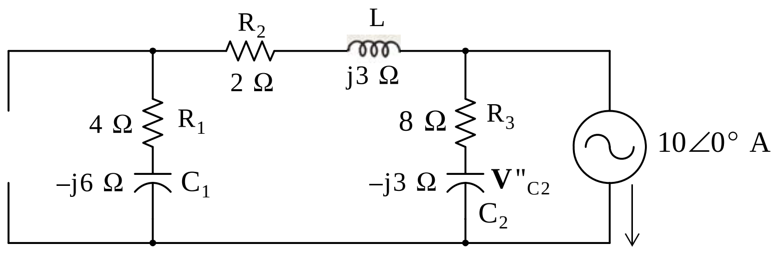


Figure 20.82. Circuit with the $10\angle 0°$ A *current source acting alone*

and by application of the current division expression, the current $\mathbf{I}''_{C2}$ through C_2 is

$$\mathbf{I}''_{C2} = \frac{4 - j6 + 2 + j3}{4 - j6 + 2 + j3 + 8 - j3}(-10\angle 0°)$$
$$= \frac{6.708\angle -26.6°}{15.232\angle -23.2°}10\angle 180° = 4.404\angle 176.6°$$

The voltage across C_2 with the $10\angle 0°$ current source acting alone is

$$\mathbf{V}''_{C2} = (-j3)(4.404\angle 176.6°) = (3\angle -90°)(4.404\angle 176.6°)$$
$$= (13.213\angle 86.6 = 0.784 + j13.189) \tag{20.62}$$

Addition of (20.61) with (20.62) yields

$$\mathbf{V}_{C2} = \mathbf{V}'_{C2} + \mathbf{V}''_{C2} = -3.878 - j5.949 + 0.784 + j13.189$$

or

$$\mathbf{V}_{C2} = -3.094 + j7.240 = 7.873\angle 113.1°$$

The models for the computation of $\mathbf{V}'_{C2}$ and $\mathbf{V}''_{C2}$ are shown in Figures 20.83 and 20.84 respectively.

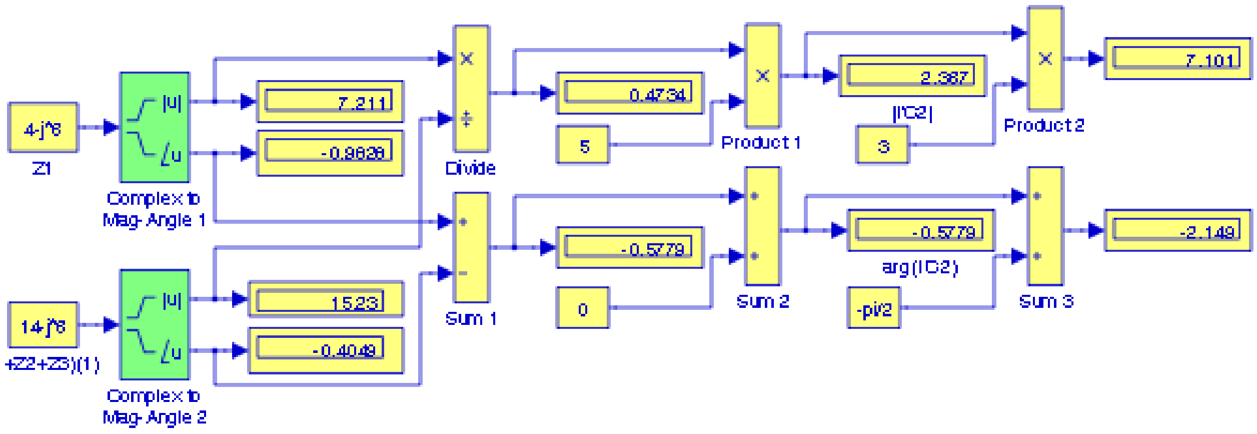


Figure 20.83. Model for the computation of V'_{C2}

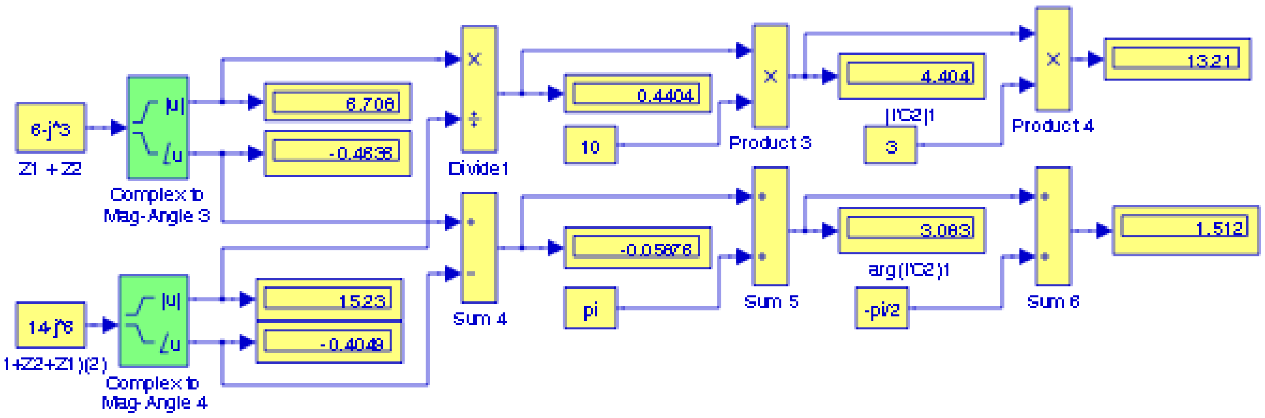


Figure 20.84. Model for the computation of V''_{C2}

The final step is to add $\mathbf{V}'_{C2}$ with $\mathbf{V}''_{C2}$. This addition is performed with the model of Figure 20.85 where the models of Figures 20.83 and 20.84 have been converted to Subsystems 1 and 2 respectively.

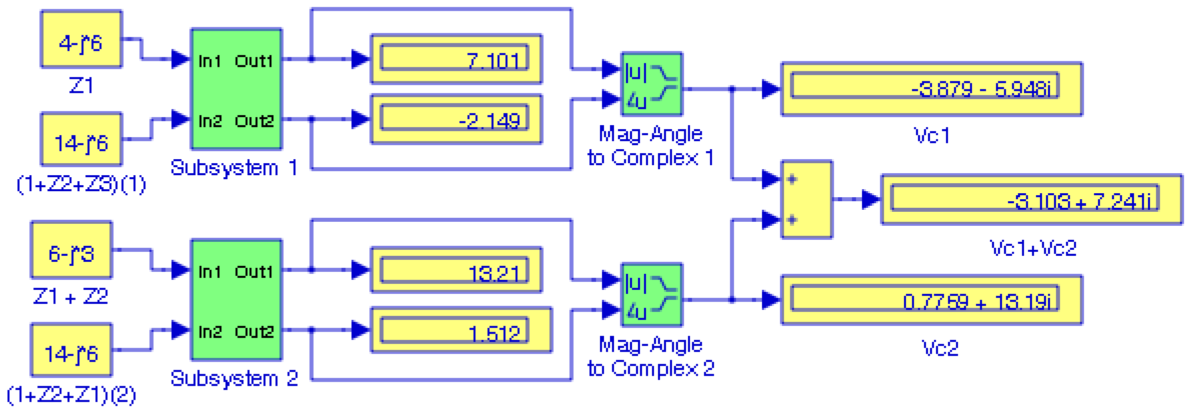


Figure 20.85. Model for the addition of V'_{C2} *with* V''_{C2}

The model in Figure 20.85 can now be used with the circuit of Figure 20.80 for any values of the impedances Z.

20.8 Transformations

The conversions from complex to magnitude–angle and magnitude–angle to complex used in the previous section, can also be performed with the Cartesian to Polar and Polar to Cartesian blocks. Examples are presented in the model in Figure 20.70 where transformations from Cartesian to Spherical and Spherical to Cartesian are shown. The equations used in these transformations are shown in the **Block Parameters** dialog box for each block.

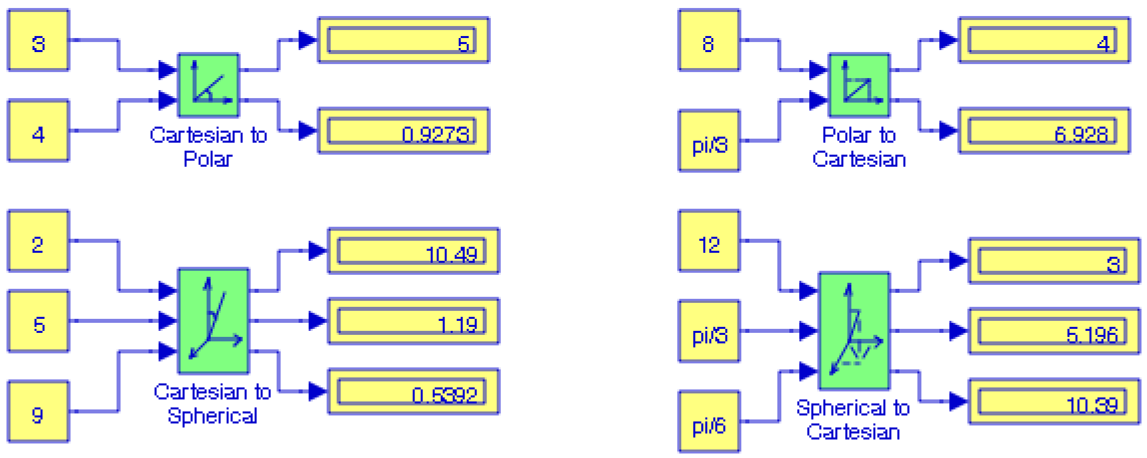


Figure 20.86. Transformation examples

Other transformation blocks include Fahrenheit to Celsius, Celsius to Fahrenheit, Degrees to Radians, and Radians to Degrees. Examples for these were presented in Chapter 19, Simulink Extras.

20.9 Discrete Time Integration with Variable Amplitude Input

In Chapter 2, Exercise 12, we showed that when the input signal is a pulse, a Discrete Forward Euler Integrator and a Discrete Trapezoidal Integrator will produce the same result. In this example, we will use an input that varies in amplitude during a sample period. This is illustrated with the model in Figure 20.87.

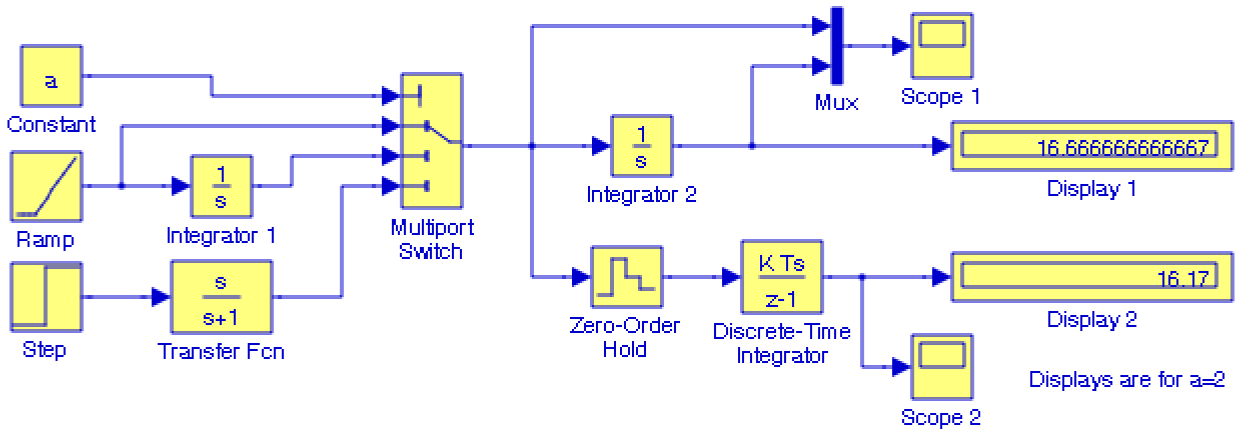


Figure 20.87. Model for Discrete Time Integration with variable amplitude input

For the model in Figure 20.71, we have used the following settings:

Simulation Configuration Parameters
Solver: Ode4 (Runge-Kutta)
Type: Fixed Step Size
Fixed Step Size: 0.01
Start Time: 0
Stop Time: 10

Ramp block
Slope: 0.1

Step block
Final Value: 5

Transfer Function block
Numerator: [1 0]
Denominator: [1 1]

Multiport Switch block
Number of inputs: 3

Zero Order Hold block
Sample time: 0.2

Discrete Time Integrator block
Integrator method: User's choice
Sample time: −1 (Inherent from input)

Display 1 and Display 2 blocks
Format: Long

In MATLAB command prompt enter:
a=1 for testing a discrete integrator with a ramp input signal
a=2 for testing a discrete integrator with a parabolic input signal – chosen for this model
a=3 for testing a discrete integrator with an exponentially decaying signal

All other unlisted parameters are left in their default states

Upon execution of the simulation command, the waveforms displayed by the Scope 1 and Scope 2 blocks are shown in Figures 20.72 and 20.73 respectively.

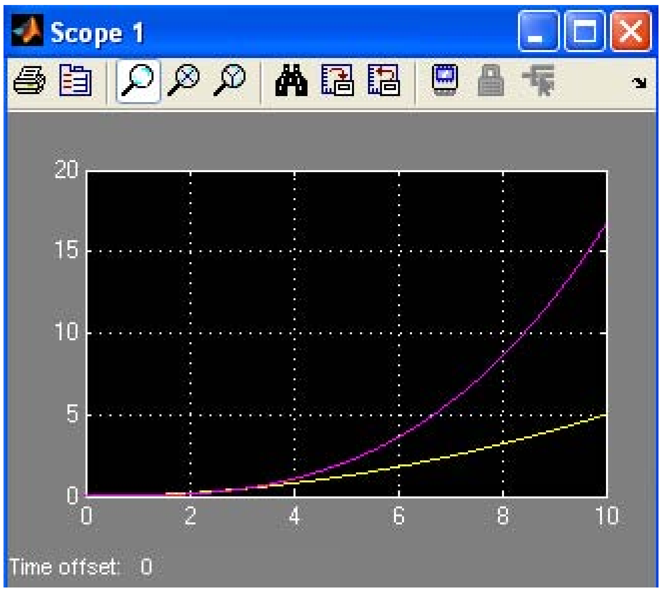


Figure 20.88. Waveforms displayed by the Scope 1 block in Figure 20.71

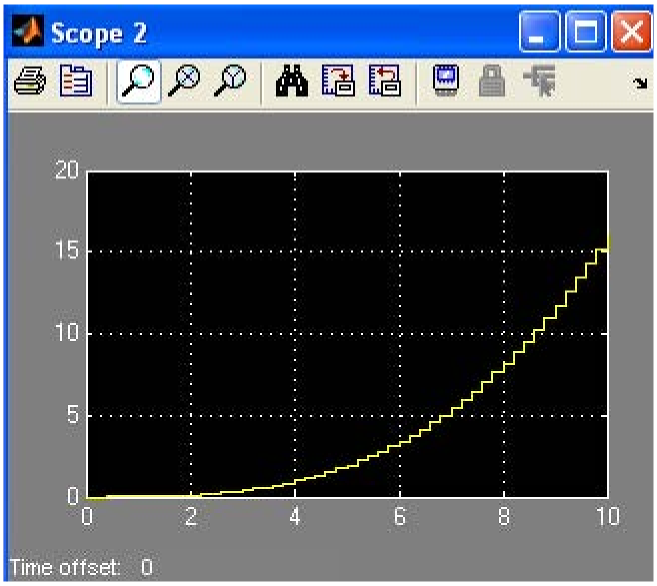
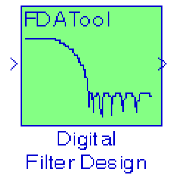
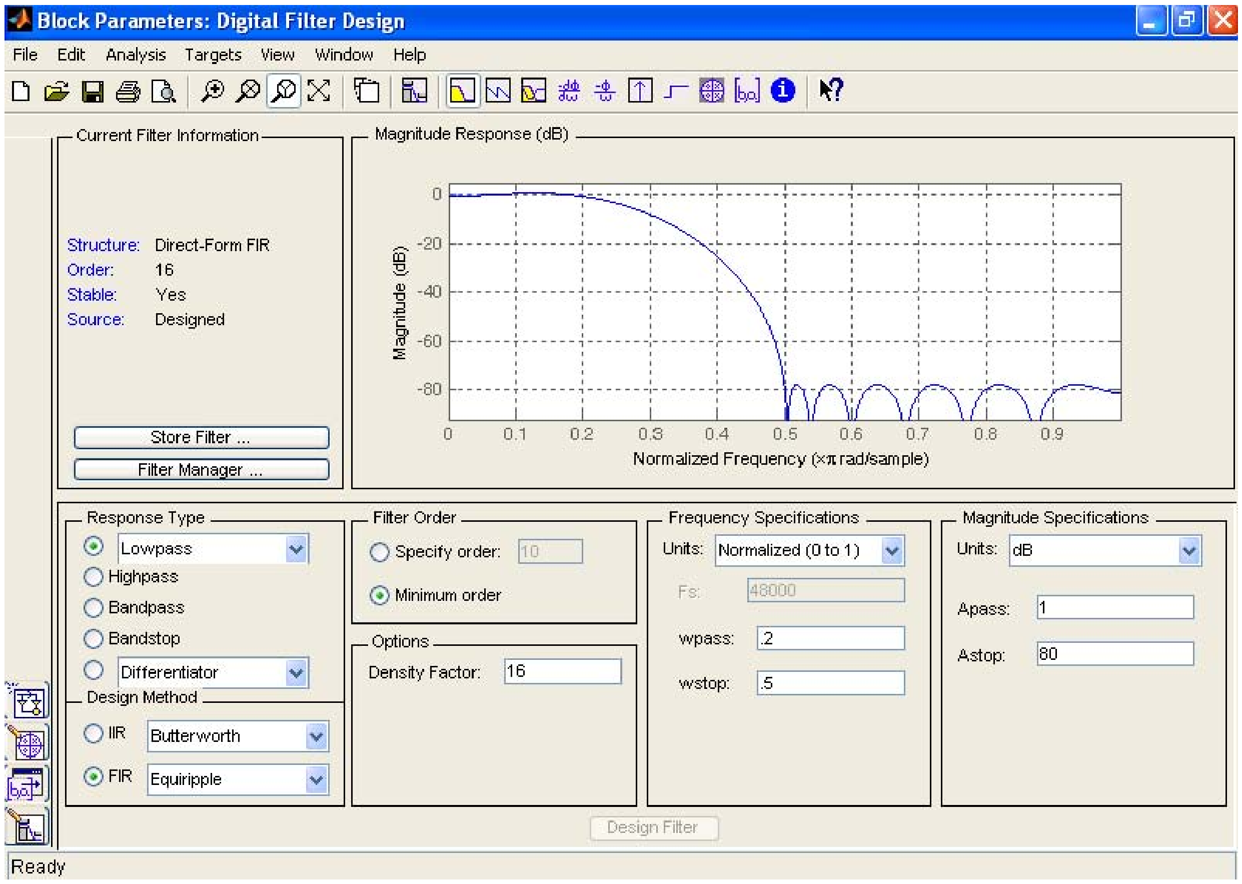


Figure 20.89. Waveform displayed by the Scope 2 block in Figure 20.71

20.10 The Digital Filter Design Block



The **Digital Filter Design** block is included in the Simulink Signal Processing Blockset* and requires the installation of the Simulink program to create models related to digital filter design applications. The functionality of this block can be observed by dragging this block into a model and double–clicking it. When this is done, the **Block Parameters** dialog box appears as shown in Figure 20.90.



Current Filter Information

Structure: Direct-Form FIR
Order: 16
Stable: Yes
Source: Designed

Response Type: [✓ Lowpass] Highpass Bandpass Bandstop Differentiator

Design Method: IIR Butterworth; [✓ FIR] Equiripple

Filter Order: Specify order: 10; [✓ Minimum order]

Options: Density Factor: 16

Frequency Specifications: Units: Normalized (0 to 1); Fs: 48000; wpass: .2; wstop: .5

Magnitude Specifications: Units: dB; Apass: 1; Astop: 80

Ready

Figure 20.90. The Digital Filter Design Block Parameters dialog box

* ***Blocksets*** *are built–in blocks in Simulink that provide a comprehensive block library for different system components. FDA stands for Filter Design and Analysis. This blockset can be obtained from The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760–2098, Phone: 508–647–7000, www.mathworks.com.*

As indicated on the left lower part of this box, we can choose the **Response Type** (Low–Pass, High–Pass, Band–Pass, or Band–Elimination), the **Design Method** (IIR or FIR) where an IIR filter can be Butterworth, Chebyshev Type I, Chebyshev Type II, or Elliptic, and FIR can be Window, Maximally Flat, etc., and the **Window**[*] can be Kaiser, Hamming, etc. We must click on the Design Filter button at the bottom of the Block Parameters dialog box to update the specifications. Example 20.4 below is very similar to that of Example 11.23, Page 11–68.

Example 20.4

The signal represented by the waveform of Figure 20.91 is the summation of the sinusoidal signals x, y, and z defined in the MATLAB script below.

```
t=0:pi/32:16*pi; x=sin(0.25.*t); y=2.*sin(0.75.*t+pi/6); z=5.*sin(1.5.*t+pi/3); plot(t,x+y+z); grid
```

During transmission of this signal from its source to its destination, this signal is corrupted by the addition of unwanted Gaussian random noise. In this example, we will create a Simulink model that includes a digital filter to remove the Gaussian random noise.

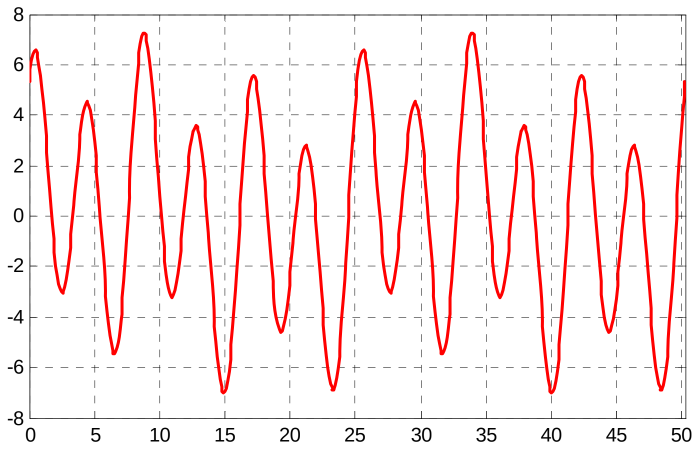


Figure 20.91. Signal to be transmitted for Example 20.4

The Simulink model of Figure 20.92 below contains a **Random Source** block to incorporate noise into the system.This block and the three **DSP Sine Wave** blocks are dragged from the **Signal Processing Sources** sub–library under **Signal Management** in the **Signal Processing Blockset** into the model.

* *A window function multiplies the infinite length impulse response (IIR) by a finite width function, referred to as window function, so that the infinite length series will be terminated after a finite number of terms in the series. The most common window functions are described in the Signal Processing Toolbox User's Guide The MathWorks, Inc.*

The **Add** (Sum) and **Scope** blocks are dragged from the **Commonly Used Blocks** main Simulink Library, and the **Scope 1** and **Scope 2** blocks are configured with four and two inputs (axes) respectively from the **Scope Parameters** dialog box.

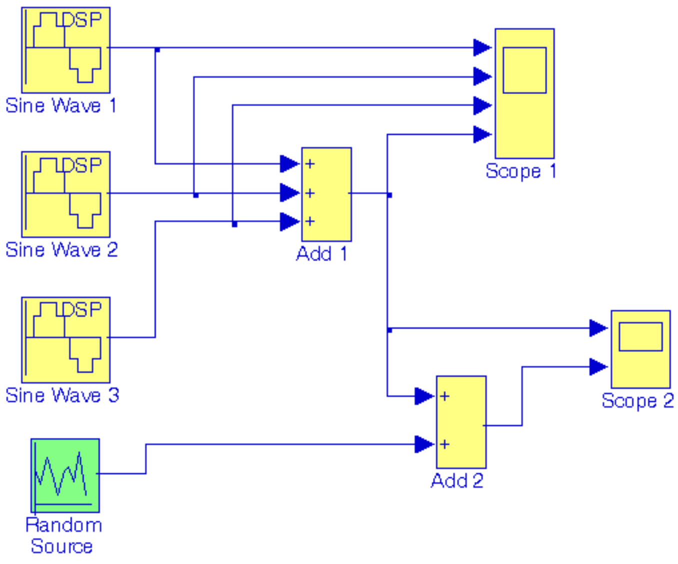


Figure 20.92. Simulink model for Example 20.4

The **DSP Sine Wave** blocks are configured as follows:

DSP Sine Wave 1:

Amplitude: 1, **Freq (Hz)**: 0.25, **Phase**: 0, **Sample Time**: 0.05, All other parameters in their default state

DSP Sine Wave 2:

Amplitude: 2, **Freq (Hz)**: 0.75, **Phase**: pi/6, **Sample Time**: 0.05, All other parameters in their default state

DSP Sine Wave 3:

Amplitude: 5, **Freq (Hz)**: 1.5, **Phase**: pi/3, **Sample Time**: 0.05, All other parameters in their default state

The **Random Source** block is configured as follows:

Source type: Gaussian, **Method**: Ziggurat, **Initial seed**: [23341], **Sample Time**: 0.05

When the simulation command is executed, the **Scope 1** block in the model of Figure 20.92, displays the input and output waveforms shown in Figure 20.93, and the **Scope 2** block displays the input and output waveforms shown in Figure 20.94.

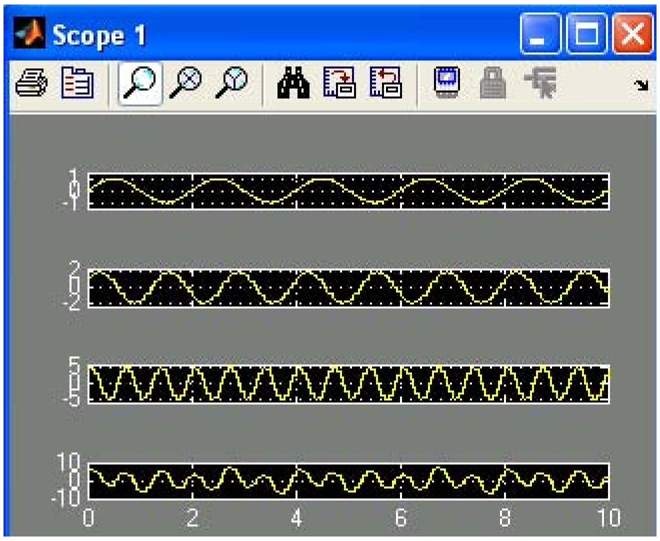


Figure 20.93. Input and output waveforms displayed in Scope 1 block of Figure 20.92

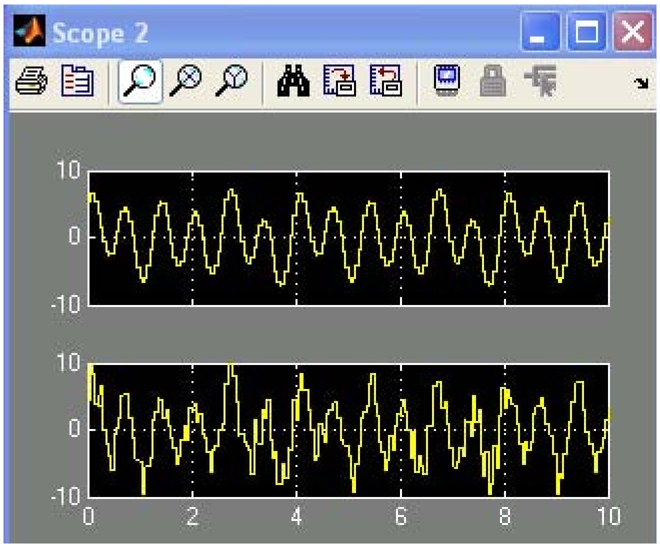


Figure 20.94. Input and output waveforms displayed in Scope 2 block of Figure 20.92

Next, we add an **FDA Tool Digital Filter Design** block as shown in Figure 20.95 to remove the unwanted noise created by the Random Source block. The Block Parameters dialog box for the **FDA Tool Digital Filter Design** block is configured as follows:

Response Type: Lowpass, **Design Method**: FIR, Window, **Window**: Rectangular, and all other unlisted parameters in their default state. Of course, we can choose any other design options. With those specifications, the **Scope 2** block displays the waveforms shown in Figure 20.96.

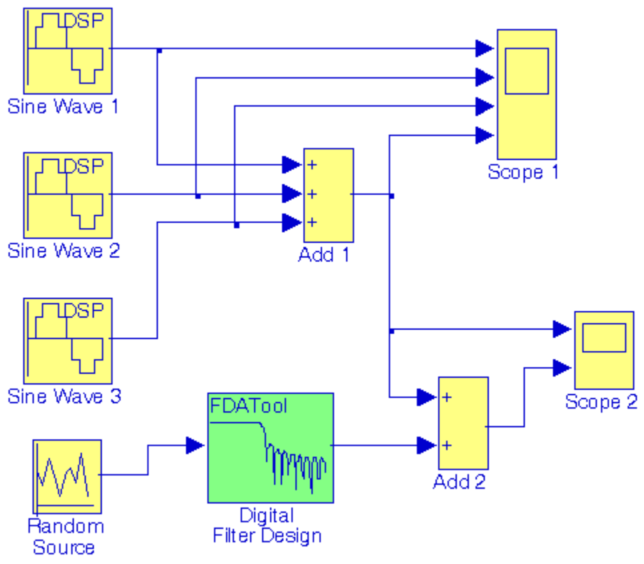


Figure 20.95. The model of Figure 20.92 with the addition of an FDA Tool Digital Filter Design block.

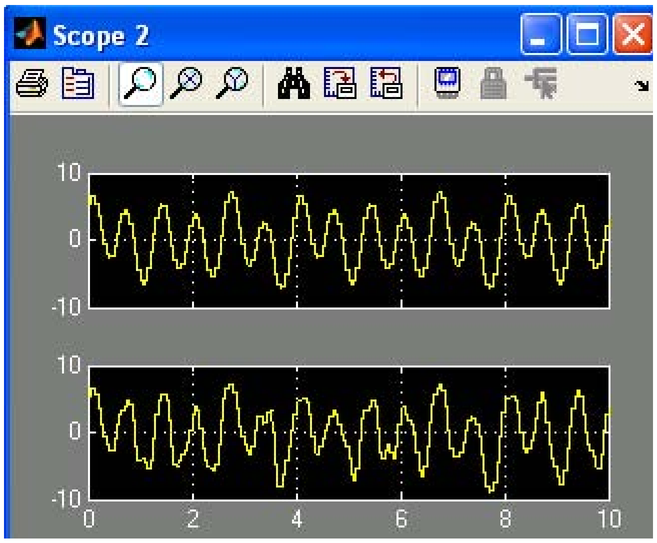


Figure 20.96. Input and output waveforms displayed in Scope 2 block of Figure 20.95

Figure 20.96 reveals that with the addition of the **FDA Tool Digital Filter Design** block, most of the unwanted noise has been removed. However, we can remove the remaining noise with the addition of an *adaptive filter*.[*] The **Signal Processing Blockset** contains blocks that implement the **Least–Mean–Square (LMS)** block, the **Fast Block LMS**, and **Recursive Least Squares**

[*] *An **adaptive filter** is a digital filter that performs digital signal processing and can adapt its performance based on the input signal. All filters we've considered thus far are non–adaptive filter and their characteristics are defined by their transfer function.*

(RLS) adaptive filter algorithms. For our example, we will add an LMS adaptive filter to the model of Figure 20.95. Thus, from the Signal Processing Blockset, we click on the Filtering Library, then on the Adaptive Filters sub–library, and we drag the **LMS Filter** block into our model which is connected as shown in Figure 20.97 where the **Wts** (Weights) port of the **LMS Filter** block which outputs the filter weights is left unconnected. The waveforms displayed by the **Scope 3** block are shown in Figure 20.98 where last waveform indicates the output of the Error port which is the difference between the desired signal of the LMS filter and its output.

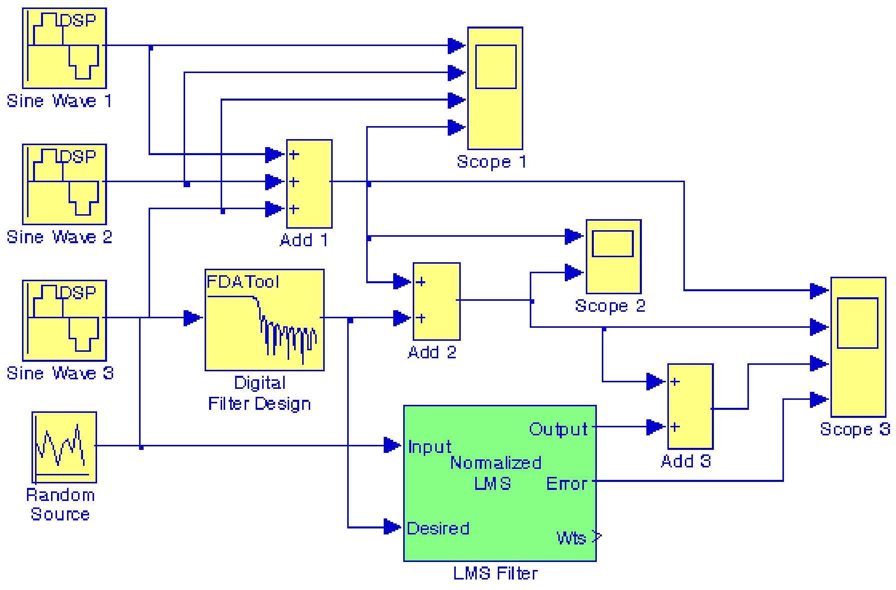


Figure 20.97. Model for Example 20.4 with LMS Filter block

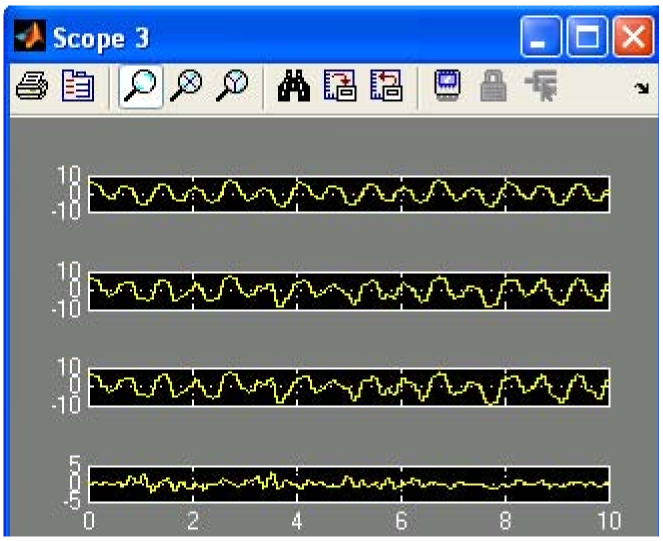


Figure 20.98. Waveforms displayed by Scope 3 block in the model of Figure 20.97

The error is never exactly zero and thus the adaptive filter continuously modifies the filter coefficients to provide a better approximation of the noise. We can view these coefficients as they change with time by connecting a **Vector Scope** block to the **Wts** output port of the **LMS filter** block as shown in Figure 20.99.

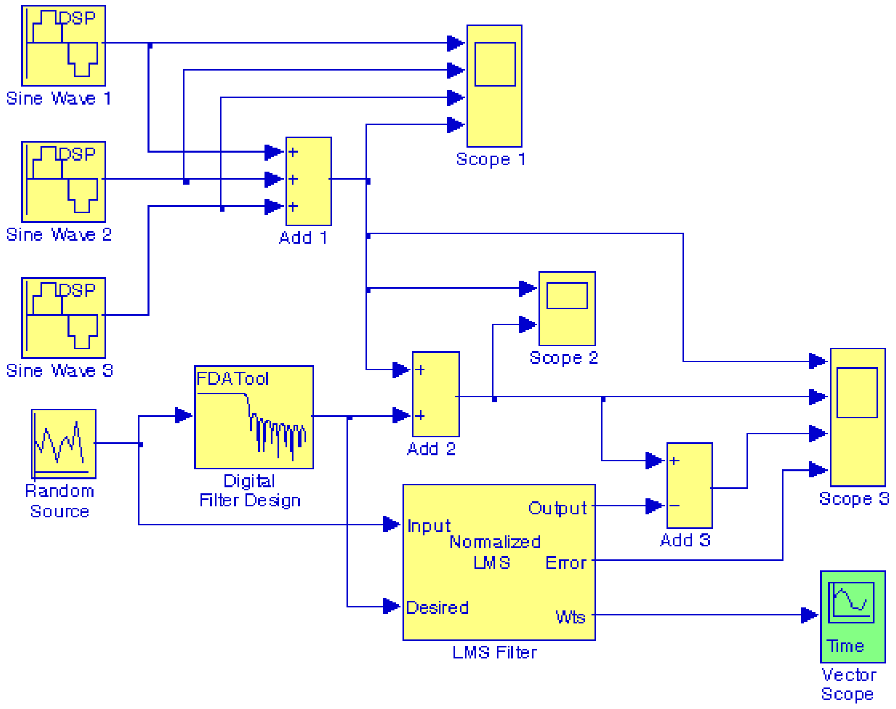


Figure 20.99. Model for Example 20.4 with Vector Scope block

The **Block Parameters** dialog box for the **Vector Scope** block contains four tabs, and for the model of Figure 20.99 these are configured as follows:

Scope Properties tab: Input domain: **Time**, Time display span (number of frames): **1**

Display Properties tab: Select the following check boxes: **Show grid, Frame Number, Compact Display,** and **Open scope at start of simulation**

Axis Properties tab: Minimum Y–limit: **–0.1**, Maximum Y–limit: **0.5**, Y–axis title: **Filter Weights**

Line Properties tab: Line visibilities: **on**, Line style: —, Line markers: **o**, Line colors: **[1 0 0]**

Before execution of the simulation command, the configuration parameters are specified as follows:

From the **Simulation** drop menu, in the **Solver** pane, for the **Stop time** parameter, we enter **inf**. From the **Type** list, we choose **Fixed–step**, and from the **Solver** list we choose **discrete (no continuous states)**. We close the configuration parameters dialog box by clicking **OK**.

When the simulation command is issued, we observe that the **Vector Scope** window opens automatically, and the filter coefficients change with time and eventually approach their steady–state values as shown in Figure 20.100.

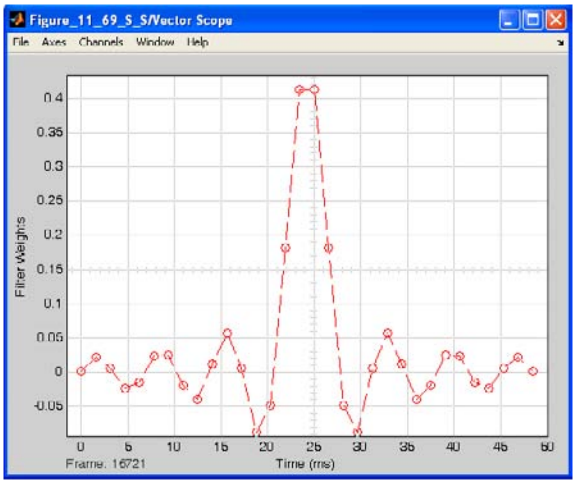


Figure 20.100. The filter coefficients displayed in the Vector Scope Window in the model of Figure 20.99

Next, we double–click on the **Scope 3** block in the model of Figure 20.99, and after some time we observe that the error decreases to zero as shown in Figure 20.101, and the output of the adaptive LMS filter is practically the same as the original input signal.

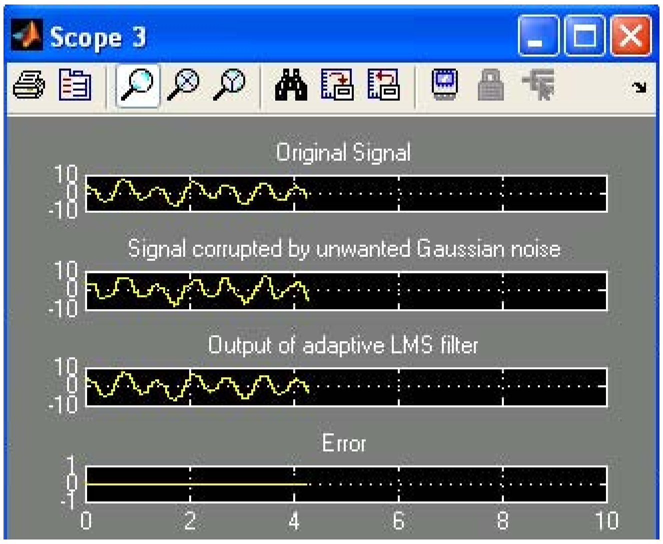

Scope 3
Original Signal
Signal corrupted by unwanted Gaussian noise
Output of adaptive LMS filter
Error
10
0
-10
1
0
-1
0 2 4 6 8 10

Figure 20.101. Waveforms displayed in the Scope 3 in the model of Figure 20.99

Since for the **Stop time** parameter we have specified **inf**, the simulation time goes on forever, and we observe that the waveforms in Figure 20.101 are updated continuously. To stop the simulation, we must click on the **Stop simulation** icon which is indicated by a small black square immediately to the left of the **Stop time** field in the window of our model. The **Stop simulation** is active only when the **Stop time** is specified as **inf** and the simulation command has been issued. To pause the simulation, we must click on the **Pause simulation** icon indicated by two small vertical bars immediately to the left of the **Stop simulation** icon.

20.11 S–Function Examples

An S–Function example is presented in Subsection 11.18, Chapter 11, Page 11–49. In Subsections 20.11.1 and 20.11.2 below, we present two more examples.

20.11.1 Temperature Coefficients for Semiconductor Diodes

For semiconductor diodes, the empirical equations describing the temperature coefficient dV_F/dT in $mV/°C$ as a function of forward current I_F in mA are

$$\frac{dV_{F1}}{dT} = 0.6\log 10(I_{ff}) - 1.92 \qquad \text{for gold doped diodes}$$

$$\frac{dV_{F1}}{dT} = 0.33\log 10(I_{ff} - I_{fv}) - 1.66 \qquad \text{for non–gold doped diodes}$$

where, for this example,

I_{ff} = final value of forward current

I_{fv} = variable value of forward current

We begin with the user–defined m–file below which we type in the Editor Window and we save it as diode.m

```
function dx=diode(t,x,Ifv)
%
% Model for gold-doped and non-gold-doped diodes
%
Vf1 = x(1);  % Gold-doped diode forward voltage, volts
Vf2 = x(2);  % Non-gold-doped diode forward voltage, volts
Iff = 100;   % Iff = final value in  of forward current in mA

dVf1 = 0.6*log10(Iff)-1.92;
dVf2 = 0.33*log10(Iff-Ifv)-1.66; % Ifv = variable value of forward current in mA

dx = [dVf1;dVf2];
```

To test this function for correctness, on MATLAB's Command Window we type and execute the command

```
[t,x,Ifw]=ode45(@diode, [0  10], [1;10],[ ], 50)
```

where the vector [0 10] specifies the start and the end of the simulation time, the vector [1;10] specifies an initial value column vector, the null vector [ ] can be used for other options, and the input value is set to 50.

Next, using the Editor Window we write the m–file below and we save it as diode_sfcn.m

```
function [sys,x0,str,ts]=...
           diode_sfcn(t,x,u,flag,Vf1init,Vf2init)

switch flag

    case 0                      % Initialize

        str = [];
        ts = [0 0];

        s = simsizes;

            s.NumContStates = 2;
            s.NumDiscStates = 0;
            s.NumOutputs = 2;
            s.NumInputs = 1;
            s.DirFeedthrough = 0;
            s.NumSampleTimes = 1;

        sys =simsizes(s);

        x0 = [Vf1init,Vf2init];

    case 1                       % Derivatives

        Ifw = u

        sys = diode(t,x,Ifw);

    case 3                       % Output

        sys = x;

    case {2 4 9}                 % 2:discrete
                                 % 3:calcTimeHit
                                 % 9:termination
        sys = [];

    otherwise
        error(['unhandled flag =',num2str(flag)]);

end
```

The syntax for the diode_sfcn.m file above is the same as that of Example 11.14, Chapter 11, Page 11–44.

Next, we open a new model window, from the User–Defined Functions Library we drag an S–Function block into it, we double–click this block, in the Function Block Parameters dialog box we name it diode_sfcn, and we add and interconnect the other blocks shown in Figure 20.74.

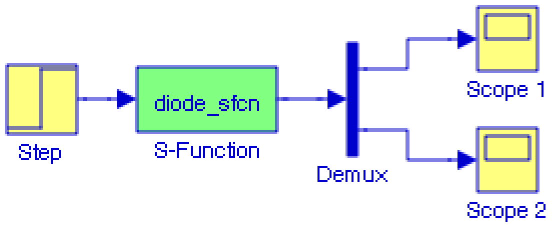


Figure 20.102. Another example illustrating the construction of an S–Function block

The waveforms displayed by the Scope 1 and Scope 2 blocks are shown in Figures 20.75 and 20.76 respectively.

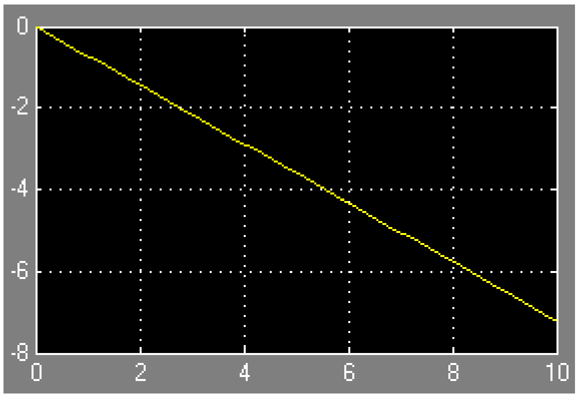


Figure 20.103. Waveform displayed by the Scope 1 block in the model of Figure 20.53

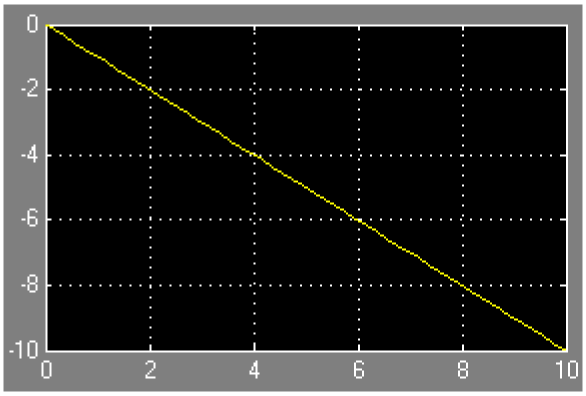


Figure 20.104. Waveform displayed by the Scope 2 block in the model of Figure 20.53

20.11.2 Simple Pendulum

Equation (20.63) below is same as equation (20.33) in Subsection 20.1.9.

$$M = J\frac{d^2\theta}{dt^2} + c\frac{d\theta}{dt} + mgL\sin\theta \qquad (20.63)$$

or

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}\left(M - c\frac{d\theta}{dt} - mgL\sin\theta\right) \tag{20.64}$$

Let $\theta = x_1$, and $d\theta/dt = x_2$. Then $\dot{x}_1 = x_2$, and $\dot{x}_2 = d^2\theta/dt^2 = (1/J)(M - cx_2 - mgLx_1)$.

For this example we let $J = 2$, $M = 1$, $c = 0.2$, and $mgL = 2$. Then, our state–space equations are:

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -x_1 - 0.1x_2 + 0.5$$

and in matrix form

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -0.1 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \cdot u \tag{20.65}$$

where $u = M = \text{input}$. Thus,

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{20.66}$$

and

$$A = \begin{bmatrix} 0 & 1 \\ -1 & -0.1 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad C = [1 \quad 1] \qquad D = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{20.67}$$

The S–function script is shown below.

```
% Function file simple_pendulum for Subsection 20.11.2
% Reference: Equation (20.64), Subsection 20.11.2
% where input is constant moment (torque) M denoted as u, x is the
% state vector, y is the vector of outputs, and t is time.
%
function [sys,x0,str,ts]=simple_pendulum(t,x,u,flag)
%
% The state-space equations below are those in (20.67)
%
A=[0 1; -1 -0.1]; B=[0; 1]; C=[0 1]; D=[0; 1];
%
switch flag
%
% Initialization
    case 0
        [sys, x0,str, ts]=mdlInitializeSizes(A,B,C,D);
%
% Derivatives
%
    case 1
        sys=mdlDerivatives(t,x,u,A,B,C,D);
```

```
%
% Outputs
%
    case 3
        sys=mdlOutputs(t,x,u,A,B,C,D);
%
% Terminate
%
    case 9
        % sys=[] % Do nothing
end
%
% mdlInitializeSizes
% Return the sizes, initial conditions, and sample times for the
% S–function
%
function [sys,x0,str,ts]=mdlInitializeSizes(A,B,C,D)

sizes=simsizes;

sizes.NumContStates=size(A,1);
sizes.NumDiscStates=0;
sizes.NumOutputs=size(D,1);
sizes.NumInputs=size(D,2);
sizes.DirFeedthrough=any(any(D~=0));
sizes.NumSampleTimes=1;

sys=simsizes(sizes);
x0=ones(size(A,1),1);
str=[];
ts=[0 0];
%
% end mdlInitializeSizes
%
% mdlDerivatives
% Return the derivatives for the continuous states
%
function sys=mdlDerivatives(t,x,u,A,B,C,D)

sys=A*x+B*u;
%
% end mdlDerivatives
%
% mdlOutputs
% Return the output vector for the S–function
%
function sys=mdlOutputs(t,x,u,A,B,C,D)

sys=C*x+D*u;
%
% end mdlOutputs
```

Next, we open a new model, we drag a **Constant** block, an **S–Function** block, and a **Scope** block and we interconnect them as shown in Figure 20.105, where in the **Function Block Parameters** dialog box for the **S–Function** block we changed the S–Function name from system to simple–pendulum.

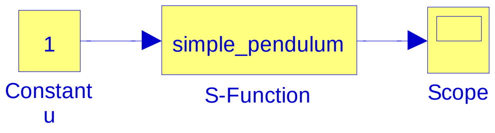


Figure 20.105. S–Function model for a simple pendulum

When the simulation command is executed with the simulation time set from 0 to 50, the **Scope** block displays the waveforms shown in Figure 20.106.

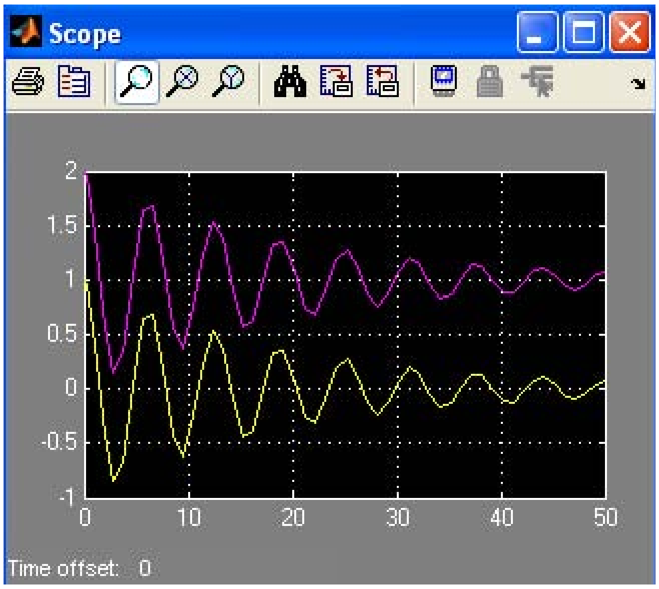


Figure 20.106. Waveforms for the model in Figure 20.105

20.12 Concluding Remarks

This text, as its title indicates, is an introduction to Simulink. In Chapters 2 through 19 we have described all blocks of all Simulink Libraries and provided examples to illustrate their application. Chapter 1 and this chapter provided additional examples. This text is not a substitute for the Simulink User's Manual which provides much more information on MATLAB and Simulink, and should be treated as a supplement. Moreover, the demos provided with Simulink are real–world examples and should be studied in thoroughly after reading this text. Undoubtedly, new MATLAB and Simulink releases will include new functions and new blocks.

Many Simulink demos provided by The MathWorks include masked subsystems and these are described in Appendix B.

20.13 Summary

- Several applications with differential equations and their solutions are presented in Section 20.1.
- Examples of using Zero–Order Hold and First–Order Hold blocks as reconstructors for digital–to–analog conversion are presented in Section 20.2.
- The four forms of digital filter realization forms are presented in Section 20.3.
- Models for binary counters are presented in Section 20.4.
- Three models for mechanical systems are presented in Section 20.5.
- A brief review of feedback control systems is provided in Section 20.6.
- Two models for AC electric circuit analysis are presented in Section 20.7.
- Four transformations blocks are introduced in Section 20.8.
- A discrete–time integration with variable input amplitude is presented in Section 20.9.
- An S–Function example is presented in Section 11.18, Chapter 11. Two additional examples are presented in Section 20.11, this chapter.
- Masked Subsystems are described in Appendix B.

Appendix A

Introduction to MATLAB®

This appendix serves as an introduction to the basic MATLAB commands and functions, procedures for naming and saving the user generated files, comment lines, access to MATLAB's Editor / Debugger, finding the roots of a polynomial, and making plots. Several examples are provided with detailed explanations.

A.1 MATLAB® and Simulink®

MATLAB and Simulink are products of The MathWorks,™ Inc. These are two outstanding software packages for scientific and engineering computations and are used in educational institutions and in industries including automotive, aerospace, electronics, telecommunications, and environmental applications. MATLAB enables us to solve many advanced numerical problems rapidly and efficiently.

A.2 Command Window

To distinguish the screen displays from the user commands, important terms, and MATLAB functions, we will use the following conventions:

Click: Click the left button of the mouse
`Courier Font`: Screen displays
Helvetica Font: User inputs at MATLAB's command window prompt >> or `EDU>>`*
Helvetica Bold: MATLAB functions
Normal Font Bold Italic: Important terms and facts, notes and file names

When we first start MATLAB, we see various help topics and other information. Initially, we are interested in the *command screen* which can be selected from the Window drop menu. When the command screen, we see the prompt >> or `EDU>>`. This prompt is displayed also after execution of a command; MATLAB now waits for a new command from the user. It is highly recommended that we use the *Editor/Debugger* to write our program, save it, and return to the command screen to execute the program as explained below.

To use the Editor/Debugger:

1. From the *File* menu on the toolbar, we choose *New* and click on M–*File*. This takes us to the *Editor Window* where we can type our *script* (list of statements) for a new file, or open a previ-

* EDU>> *is the MATLAB prompt in the Student Version*

ously saved file. We must save our program with a file name which starts with a letter. ***Important!*** MATLAB is *case sensitive*, that is, it distinguishes between upper– and lower–case letters. Thus, *t* and *T* are two different letters in MATLAB language. The files that we create are saved with the file name we use and the extension ***.m***; for example, ***myfile01.m***. It is a good practice to save the script in a file name that is descriptive of our script content. For instance, if the script performs some matrix operations, we ought to name and save that file as ***matrices01.m*** or any other similar name. We should also use a floppy disk or an external drive to backup our files.

2. Once the script is written and saved as an *m–file*, we may exit the *Editor/Debugger* window by clicking on *Exit Editor/Debugger* of the *File* menu. MATLAB then returns to the command window.

3. To execute a program, we type the file name ***without*** the ***.m*** extension at the >> prompt; then, we press <enter> and observe the execution and the values obtained from it. If we have saved our file in drive ***a*** or any other drive, we must make sure that it is added it to the desired directory in MATLAB's search path. The MATLAB User's Guide provides more information on this topic.

Henceforth, it will be understood that each input command is typed after the >> prompt and followed by the <enter> key.

The command **help matlab\iofun** will display input/output information. To get help with other MATLAB topics, we can type help followed by any topic from the displayed menu. For example, to get information on graphics, we type help matlab\graphics. The MATLAB User's Guide contains numerous help topics.

To appreciate MATLAB's capabilities, we type demo and we see the `MATLAB Demos` menu. We can do this periodically to become familiar with them. Whenever we want to return to the command window, we click on the `Close` button.

When we are done and want to leave MATLAB, we type **quit** or **exit**. But if we want to clear all previous values, variables, and equations without exiting, we should use the command **clear**. This command erases everything; it is like exiting MATLAB and starting it again. The command **clc** clears the screen but MATLAB still remembers all values, variables and equations that we have already used. In other words, if we want to clear all previously entered commands, leaving only the >> prompt on the upper left of the screen, we use the **clc** command.

All text after the **%** (percent) symbol is interpreted as a *comment line* by MATLAB, and thus it is ignored during the execution of a program. A comment can be typed on the same line as the function or command or as a separate line. For instance,

```
conv(p,q)    % performs multiplication of polynomials p and q

% The next statement performs partial fraction expansion of p(x) / q(x)
```

are both correct.
One of the most powerful features of MATLAB is the ability to do computations involving *complex numbers*. We can use either `i`, or `j` to denote the imaginary part of a complex number, such as `3-4i` or `3-4j`. For example, the statement

```
z=3−4j
```

displays

```
z = 3.0000−4.0000i
```

In the above example, a multiplication (*) sign between 4 and `j` was not necessary because the complex number consists of numerical constants. However, if the imaginary part is a function, or variable such as `cos(x)`, we must use the multiplication sign, that is, we must type `cos(x)*j` or `j*cos(x)` for the imaginary part of the complex number.

A.3 Roots of Polynomials

In MATLAB, a polynomial is expressed as a *row vector* of the form $[a_n \ \ a_{n-1} \ \ \ldots \ a_2 \ \ a_1 \ \ a_0]$. These are the coefficients of the polynomial in descending order. ***We must include terms whose coefficients are zero.***

We find the roots of any polynomial with the **roots(p)** function; **p** is a row vector containing the polynomial coefficients in descending order.

Example A.1

Find the roots of the polynomial

$$p_1(x) = x^4 - 10x^3 + 35x^2 - 50x + 24$$

Solution:

The roots are found with the following two statements where we have denoted the polynomial as p1, and the roots as roots_ p1.

```
p1=[1 −10 35 −50 24]       % Specify and display the coefficients of p1(x)

p1 =
     1   -10    35   -50    24

roots_ p1=roots(p1)        % Find the roots of p1(x)

roots_p1 =
   4.0000
   3.0000
   2.0000
   1.0000
```

We observe that MATLAB displays the polynomial coefficients as a row vector, and the roots as a column vector.

Example A.2

Find the roots of the polynomial

$$p_2(x) = x^5 - 7x^4 + 16x^2 + 25x + 52$$

Solution:

There is no cube term; therefore, we must enter zero as its coefficient. The roots are found with the statements below, where we have defined the polynomial as p2, and the roots of this polynomial as roots_ p2. The result indicates that this polynomial has three real roots, and two complex roots. Of course, complex roots always occur in *complex conjugate*[*] pairs.

```
p2=[1 −7  0 16 25 52]

p2 =
     1    -7     0    16    25    52

roots_ p2=roots(p2)

roots_p2 =
   6.5014
   2.7428
  -1.5711
  -0.3366 + 1.3202i
  -0.3366 - 1.3202i
```

A.4 Polynomial Construction from Known Roots

We can compute the coefficients of a polynomial, from a given set of roots, with the **poly(r)** function where **r** is a row vector containing the roots.

Example A.3

It is known that the roots of a polynomial are $1, 2, 3,$ and 4. Compute the coefficients of this polynomial.

[*] *By definition, the conjugate of a complex number* $A = a + jb$ *is* $A^* = a - jb$

Solution:

We first define a row vector, say $r3$, with the given roots as elements of this vector; then, we find the coefficients with the **poly(r)** function as shown below.

```
r3=[1 2 3 4]          % Specify the roots of the polynomial
```

```
r3 =
     1     2     3     4
```

```
poly_r3=poly(r3)      % Find the polynomial coefficients
```

```
poly_r3 =
     1   -10    35   -50    24
```

We observe that these are the coefficients of the polynomial $p_1(x)$ of Example A.1.

Example A.4

It is known that the roots of a polynomial are -1, -2, -3, $4+j5$, and $4-j5$. Find the coefficients of this polynomial.

Solution:

We form a row vector, say $r4$, with the given roots, and we find the polynomial coefficients with the **poly(r)** function as shown below.

```
r4=[ −1  −2  −3  4+5j  4−5j ]
```

```
r4 =
  Columns 1 through 4
  -1.0000   -2.0000   -3.0000   -4.0000+ 5.0000i
  Column 5
  -4.0000- 5.0000i
```

```
poly_r4=poly(r4)
```

```
poly_r4 =
     1    14   100   340   499   246
```

Therefore, the polynomial is

$$p_4(x) = x^5 + 14x^4 + 100x^3 + 340x^2 + 499x + 246$$

A.5 Evaluation of a Polynomial at Specified Values

The **polyval(p,x)** function evaluates a polynomial $p(x)$ at some specified value of the independent variable x.

Example A.5

Evaluate the polynomial

$$p_5(x) = x^6 - 3x^5 + 5x^3 - 4x^2 + 3x + 2 \tag{A.1}$$

at $x = -3$.

Solution:

```
p5=[1 –3  0  5 –4  3  2];  % These are the coefficients of the given polynomial
                           % The semicolon (;) after the right bracket suppresses the
                           %  display of the row vector that contains the coefficients of p5.
%
val_minus3=polyval(p5, –3)  % Evaluate p5 at x=–3; no semicolon is used here
                           % because we want the answer to be displayed
```

```
val_minus3 =
        1280
```

Other MATLAB functions used with polynomials are the following:

conv(a,b) – multiplies two polynomials **a** and **b**

[q,r]=deconv(c,d) –divides polynomial **c** by polynomial **d** and displays the quotient **q** and remainder **r**.

polyder(p) – produces the coefficients of the derivative of a polynomial **p**.

Example A.6

Let

$$p_1 = x^5 - 3x^4 + 5x^2 + 7x + 9$$

and

$$p_2 = 2x^6 - 8x^4 + 4x^2 + 10x + 12$$

Compute the product $p_1 \cdot p_2$ using the **conv(a,b)** function.

Solution:

```
p1=[1 –3  0 5  7  9];          % The coefficients of p1
p2=[2  0 –8  0  4  10  12];    % The coefficients of p2
p1p2=conv(p1,p2)               % Multiply p1 by p2 to compute coefficients of the product p1p2
```

```
p1p2 =
  2  -6  -8  34  18  -24  -74  -88  78  166  174  108
```

Therefore,

$$p_1 \cdot p_2 = 2x^{11} - 6x^{10} - 8x^9 + 34x^8 + 18x^7 - 24x^6$$
$$-74x^5 - 88x^4 + 78x^3 + 166x^2 + 174x + 108$$

Example A.7

Let

$$p_3 = x^7 - 3x^5 + 5x^3 + 7x + 9$$

and

$$p_4 = 2x^6 - 8x^5 + 4x^2 + 10x + 12$$

Compute the quotient p_3/p_4 using the **[q,r]=deconv(c,d)** function.

Solution:

```
% It is permissible to write two or more statements in one line separated by semicolons
p3=[1  0 –3  0  5  7  9];  p4=[2 –8  0  0  4  10  12];  [q,r]=deconv(p3,p4)
```

```
q =
    0.5000
r =
     0     4    -3     0     3     2     3
```

Therefore,

$$q = 0.5 \qquad r = 4x^5 - 3x^4 + 3x^2 + 2x + 3$$

Example A.8

Let

$$p_5 = 2x^6 - 8x^4 + 4x^2 + 10x + 12$$

Compute the derivative $\frac{d}{dx}p_5$ using the **polyder(p)** function.

Solution:

```
p5=[2  0  −8  0  4  10  12];     % The coefficients of p5
der_p5=polyder(p5)               % Compute the coefficients of the derivative of p5
```

```
der_p5 =
    12      0    -32      0      8     10
```

Therefore,

$$\frac{d}{dx}p_5 = 12x^5 - 32x^3 + 4x^2 + 8x + 10$$

A.6 Rational Polynomials

Rational Polynomials are those which can be expressed in ratio form, that is, as

$$R(x) = \frac{Num(x)}{Den(x)} = \frac{b_n x^n + b_{n-1}x^{n-1} + b_{n-2}x^{n-2} + \ldots + b_1 x + b_0}{a_m x^m + a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \ldots + a_1 x + a_0} \tag{A.2}$$

where some of the terms in the numerator and/or denominator may be zero. We can find the roots of the numerator and denominator with the **roots(p)** function as before.

As noted in the comment line of Example A.7, we can write MATLAB statements in one line, if we separate them by commas or semicolons. ***Commas will display the results whereas semicolons will suppress the display.***

Example A.9

Let

$$R(x) = \frac{p_{num}}{p_{den}} = \frac{x^5 - 3x^4 + 5x^2 + 7x + 9}{x^6 - 4x^4 + 2x^2 + 5x + 6}$$

Express the numerator and denominator in factored form, using the **roots(p)** function.

Solution:

```
num=[1  −3  0  5  7  9]; den=[1  0  −4  0  2  5  6];    % Do not display num and den coefficients
roots_num=roots(num), roots_den=roots(den)             % Display num and den roots
```

```
roots_num =
   2.4186 + 1.0712i    2.4186 - 1.0712i   -1.1633
  -0.3370 + 0.9961i   -0.3370 - 0.9961i
```

```
roots_den =
   1.6760 + 0.4922i     1.6760 - 0.4922i  -1.9304
  -0.2108 + 0.9870i    -0.2108 - 0.9870i  -1.0000
```

As expected, the complex roots occur in complex conjugate pairs.

For the numerator, we have the factored form

$$p_{num} = (x-2.4186 - j1.0712)(x-2.4186 + j1.0712)(x + 1.1633)$$
$$(x + 0.3370 - j0.9961)(x + 0.3370 + j0.9961)$$

and for the denominator, we have

$$p_{den} = (x-1.6760 - j0.4922)(x-1.6760 + j0.4922)(x + 1.9304)$$
$$(x + 0.2108-j0.9870)(x + 0.2108 + j0.9870)(x + 1.0000)$$

We can also express the numerator and denominator of this rational function as a combination of *linear* and *quadratic* factors. We recall that, in a quadratic equation of the form $x^2 + bx + c = 0$ whose roots are x_1 and x_2, the negative sum of the roots is equal to the coefficient b of the x term, that is, $-(x_1 + x_2) = b$, while the product of the roots is equal to the constant term c, that is, $x_1 \cdot x_2 = c$. Accordingly, we form the coefficient b by addition of the complex conjugate roots and this is done by inspection; then we multiply the complex conjugate roots to obtain the constant term c using MATLAB as follows:

```
(2.4186 + 1.0712i)*(2.4186 –1.0712i)
ans = 6.9971
(–0.3370+ 0.9961i)*(–0.3370–0.9961i)
ans = 1.1058
(1.6760+ 0.4922i)*(1.6760–0.4922i)
ans = 3.0512
(–0.2108+ 0.9870i)*(–0.2108–0.9870i)
ans = 1.0186
```

Thus,

$$R(x) = \frac{p_{num}}{p_{den}} = \frac{(x^2 - 4.8372x + 6.9971)(x^2 + 0.6740x + 1.1058)(x + 1.1633)}{(x^2 - 3.3520x + 3.0512)(x^2 + 0.4216x + 1.0186)(x + 1.0000)(x + 1.9304)}$$

We can check this result of Example A.9 above with MATLAB's *Symbolic Math Toolbox* which is a collection of tools (functions) used in solving symbolic expressions. They are discussed in detail in MATLAB's Users Manual. For the present, our interest is in using the **collect(s)** function that is used to multiply two or more symbolic expressions to obtain the result in polynomial form. We must remember that the **conv(p,q)** function is used with numeric expressions only, that is, polynomial coefficients.

Before using a symbolic expression, we must create one or more symbolic variables such as x, y, t, and so on. For our example, we use the following script:

```
syms x % Define a symbolic variable and use collect(s) to express numerator in polynomial form
collect((x^2–4.8372*x+6.9971)*(x^2+0.6740*x+1.1058)*(x+1.1633))
```

```
ans =
  x^5-29999/10000*x^4-1323/3125000*x^3+7813277909/
  1562500000*x^2+1750276323053/2500000000000*x+4500454743147/
  5000000000000
```

and if we simplify this, we find that is the same as the numerator of the given rational expression in polynomial form. We can use the same procedure to verify the denominator.

A.7 Using MATLAB to Make Plots

Quite often, we want to plot a set of ordered pairs. This is a very easy task with the MATLAB **plot(x,y)** command that plots *y* versus *x*, where *x* is the horizontal axis (abscissa) and *y* is the vertical axis (ordinate).

Example A.10

Consider the electric circuit of Figure A.1, where the radian frequency ω (radians/second) of the applied voltage was varied from 300 to 3000 in steps of 100 radians/second, while the amplitude was held constant.

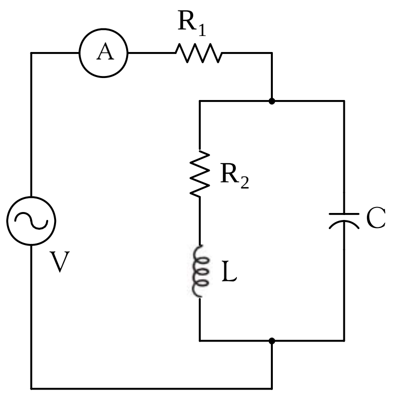


Figure A.1. Electric circuit for Example A.10

The ammeter readings were then recorded for each frequency. The magnitude of the impedance $|Z|$ was computed as $|Z| = |V/A|$ and the data were tabulated on Table A.1.

TABLE A.1 Table for Example A.10

ω (rads/s)	|Z| Ohms	ω (rads/s)	|Z| Ohms
300	39.339	1700	90.603
400	52.589	1800	81.088
500	71.184	1900	73.588
600	97.665	2000	67.513
700	140.437	2100	62.481
800	222.182	2200	58.240
900	436.056	2300	54.611
1000	1014.938	2400	51.428
1100	469.83	2500	48.717
1200	266.032	2600	46.286
1300	187.052	2700	44.122
1400	145.751	2800	42.182
1500	120.353	2900	40.432
1600	103.111	3000	38.845

Plot the magnitude of the impedance, that is, $|Z|$ versus radian frequency ω.

Solution:

We cannot type ω (omega) in the MATLAB Command prompt, so we will use the English letter w instead.

If a statement, or a row vector is too long to fit in one line, it can be continued to the next line by typing three or more periods, then pressing <*enter*> to start a new line, and continue to enter data. This is illustrated below for the data of w and z. Also, as mentioned before, we use the semicolon (;) to suppress the display of numbers that we do not care to see on the screen.

The data are entered as follows:

```
w=[300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900....
2000 2100 2200 2300 2400 2500 2600 2700 2800 2900 3000];
%
z=[39.339  52.789  71.104  97.665  140.437  222.182  436.056....
1014.938  469.830  266.032 187.052 145.751 120.353  103.111....
90.603  81.088  73.588  67.513  62.481  58.240  54.611  51.468....
48.717  46.286  44.122  42.182  40.432  38.845];
```

Of course, if we want to see the values of *w* or *z* or both, we simply type w or z, and we press

<*enter*>. To plot z (y–axis) versus w (x–axis), we use the **plot(x,y)** command. For this example, we use **plot(w,z)**. When this command is executed, MATLAB displays the plot on MATLAB's *graph screen* and MATLAB denotes this plot as Figure 1. This plot is shown in Figure A.2.

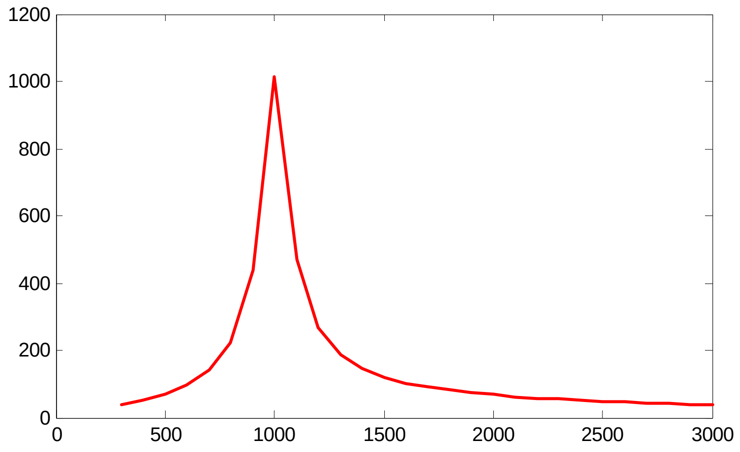


Figure A.2. Plot of impedance |z| *versus frequency* ω *for Example A.10*

This plot is referred to as the *magnitude frequency response* of the circuit.

To return to the command window, we press any key, or from the *Window* pull–down menu, we select *MATLAB Command Window*. To see the graph again, we click on the Window pull–down menu, and we choose *Figure 1*.

We can make the above, or any plot, more presentable with the following commands:

grid on: This command adds grid lines to the plot. The **grid off** command removes the grid. The command **grid** toggles them, that is, changes from off to on or vice versa. The default* is off.

box off: This command removes the box (the solid lines which enclose the plot), and **box on** restores the box. The command **box** toggles them. The default is on.

title('string'): This command adds a line of the text **string** (label) at the top of the plot.

xlabel('string') and **ylabel('string')** are used to label the x– and y–axis respectively.

The magnitude frequency response is usually represented with the x–axis in a logarithmic scale. We can use the **semilogx(x,y)** command which is similar to the **plot(x,y)** command, except that the x–axis is represented as a log scale, and the y–axis as a linear scale. Likewise, the **semilogy(x,y)** command is similar to the **plot(x,y)** command, except that the y–axis is represented as a

* *A default is a particular value for a variable that is assigned automatically by an operating system and remains in effect unless canceled or overridden by the operator.*

log scale, and the x–axis as a linear scale. The **loglog(x,y)** command uses logarithmic scales for both axes.

Throughout this text it will be understood that ***log*** is the common (base 10) logarithm, and ***ln*** is the natural (base e) logarithm. We must remember, however, the function **log(x)** in MATLAB is the natural logarithm, whereas the common logarithm is expressed as **log10(x)**, and the logarithm to the base 2 as **log2(x).**

Let us now redraw the plot with the above options by adding the following statements:

```
semilogx(w,z); grid;            % Replaces the plot(w,z) command
title('Magnitude of Impedance vs. Radian Frequency');
xlabel('w in rads/sec'); ylabel('|Z| in Ohms')
```

After execution of these commands, the plot is as shown in Figure A.3.

If the y–axis represents power, voltage or current, the x–axis of the frequency response is more often shown in a logarithmic scale, and the y–axis in dB (decibels).

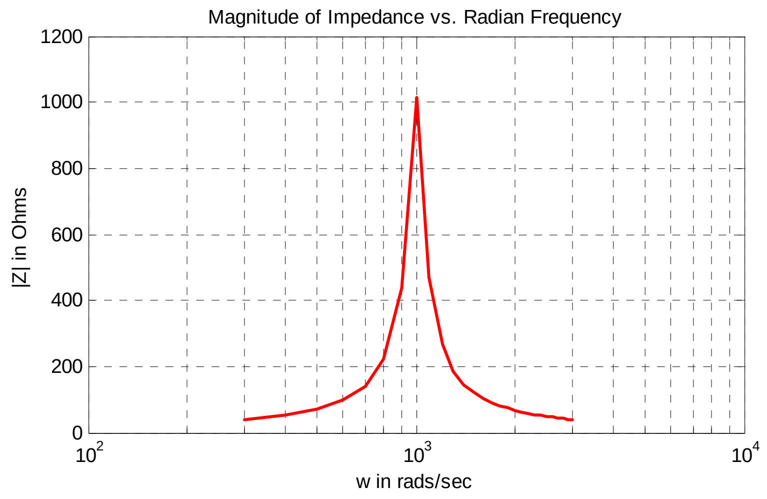


Figure A.3. Modified frequency response plot of Figure A.2.

To display the voltage v in a dB scale on the y–axis, we add the relation dB=20*log10(v), and we replace the **semilogx(w,z)** command with semilogx(w,dB).

The command **gtext('string')**[*] switches to the current *Figure Window*, and displays a cross–hair that can be moved around with the mouse. For instance, we can use the command gtext('Impedance |Z| versus Frequency'), and this will place a cross–hair in the *Figure* window. Then, using

* *With the latest MATLAB Versions 6 and 7 (Student Editions 13 and 14), we can add text, lines and arrows directly into the graph using the tools provided on the Figure Window. For advanced MATLAB graphics, please refer to The MathWorks **Using MATLAB Graphics** documentation.*

the mouse, we can move the cross–hair to the position where we want our label to begin, and we press <enter>.

The command **text(x,y,'string')** is similar to **gtext('string')**. It places a label on a plot in some specific location specified by **x** and **y**, and **string** is the label which we want to place at that location. We will illustrate its use with the following example which plots a *3–phase* sinusoidal waveform.

The first line of the script below has the form

linspace(first_value, last_value, number_of_values)

This function specifies ***the number of data points*** but not the increments between data points. An alternate function is

x=first: increment: last

and this specifies ***the increments between points*** but not the number of data points.

The script for the 3–phase plot is as follows:

```
x=linspace(0, 2*pi, 60);          % pi is a built–in function in MATLAB;
% we could have used x=0:0.02*pi:2*pi or x = (0: 0.02: 2)*pi instead;
y=sin(x); u=sin(x+2*pi/3); v=sin(x+4*pi/3);
plot(x,y,x,u,x,v);                % The x–axis must be specified for each function
grid on, box on,                  % turn grid and axes box on
text(0.75, 0.65, 'sin(x)'); text(2.85, 0.65, 'sin(x+2*pi/3)'); text(4.95, 0.65, 'sin(x+4*pi/3)')
```

These three waveforms are shown on the same plot of Figure A.4.

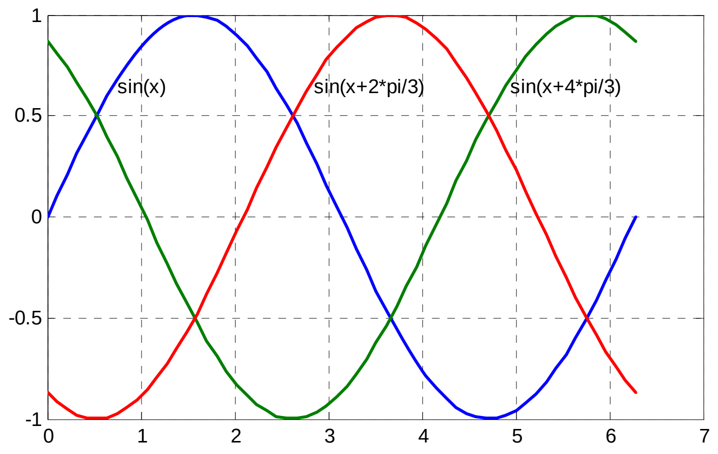


Figure A.4. Three–phase waveforms

In our previous examples, we did not specify line styles, markers, and colors for our plots. However, MATLAB allows us to specify various line types, plot symbols, and colors. These, or a combination of these, can be added with the **plot(x,y,s)** command, where **s** is a character string containing one or more characters shown on the three columns of Table A.2. MATLAB has no default color; it starts with blue and cycles through the first seven colors listed in Table A.2 for each additional line in the plot. Also, there is no default marker; no markers are drawn unless they are selected. The default line is the solid line. But with the latest MATLAB versions, we can select the line color, line width, and other options directly from the *Figure Window.*

TABLE A.2 Styles, colors, and markets used in MATLAB

Symbol	*Color*	*Symbol*	*Marker*	*Symbol*	*Line Style*
b	blue	.	point	–	solid line
g	green	o	circle	:	dotted line
r	red	x	x–mark	–.	dash–dot line
c	cyan	+	plus	––	dashed line
m	magenta	*	star		
y	yellow	s	square		
k	black	d	diamond		
w	white	v	triangle down		
		^	triangle up		
		<	triangle left		
		>	triangle right		
		p	pentagram		
		h	hexagram		

For example, **plot(x,y,'m*:')** plots a magenta dotted line with a star at each data point, and **plot(x,y,'rs')** plots a red square at each data point, but does not draw any line because no line was selected. If we want to connect the data points with a solid line, we must type **plot(x,y,'rs–')**. For additional information we can type **help plot** in MATLAB's command screen.

The plots we have discussed thus far are two–dimensional, that is, they are drawn on two axes. MATLAB has also a three–dimensional (three–axes) capability and this is discussed next.

The **plot3(x,y,z)** command plots a line in *3–space* through the points whose coordinates are the elements of x, y and z, where x, y and z are three vectors of the same length.

The general format is **plot3(x_1,y_1,z_1,s_1,x_2,y_2,z_2,s_2,x_3,y_3,z_3,s_3,...)** where $\mathbf{x_n}$, $\mathbf{y_n}$ and $\mathbf{z_n}$ are vectors or matrices, and $\mathbf{s_n}$ are strings specifying color, marker symbol, or line style. These strings are the same as those of the two–dimensional plots.

Example A.11

Plot the function

$$z = -2x^3 + x + 3y^2 - 1 \qquad (A.3)$$

Solution:

We arbitrarily choose the interval (length) shown on the script below.

```
x= –10: 0.5: 10;             % Length of vector x
y= x;                        % Length of vector y must be same as x
z= –2.*x.^3+x+3.*y.^2–1;     % Vector z is function of both x and y*
plot3(x,y,z); grid
```

The three–dimensional plot is shown in Figure A.5.

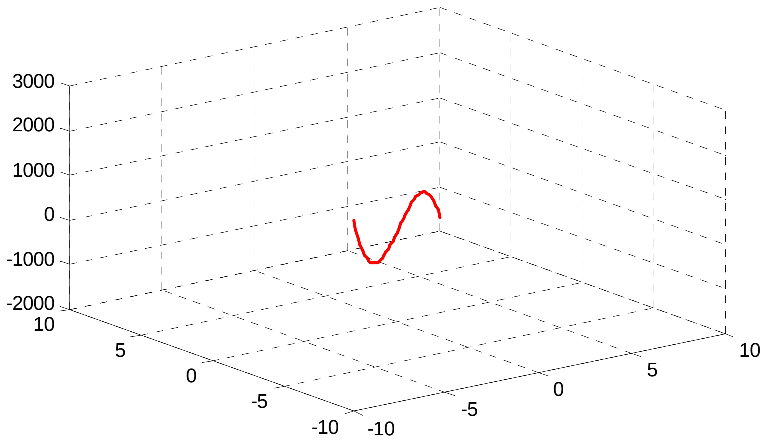


Figure A.5. Three dimensional plot for Example A.11

In a two–dimensional plot, we can set the limits of the *x*– and *y–axes* with the **axis([xmin xmax ymin ymax])** command. Likewise, in a three–dimensional plot we can set the limits of all three axes with the **axis([xmin xmax ymin ymax zmin zmax])** command. It must be placed after the **plot(x,y)** or **plot3(x,y,z)** commands, or on the same line without first executing the **plot** command. This must be done for each plot. The three–dimensional **text(x,y,z,'string')** command will place **string** beginning at the co–ordinate (*x*,*y*,*z*) on the plot.

For three–dimensional plots, **grid on** and **box off** are the default states.

We can also use the **mesh(x,y,z)** command with two vector arguments. These must be defined as

* *This statement uses the so called dot multiplication, dot division, and dot exponentiation where the multiplication, division, and exponential operators are preceded by a dot. These important operations will be explained in Section A.9.*

length(x) = n and length(y) = m where [m, n] = size(Z). In this case, the vertices of the mesh lines are the triples {x(j), y(i), Z(i, j)}. We observe that **x** corresponds to the columns of Z, and **y** corresponds to the rows.

To produce a mesh plot of a function of two variables, say $z = f(x, y)$, we must first generate the X and Y matrices that consist of repeated rows and columns over the range of the variables *x* and *y*. We can generate the matrices X and Y with the **[X,Y]=meshgrid(x,y)** function that creates the matrix X whose rows are copies of the vector **x**, and the matrix Y whose columns are copies of the vector **y**.

Example A.12

The volume V of a right circular cone of radius r and height h is given by

$$V = \frac{1}{3}\pi r^2 h \tag{A.4}$$

Plot the volume of the cone as r and h vary on the intervals $0 \le r \le 4$ and $0 \le h \le 6$ meters.

Solution:

The volume of the cone is a function of both the radius *r* and the height *h*, that is,

$$V = f(r, h)$$

The three−dimensional plot is created with the following MATLAB script where, as in the previous example, in the second line we have used the dot multiplication, dot division, and dot exponentiation. This will be explained in Section A.9.

```
[R,H]=meshgrid(0: 4, 0: 6);    % Creates R and H matrices from vectors r and h;...
V=(pi .* R .^ 2 .* H) ./ 3;  mesh(R, H, V);...
xlabel('x−axis, radius r (meters)'); ylabel('y−axis, altitude h (meters)');...
zlabel('z−axis, volume (cubic meters)'); title('Volume of Right Circular Cone'); box on
```

The three−dimensional plot of Figure A.6 shows how the volume of the cone increases as the radius and height are increased.

The plots of Figure A.5 and A.6 are rudimentary; MATLAB can generate very sophisticated three−dimensional plots. The MATLAB User's Manual and the Using MATLAB Graphics Manual contain numerous examples.

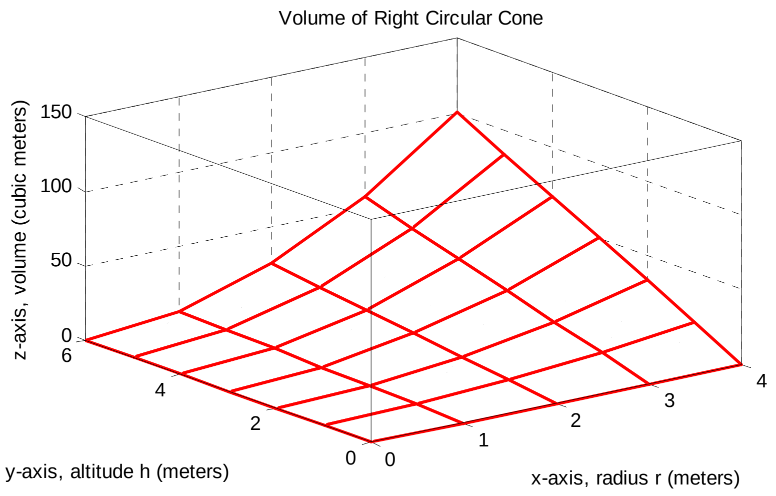


Figure A.6. Volume of a right circular cone.

A.8 Subplots

MATLAB can display up to four windows of different plots on the *Figure* window using the command **subplot(m,n,p)**. This command divides the window into an $m \times n$ matrix of plotting areas and chooses the *pth* area to be active. No spaces or commas are required between the three integers *m*, *n* and *p*. The possible combinations are shown in Figure A.7.

We will illustrate the use of the **subplot(m,n,p)** command following the discussion on multiplication, division and exponentiation that follows.

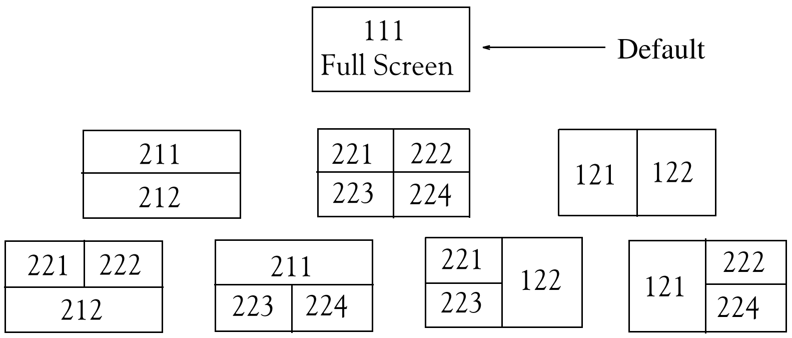


Figure A.7. Possible subplot arrangements in MATLAB

A.9 Multiplication, Division, and Exponentiation

MATLAB recognizes two types of multiplication, division, and exponentiation. These are the ***matrix*** multiplication, division, and exponentiation, and the ***element–by–element*** multiplication, division, and exponentiation. They are explained in the following paragraphs.

In Section A.2, the arrays `[a b c ...]`, such a those that contained the coefficients of polynomials, consisted of one row and multiple columns, and thus are called ***row vectors***. If an array has one column and multiple rows, it is called a ***column vector***. We recall that the elements of a row vector are separated by spaces. To distinguish between row and column vectors, the elements of a column vector must be separated by semicolons. An easier way to construct a column vector, is to write it first as a row vector, and then transpose it into a column vector. MATLAB uses the single quotation character (′) to transpose a vector. Thus, a column vector can be written either as

```
b=[−1; 3; 6; 11]
```

or as

```
b=[−1  3  6  11]'
```

As shown below, MATLAB produces the same display with either format.

```
b=[−1; 3; 6; 11]

b  =
    -1
     3
     6
    11

b=[−1  3  6  11]'         % Observe the single quotation character (‘)

b  =
    -1
     3
     6
    11
```

We will now define Matrix Multiplication and Element–by–Element multiplication.

1. **Matrix Multiplication** (multiplication of row by column vectors)

   Let

$$\mathbf{A} = [a_1 \quad a_2 \quad a_3 \quad \ldots \quad a_n]$$

   and

$$\mathbf{B} = [b_1 \quad b_2 \quad b_3 \quad \ldots \quad b_n]'$$

   be two vectors. We observe that $\mathbf{A}$ is defined as a row vector whereas $\mathbf{B}$ is defined as a column vector, as indicated by the transpose operator (′). Here, multiplication of the row vector $\mathbf{A}$ by the column vector $\mathbf{B}$, is performed with the matrix multiplication operator (*). Then,

$$\mathbf{A*B} = [a_1b_1 + a_2b_2 + a_3b_3 + \ldots + a_nb_n] = \text{single value} \tag{A.5}$$

For example, if

$$\mathbf{A} = [1 \quad 2 \quad 3 \quad 4 \quad 5]$$

and

$$\mathbf{B} = [-2 \quad 6 \quad -3 \quad 8 \quad 7]'$$

the matrix multiplication **A*B** produces the single value 68, that is,

$$\mathbf{A}^*\mathbf{B} = 1\times(-2)+2\times6+3\times(-3)+4\times8+5\times7 = 68$$

and this is verified with the MATLAB script

```
A=[1  2   3  4   5]; B=[ –2   6  –3   8   7]'; A*B    % Observe transpose operator (‘) in B
ans =
    68
```

Now, let us suppose that both **A** and **B** are row vectors, and we attempt to perform a row–by–row multiplication with the following MATLAB statements.

```
A=[1  2   3  4  5]; B=[–2  6  –3  8  7]; A*B           % No transpose operator (‘) here
```

When these statements are executed, MATLAB displays the following message:

```
??? Error using ==> *
Inner matrix dimensions must agree.
```

Here, because we have used the matrix multiplication operator (*) in A*B, MATLAB expects vector **B** to be a column vector, not a row vector. It recognizes that **B** is a row vector, and warns us that we cannot perform this multiplication using the matrix multiplication operator (*). Accordingly, we must perform this type of multiplication with a different operator. This operator is defined below.

2. **Element–by–Element Multiplication** (multiplication of a row vector by another row vector)

Let

$$\mathbf{C} = [c_1 \quad c_2 \quad c_3 \quad \dots \quad c_n]$$

and

$$\mathbf{D} = [d_1 \quad d_2 \quad d_3 \quad \dots \quad d_n]$$

be two row vectors. Here, multiplication of the row vector **C** by the row vector **D** is performed with the ***dot multiplication operator*** (.*). There is no space between the dot and the multiplication symbol. Thus,

$$\mathbf{C}.^*\mathbf{D} = [c_1d_1 \quad c_2d_2 \quad c_3d_3 \quad \dots \quad c_nd_n] \tag{A.6}$$

This product is another row vector with the same number of elements, as the elements of $\mathbf{C}$ and $\mathbf{D}$.

As an example, let

$$\mathbf{C} = [1 \quad 2 \quad 3 \quad 4 \quad 5]$$

and

$$\mathbf{D} = [-2 \quad 6 \quad -3 \quad 8 \quad 7]$$

Dot multiplication of these two row vectors produce the following result.

$$\mathbf{C.{*}D} = 1\times(-2) \quad 2\times 6 \quad 3\times(-3) \quad 4\times 8 \quad 5\times 7 = -2 \quad 12 \quad -9 \quad 32 \quad 35$$

Check with MATLAB:

```
C=[1  2   3   4  5];       %  Vectors C and D must have
D=[–2  6 –3   8  7];       %  same number of elements
C.*D                       % We observe that this is a dot multiplication
```

```
ans =
    -2      12      -9      32      35
```

Similarly, the division (/) and exponentiation (^) operators, are used for matrix division and exponentiation, whereas dot division (./) and dot exponentiation (.^) are used for element–by–element division and exponentiation, as illustrated in Examples A.11 and A.12 above.

We must remember that ***no space is allowed between the dot (.) and the multiplication, division, and exponentiation operators.***

Note: A dot (.) is never required with the plus (+) and minus (–) operators.

Example A.13

Write the MATLAB script that produces a simple plot for the waveform defined as

$$y = f(t) = 3e^{-4t}\cos 5t - 2e^{-3t}\sin 2t + \frac{t^2}{t+1} \tag{A.7}$$

in the $0 \le t \le 5$ seconds interval.

Solution:

The MATLAB script for this example is as follows:

```
t=0: 0.01: 5;                  %  Define t–axis in 0.01 increments
y=3 .* exp(–4 .* t) .* cos(5 .* t)–2 .* exp(–3 .* t) .* sin(2 .* t) + t .^2 ./ (t+1);
plot(t,y); grid; xlabel('t'); ylabel('y=f(t)'); title('Plot for Example A.13')
```

The plot for this example is shown in Figure A.8.

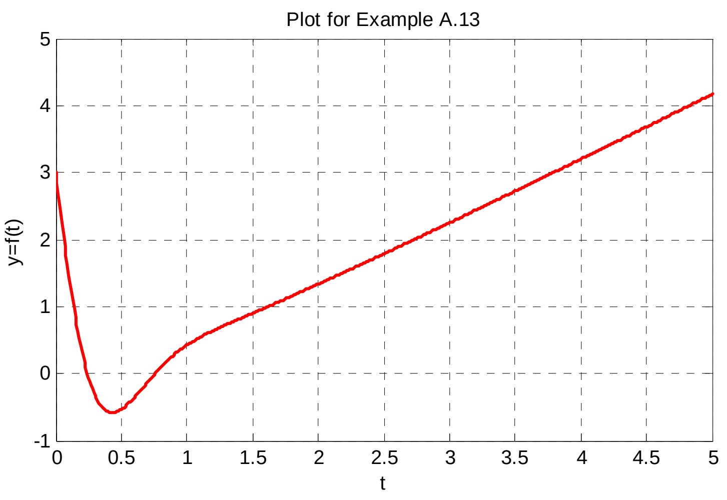


Figure A.8. Plot for Example A.13

Had we, in this example, defined the time interval starting with a negative value equal to or less than -1, say as $-3 \le t \le 3$, MATLAB would have displayed the following message:

```
Warning: Divide by zero.
```

This is because the last term (the rational fraction) of the given expression, is divided by zero when $t = -1$. To avoid division by zero, we use the special MATLAB function **eps,** which is a number approximately equal to 2.2×10^{-16}. It will be used with the next example.

The command **axis([xmin xmax ymin ymax])** scales the current plot to the values specified by the arguments **xmin, xmax, ymin and ymax.** There are no commas between these four arguments. This command must be placed ***after*** the plot command and must be repeated for each plot. The following example illustrates the use of the dot multiplication, division, and exponentiation, the **eps** number, the **axis([xmin xmax ymin ymax])** command, and also MATLAB's capability of displaying up to four windows of different plots.

Example A.14

Plot the functions

$$y = \sin^2 x, \quad z = \cos^2 x, \quad w = \sin^2 x \cdot \cos^2 x, \quad v = \sin^2 x / \cos^2 x$$

in the interval $0 \le x \le 2\pi$ using 100 data points. Use the **subplot** command to display these functions on four windows on the same graph.

Solution:

The MATLAB script to produce the four subplots is as follows:

```
x=linspace(0,2*pi,100);          % Interval with 100 data points
y=(sin(x).^ 2);  z=(cos(x).^ 2);
w=y.* z;
v=y./ (z+eps);% add eps to avoid division by zero
subplot(221);% upper left of four subplots
plot(x,y);  axis([0 2*pi 0 1]);
title('y=(sinx)^ 2');
subplot(222);                     % upper right of four subplots
plot(x,z);  axis([0 2*pi 0 1]);
title('z=(cosx)^ 2');
subplot(223);                     % lower left of four subplots
plot(x,w);  axis([0 2*pi 0 0.3]);
title('w=(sinx)^ 2*(cosx)^ 2');
subplot(224);                     % lower right of four subplots
plot(x,v);  axis([0 2*pi 0 400]);
title('v=(sinx)^ 2/(cosx)^ 2');
```

These subplots are shown in Figure A.9.

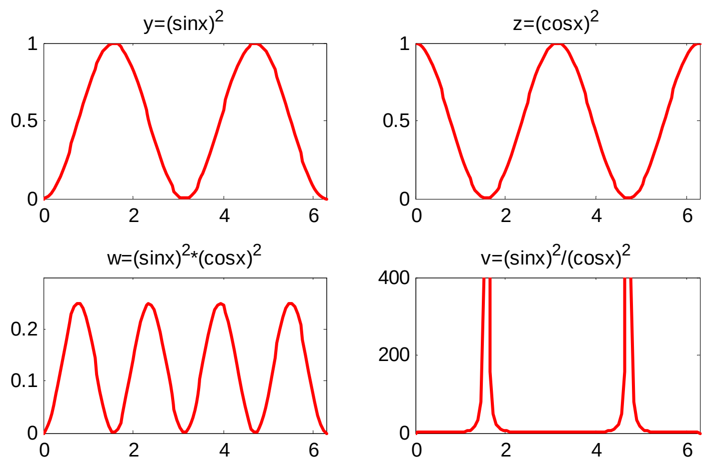


Figure A.9. Subplots for the functions of Example A.14

The next example illustrates MATLAB's capabilities with imaginary numbers. We will introduce the **real(z)** and **imag(z)** functions that display the real and imaginary parts of the complex quantity $z = x + iy$, the **abs(z)**, and the **angle(z)** functions that compute the absolute value (magnitude) and phase angle of the complex quantity $z = x + iy = r\angle\theta$. We will also use the **polar(theta,r)** function that produces a plot in polar coordinates, where **r** is the magnitude, **theta** is the angle in radians, and the **round(n)** function that rounds a number to its nearest integer.

Example A.15

Consider the electric circuit of Figure A.10.

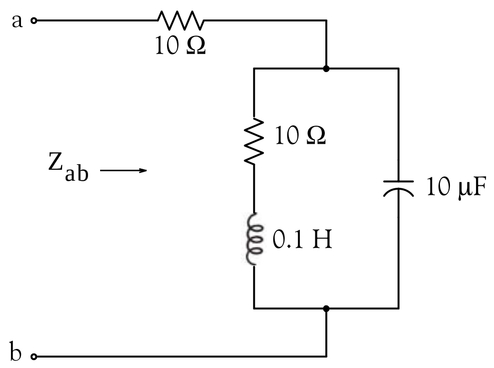


Figure A.10. Electric circuit for Example A.15

With the given values of resistance, inductance, and capacitance, the impedance Z_{ab} as a function of the radian frequency ω can be computed from the following expression:

$$Z_{ab} = Z = 10 + \frac{10^4 - j(10^6/\omega)}{10 + j(0.1\omega - 10^5/\omega)} \tag{A.8}$$

a. Plot Re{Z} (the real part of the impedance Z) versus frequency ω.

b. Plot Im{Z} (the imaginary part of the impedance *Z*) versus frequency ω.

c. Plot the impedance *Z* versus frequency ω in polar coordinates.

Solution:

The MATLAB script below computes the real and imaginary parts of Z_{ab} which, for simplicity, are denoted as z, and plots these as two separate graphs (parts a & b). It also produces a polar plot (part c).

```
w=0: 1: 2000;                    % Define interval with one radian interval;...
z=(10+(10 .^ 4 –j .* 10 .^ 6 ./ (w+eps)) ./ (10 + j .* (0.1 .* w –10.^5./ (w+eps))));...
%
% The first five statements (next two lines) compute and plot Re{z}
real_part=real(z); plot(w,real_part);...
xlabel('radian frequency w'); ylabel('Real part of Z'); grid
```

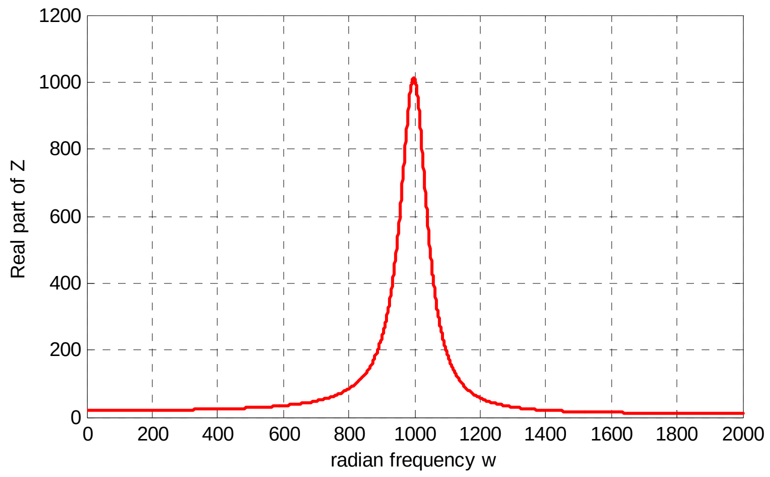


Figure A.11. Plot for the real part of the impedance in Example A.15

```
% The next five statements (next two lines) compute and plot Im{z}
imag_part=imag(z); plot(w,imag_part);...
xlabel('radian frequency w'); ylabel('Imaginary part of Z'); grid
```

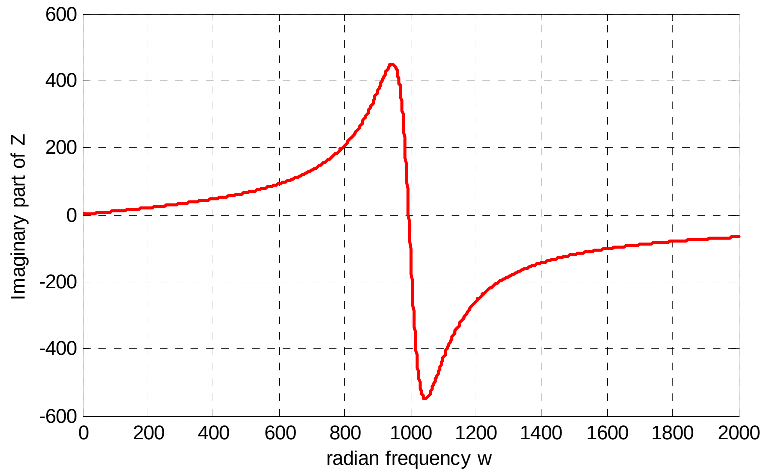


Figure A.12. Plot for the imaginary part of the impedance in Example A.15

```
% The last six statements (next five lines) below produce the polar plot of z
mag=abs(z);                    % Computes |Z|;...
rndz=round(abs(z));            % Rounds |Z| to read polar plot easier;...
theta=angle(z);                % Computes the phase angle of impedance Z;...
polar(theta,rndz);             % Angle is the first argument
ylabel('Polar Plot of Z'); grid
```

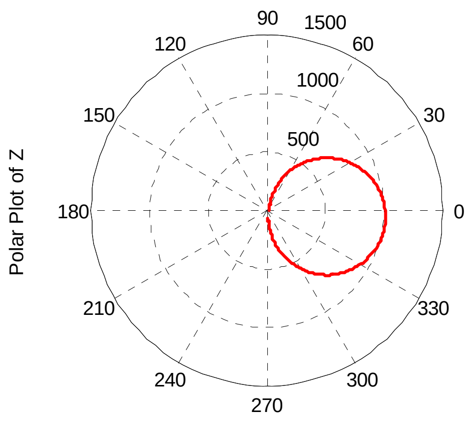


Figure A.13. Polar plot of the impedance in Example A.15

Example A.15 clearly illustrates how powerful, fast, accurate, and flexible MATLAB is.

A.10 Script and Function Files

MATLAB recognizes two types of files: ***script files*** and ***function files***. Both types are referred to as ***m–files*** since both require the *.m* extension.

A ***script file*** consists of two or more built–in functions such as those we have discussed thus far. Thus, the script for each of the examples we discussed earlier, make up a script file. Generally, a script file is one which was generated and saved as an m–file with an editor such as the MATLAB's Editor/Debugger.

A ***function file*** is a user–defined function using MATLAB. We use function files for repetitive tasks. The first line of a function file must contain the word *function*, followed by the output argument, the equal sign (=), and the input argument enclosed in parentheses. The function name and file name must be the same, but the file name must have the extension ***.m***. For example, the function file consisting of the two lines below

```
function y = myfunction(x)
y=x.^ 3 + cos(3.* x)
```

is a function file and must be saved as ***myfunction.m***

For the next example, we will use the following MATLAB functions:

fzero(f,x) – attempts to find a zero of a function of one variable, where **f** is a string containing the name of a real–valued function of a single real variable. MATLAB searches for a value near a point where the function **f** changes sign, and returns that value, or returns `NaN` if the search fails.

Important: We must remember that we use **roots(p)** to find the roots of polynomials only, such as those in Examples A.1 and A.2.

fplot(fcn,lims) – plots the function specified by the string **fcn** between the x–axis limits specified by **lims = [xmin xmax]**. Using **lims = [xmin xmax ymin ymax]** also controls the y–axis limits. The string **fcn** must be the name of an *m–file* function or a string with variable x.

NaN (Not–a–Number) is not a function; it is MATLAB's response to an undefined expression such as $0/0$, ∞/∞, or inability to produce a result as described on the next paragraph. We can avoid division by zero using the **eps** number, which we mentioned earlier.

Example A.16

Find the zeros, the minimum, and the maximum values of the function

$$f(x) = \frac{1}{(x-0.1)^2+0.01} - \frac{1}{(x-1.2)^2+0.04} - 10 \qquad \text{(A.9)}$$

in the interval $-1.5 \le x \le 1.5$

Solution:

We first plot this function to observe the approximate zeros, maxima, and minima using the following script.

```
x=–1.5: 0.01: 1.5;
y=1./ ((x–0.1).^ 2 + 0.01) –1./ ((x–1.2).^ 2 + 0.04) –10;
plot(x,y); grid
```

The plot is shown in Figure A.14.

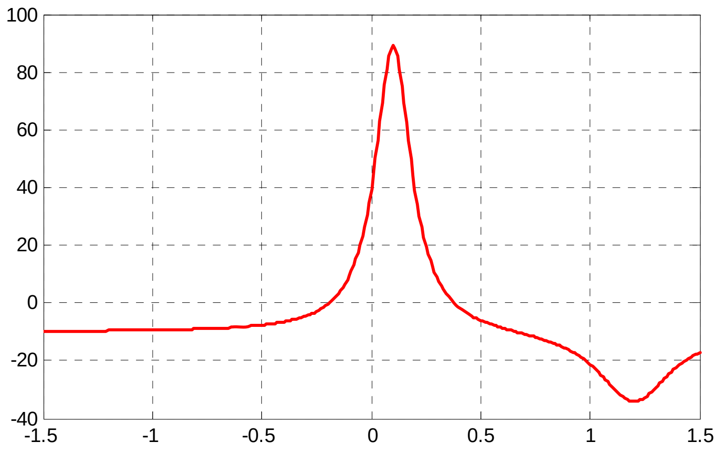


Figure A.14. Plot for Example A.16 using the plot command

The roots (zeros) of this function appear to be in the neighborhood of $x = -0.2$ and $x = 0.3$. The maximum occurs at approximately $x = 0.1$ where, approximately, $y_{max} = 90$, and the minimum occurs at approximately $x = 1.2$ where, approximately, $y_{min} = -34$.

Next, we define and save *f(x)* as the **funczero01.m** function m–file with the following script:

```
function y=funczero01(x)
% Finding the zeros of the function shown below
y=1/((x–0.1)^2+0.01)–1/((x–1.2)^2+0.04)–10;
```

To save this file, from the File drop menu on the Command Window, we choose New, and when the Editor Window appears, we type the script above and we save it as **funczero01.** MATLAB appends the extension **.m** to it.

Now, we can use the **fplot(fcn,lims)** command to plot $f(x)$ as follows:

```
fplot('funczero01', [–1.5  1.5]); grid
```

This plot is shown in Figure A.15. As expected, this plot is identical to the plot of Figure A.14 which was obtained with the **plot(x,y)** command as shown in Figure A.14.

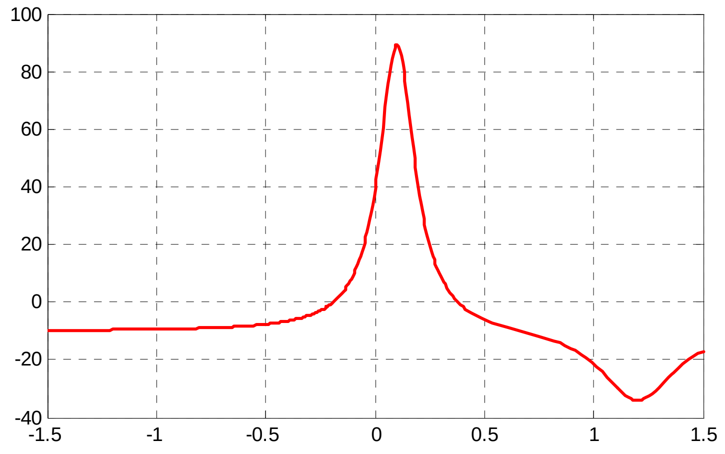


Figure A.15. Plot for Example A.16 using the fplot command

We will use the **fzero(f,x)** function to compute the roots of $f(x)$ in Equation (A.9) more precisely. The MATLAB script below will accomplish this.

```
x1= fzero('funczero01', –0.2);
x2= fzero('funczero01', 0.3);
fprintf('The roots (zeros) of this function are r1= %3.4f', x1);
fprintf(' and r2= %3.4f \n', x2)
```

MATLAB displays the following:

```
The roots (zeros) of this function are r1= -0.1919 and r2= 0.3788
```

The earlier MATLAB versions included the function **fmin(f,x1,x2)** and with this function we could compute both a minimum of some function $f(x)$ or a maximum of $f(x)$ since a maximum of $f(x)$ is equal to a minimum of $-f(x)$. This can be visualized by flipping the plot of a function $f(x)$ upside–down. This function is no longer used in MATLAB and thus we will compute the maxima and minima from the derivative of the given function.

From elementary calculus, we recall that the maxima or minima of a function $y = f(x)$ can be found by setting the first derivative of a function equal to zero and solving for the independent variable x. For this example we use the **diff(x)** function which produces the approximate derivative of a function. Thus, we use the following MATLAB script:

```
syms x ymin zmin; ymin=1/((x–0.1)^2+0.01)–1/((x–1.2)^2+0.04)–10;...
zmin=diff(ymin)
```

```
zmin =
-1/((x-1/10)^2+1/100)^2*(2*x-1/5)+1/((x-6/5)^2+1/25)^2*(2*x-12/5)
```

When the command

```
solve(zmin)
```

is executed, MATLAB displays a very long expression which when copied at the command prompt and executed, produces the following:

```
ans =
   0.6585 + 0.3437i
ans =
   0.6585 - 0.3437i
ans =
    1.2012
```

The real value 1.2012 above is the value of x at which the function y has its minimum value as we observe also in the plot of Figure A.15.

To find the value of y corresponding to this value of x, we substitute it into $f(x)$, that is,

```
x=1.2012; ymin=1 / ((x–0.1) ^ 2 + 0.01) –1 / ((x–1.2) ^ 2 + 0.04) –10
```

```
ymin = -34.1812
```

We can find the maximum value from $-f(x)$ whose plot is produced with the script

```
x=–1.5:0.01:1.5; ymax=–1./((x–0.1).^2+0.01)+1./((x–1.2).^2+0.04)+10; plot(x,ymax); grid
```

and the plot is shown in Figure A.16.

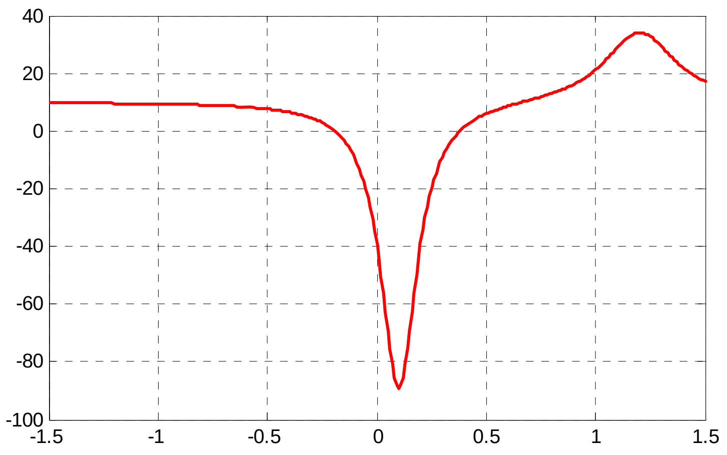


Figure A.16. Plot of $-f(x)$ *for Example A.16*

Next we compute the first derivative of $-f(x)$ and we solve for x to find the value where the maximum of $ymax$ occurs. This is accomplished with the MATLAB script below.

```
syms x ymax zmax; ymax=–(1/((x–0.1)^2+0.01)–1/((x–1.2)^2+0.04)–10); zmax=diff(ymax)
```

```
zmax =
 1/((x-1/10)^2+1/100)^2*(2*x-1/5)-1/((x-6/5)^2+1/25)^2*(2*x-12/5)
```

```
solve(zmax)
```

When the command

```
solve(zmax)
```

is executed, MATLAB displays a very long expression which when copied at the command prompt and executed, produces the following:

```
ans =
   0.6585 + 0.3437i

ans =
   0.6585 - 0.3437i

ans =
    1.2012
ans =
    0.0999
```

From the values above we choose $x = 0.0999$ which is consistent with the plots of Figures A.15 and A.16. Accordingly, we execute the following script to obtain the value of $ymin$.

```
x=0.0999;                        % Using this value find the corresponding value of ymax
ymax=1 / ((x–0.1) ^ 2 + 0.01) –1 / ((x–1.2) ^ 2 + 0.04) –10

ymax = 89.2000
```

A.11 Display Formats

MATLAB displays the results on the screen in integer format without decimals if the result is an integer number, or in short floating point format with four decimals if it a fractional number. The format displayed has nothing to do with the accuracy in the computations. MATLAB performs all computations with accuracy up to 16 decimal places.

The output format can changed with the **format** command. The available MATLAB formats can be displayed with the **help format** command as follows:

```
help format

FORMAT Set output format.
All computations in MATLAB are done in double precision.
FORMAT may be used to switch between different output display formats
as follows:

FORMAT  Default. Same as SHORT.
FORMAT SHORT Scaled fixed point format with 5 digits.
FORMAT LONG Scaled fixed point format with 15 digits.
FORMAT SHORT E Floating point format with 5 digits.
FORMAT LONG E  Floating point format with 15 digits.
FORMAT SHORT G Best of fixed or floating point format with 5 digits.
FORMAT LONG G Best of fixed or floating point format with 15 digits.
FORMAT HEX Hexadecimal format.
FORMAT + The symbols +, - and blank are printed for positive, negative,
        and zero elements.Imaginary parts are ignored.
FORMAT BANK Fixed format for dollars and cents.
FORMAT RAT Approximation by ratio of small integers.

Spacing:

FORMAT COMPACT Suppress extra line-feeds.
FORMAT LOOSE  Puts the extra line-feeds back in.

Some examples with different format displays age given below.

format short  33.3335  Four decimal digits (default)
format long  33.33333333333334 16 digits
format short e  3.3333e+01  Four decimal digits plus exponent
format short g  33.333  Better of format short or format short e
format bank  33.33 two decimal digits
format +  only + or - or zero are printed
format rat 100/3 rational approximation
```

The **disp(X)** command displays the array **X** without printing the array name. If **X** is a string, the text is displayed.

The **fprintf(format,array)** command displays and prints both text and arrays. It uses specifiers to indicate where and in which format the values would be displayed and printed. Thus, if **%f** is used, the values will be displayed and printed in fixed decimal format, and if **%e** is used, the values will be displayed and printed in scientific notation format. With this command only the real part of each parameter is processed.

This appendix is just an introduction to MATLAB.* This outstanding software package consists of many applications known as *Toolboxes*. The MATLAB Student Version contains just a few of these Toolboxes. Others can be bought directly from The MathWorks,™ Inc., as add–ons.

* *For more MATLAB applications, please refer to Numerical Analysis Using MATLAB and Spreadsheets, ISBN 0–9709511–1–6.*

Appendix B

Masked Subsystems

This appendix presents an overview of masked subsystems, and a step–by–step procedure to create custom user interfaces, i.e., masks for Simulink subsystems.

B.1 Masks Defined

A *mask* is a custom user interface for a subsystem. A *masked subsystem* conceals the subsystem's contents, and it appear to the user as an atomic block with its own icon and parameter dialog box. However, a masked subsystem provides only graphical, not functional, grouping. We can create a mask for any Simulink subsystem using the **Mask Editor**.

B.2 Advantages Using Masked Subsystems

A masked subsystem allows us to

1. Replace the parameter dialogs of a subsystem and its contents with a single parameter dialog with its own block description, parameter prompts, and help text.
2. Replace a subsystem's standard icon with a custom icon that shows its purpose.
3. Prevent accidental modification of subsystems by concealing their contents behind a mask.
4. Placing a masked subsystem in a library. We can also mask S–Function and Model blocks.

B.3 Mask Features

Masks can include any of the following features:

Mask Icon – The mask icon replaces a subsystem's standard icon, i.e., it appears in a block diagram in place of the standard icon for a subsystem block. Simulink uses MATLAB code that we supply to draw the custom icon. We can use any MATLAB drawing command in the icon code.

Mask Parameters – Masked subsystems allow us to define a set of user–specified parameters. Simulink stores the values of these parameters in the mask workspace as the value of a variable whose name you specify. These associated variables allow us to link mask parameters to specific parameters of blocks inside a masked subsystem.

Mask Parameter Dialog Box – The mask parameter dialog box contains controls that enable a user to set the values of the mask's parameters and hence the values of any internal parameters linked to the mask parameters. The mask parameter dialog box replaces the subsystem's standard parameter dialog box, i.e., clicking on the masked subsystem's icon causes the mask dialog box to appear instead of the standard parameter dialog box for a Subsystem block

Mask Initialization Code – The initialization code is MATLAB code that you specify and that Simulink runs to initialize the masked subsystem at critical times, such as model loading and the start of a simulation run (see Initialization Pane). You can use the initialization code to set the initial values of the masked subsystem's mask parameters.

Mask Workspace – Simulink associates a workspace with each masked subsystem that you create. Simulink stores the current values of the subsystem's parameters in the workspace as well as any variables created by the block's initialization code and parameter callbacks. You can use model and mask workspace variables to initialize a masked subsystem and to set the values of blocks inside the masked subsystem, subject to the following rules.

A block parameter expression can refer only to variables defined in the mask workspaces of the subsystem or nested subsystems that contain the block or in the model's workspace.

A valid reference to a variable defined on more than one level in the model hierarchy resolves to the most local definition.

For example, let us suppose that model M contains masked subsystem A, which contains masked subsystem B. Also, let us suppose that B refers to a variable x that exists in both A's and M's workspaces. In this case, the reference resolves to the value in A's workspace.

A masked subsystem's initialization code can refer only to variables in its local workspace.

The mask workspace of a Model block is not visible to the model that it references. Any variables used by the referenced model must resolve to workspaces defined in the referenced model or to the base (i.e., the MATLAB) workspace.

B.4 Creating a Masked Subsystem

It is best to illustrate the creation of a masked subsystem with an example.

Example B.1

The Simulink model in Figure B.1 below implements the quadratic equation $y = ax^2 + bx + c$.

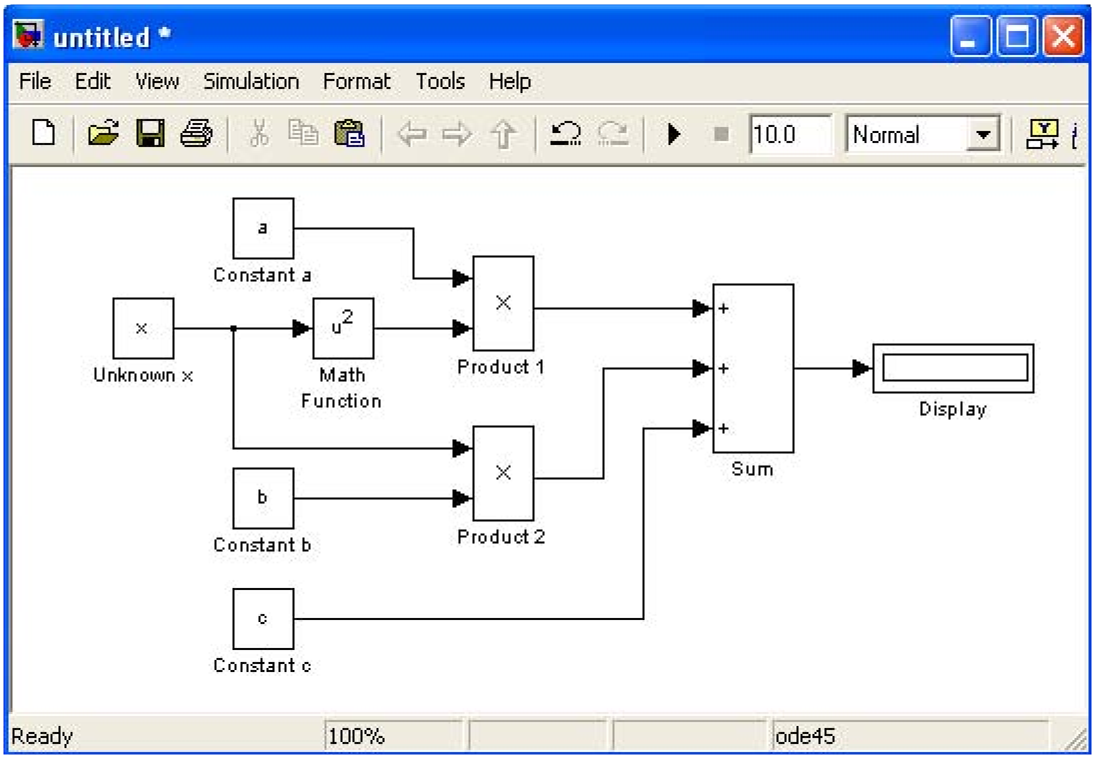


Figure B.1. Simulink model for Example B.1

To create a subsystem, we encircle all blocks except the Unknown x and **Display** blocks, and from the **Edit** drop menu we select **Create Subsystem**. The model now appears as shown in Figure B.2.

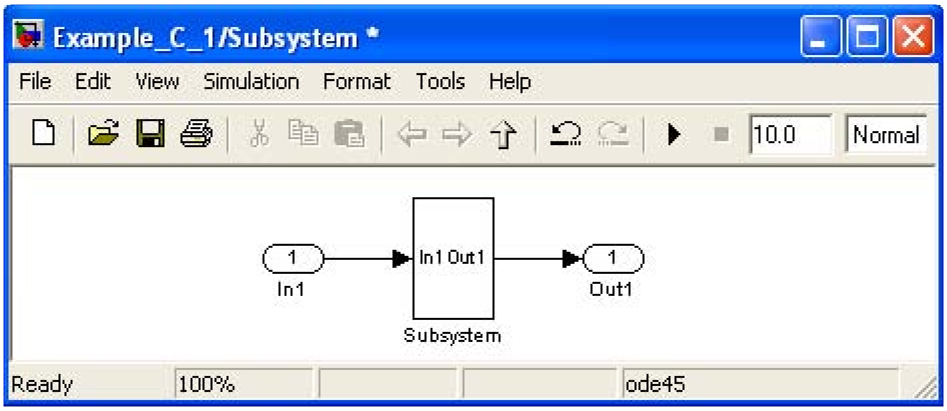


Figure B.2. The model for Example B.1 shown as a subsystem block

To see the contents of the Subsystem in Figure B.2, we double–click the Subsystem block and now the model appears as shown in Figure B.3.

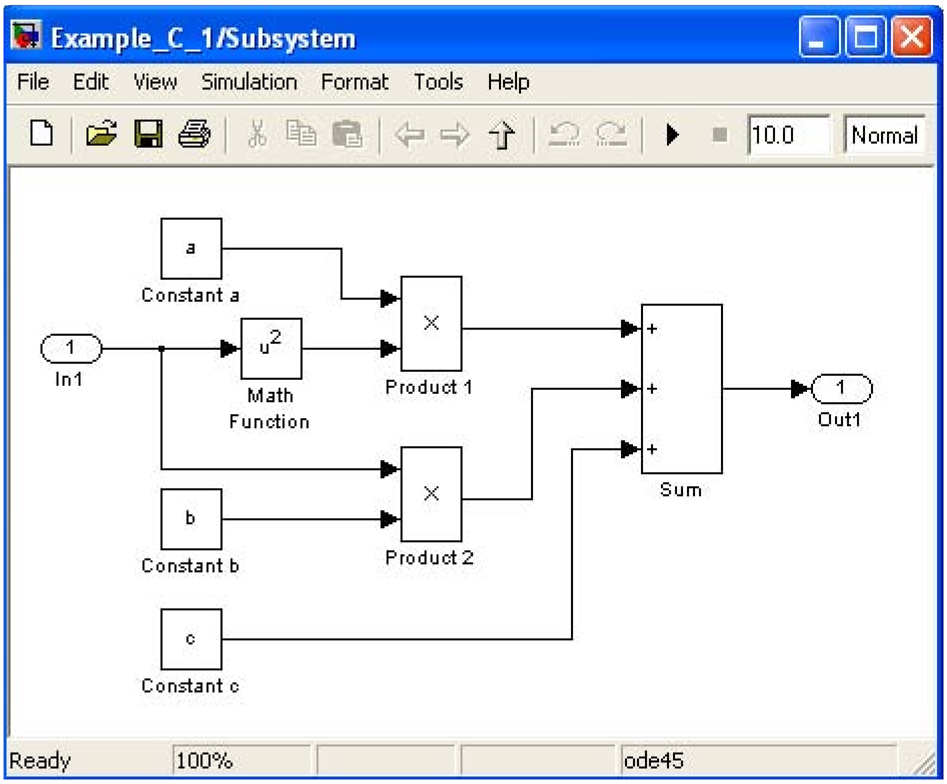
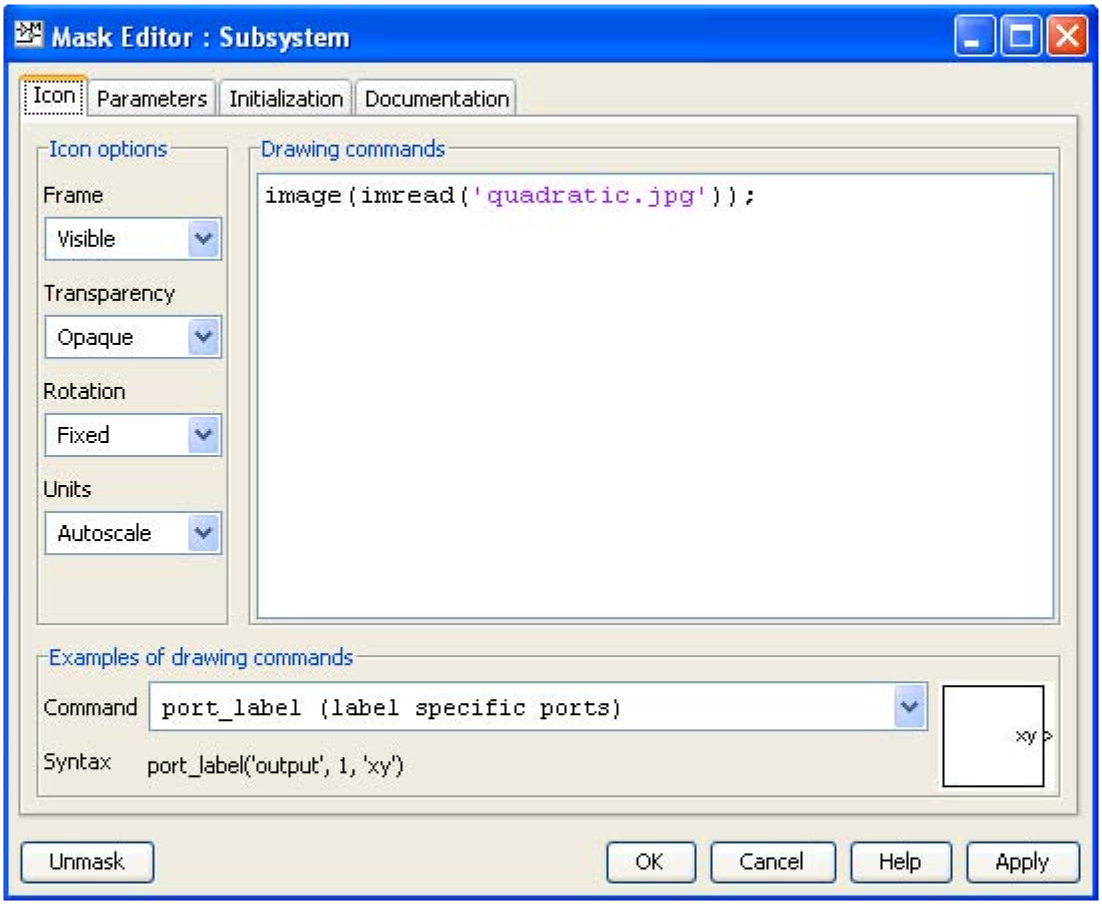


Figure B.3. The contents of the subsystem block

From the **Edit** drop menu we click on the **Mask Subsystem** and the **Mask Editor** window appears as shown in Figure B.4. With the **Icon** tab selected as shown in Figure B.4, we position the text cursor in the **Drawing commands** pane, and we enter the MATLAB command image(imread('quadratic.jpg'));, we press **Enter**, and we click **OK**. It is assumed that this image was previously created and saved in MATLAB's saved files path. The **Mask Editor** now appears as shown in Figure B.5.



Frame: Visible
Transparency: Opaque
Rotation: Fixed
Units: Autoscale

```
image(imread('quadratic.jpg'));
```

Command: port_label (label specific ports)

Syntax: port_label('output', 1, 'xy')

Figure B.4. The Mask Editor window for Example B.1

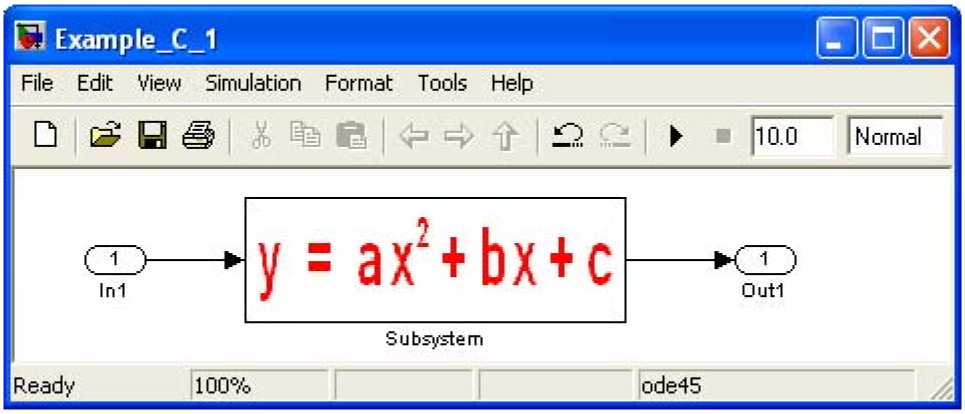


Figure B.5. The masked subsystem with an imported image

We right–click on the **Subsystem** block in Figure B.5, and from the drop menu we select **Edit Mask**. From the **Mask Editor** window which appears, we select the **Parameters** tab shown in Figure B.6 below.

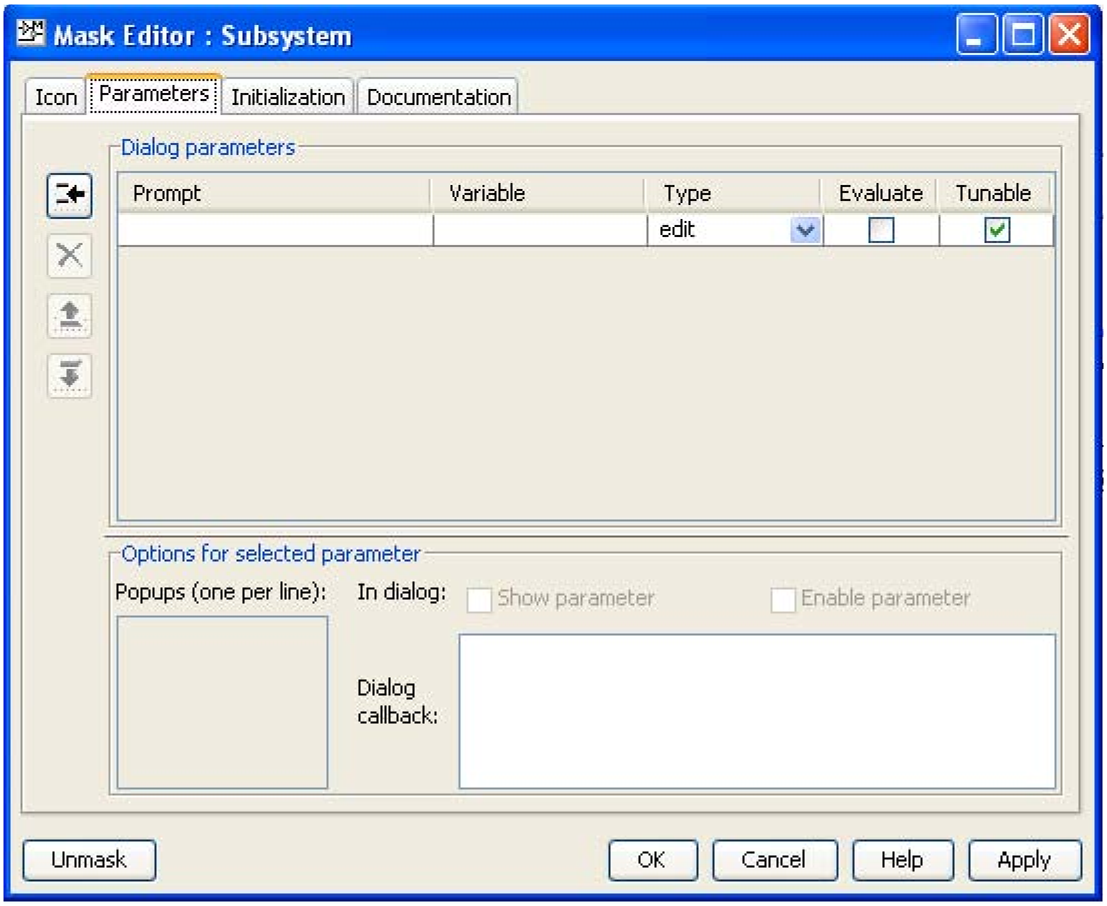
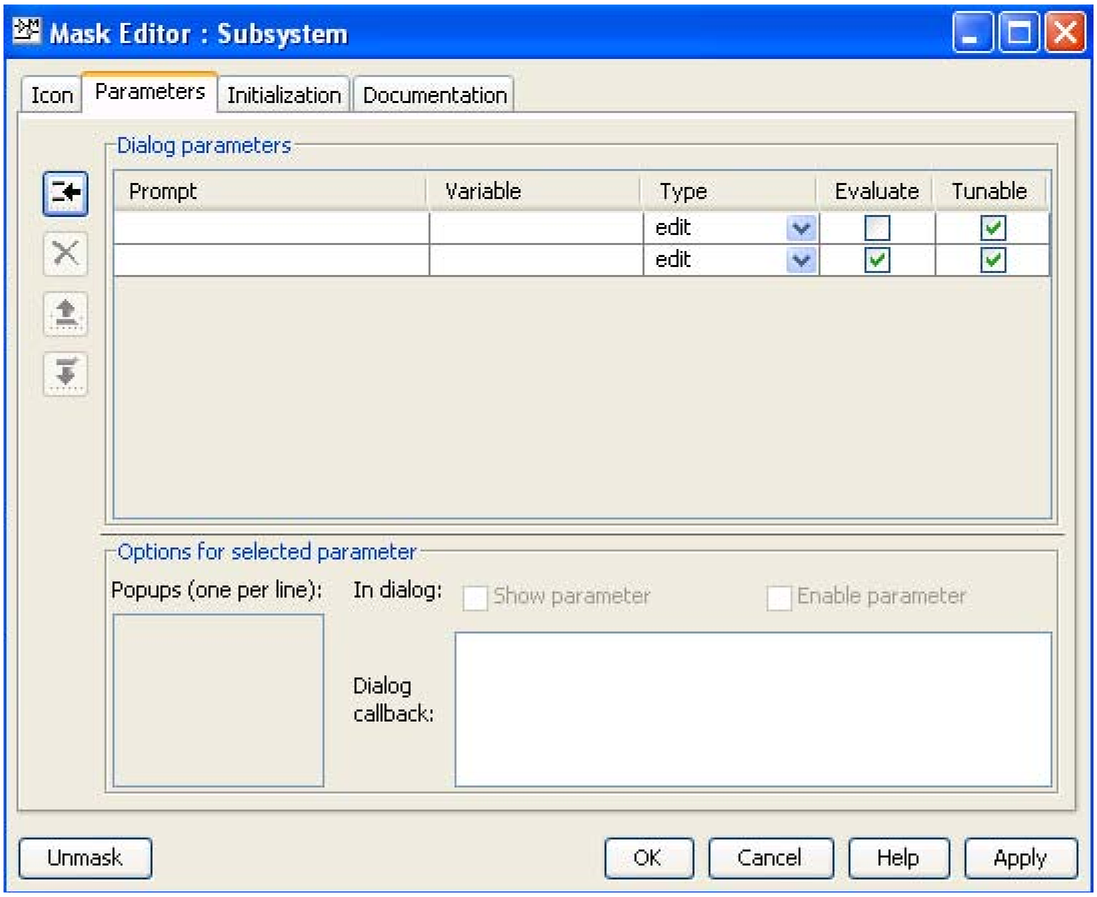


Figure B.6. The Parameters tab for the Mask Editor window

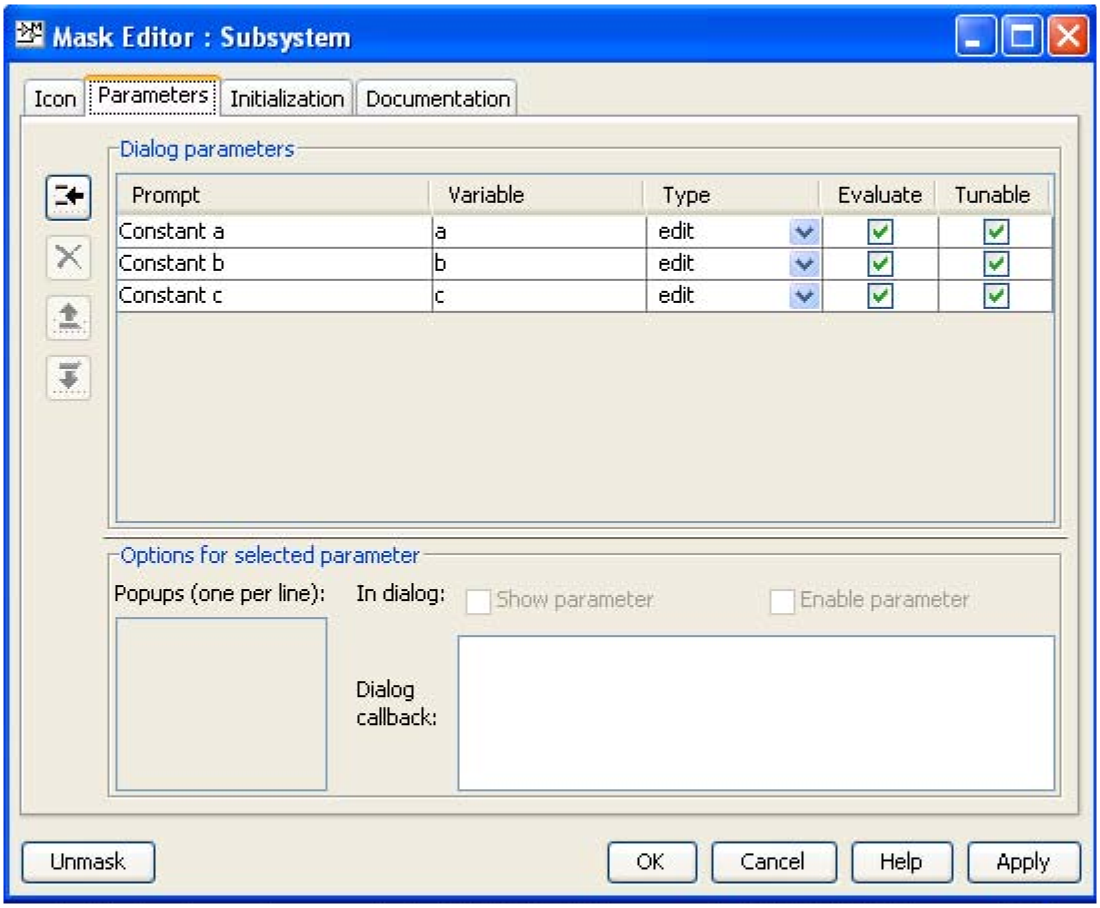
We select the Add tool and the **Mask Editor** window now appears as shown in Figure B.7.



Prompt	Variable	Type	Evaluate	Tunable
		edit	☐	✓
		edit	✓	✓

Figure B.7. The Mask Editor window for specifying the attributes of the masked parameters

The **Mask Editor** in Figure B.7 is used to specify the attributes of the masked parameters. The **Prompt** column under **Dialog parameters** is used as a text label to describe the parameter. For our example we enter Constant a, Constant b, and Constant c. The **Variable** column is used to enter the names of the variables that store the parameter values. For this example we enter a, b, and c as shown in Figure B.8.


Mask Editor : Subsystem

Icon | Parameters | Initialization | Documentation

Dialog parameters

Prompt	Variable	Type	Evaluate	Tunable
Constant a	a	edit	✓	✓
Constant b	b	edit	✓	✓
Constant c	c	edit	✓	✓

Options for selected parameter

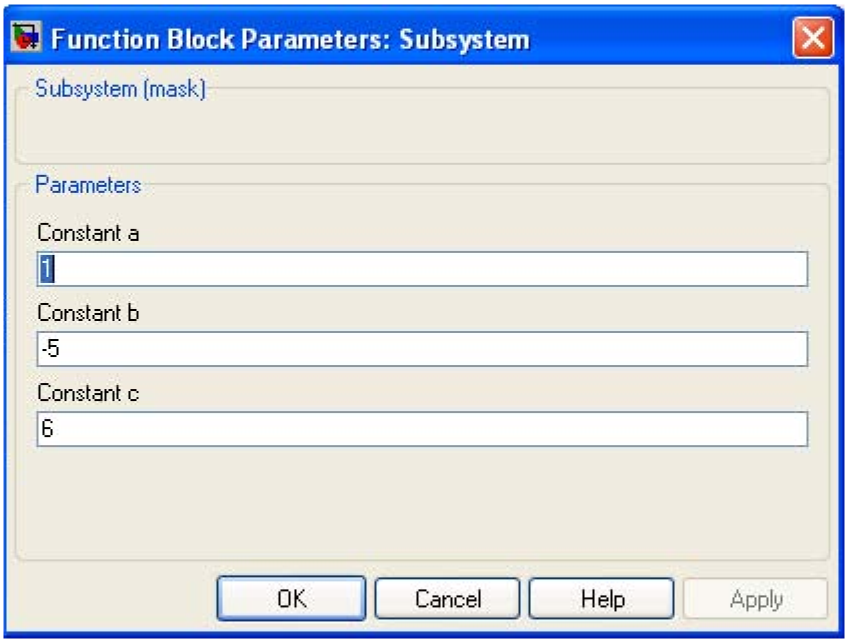
Popups (one per line): In dialog: ☐ Show parameter ☐ Enable parameter

Dialog callback:

Unmask OK Cancel Help Apply

Figure B.8. *The Masked Editor with the equation constants specified*

We right–click on the masked subsystem block shown in Figure B.5, Page B–5, and in the **Function Block Parameters** dialog box we enter the values 1, –5, and 6 for the variables a, b, and c respectively, as shown in Figure B.9.


Function Block Parameters: Subsystem

Subsystem (mask)

Parameters

Constant a: 1

Constant b: -5

Constant c: 6

Figure B.9. The Function Block Parameters window with the values of the constants

With the variables defined as above, the masked subsystem implements the quadratic equation

$$y = x^2 - 5x + 6$$

and the roots of this equation are $x_1 = 2$ and $x_2 = 3$. Our model is tested for the first root as shown in Figure B.10.

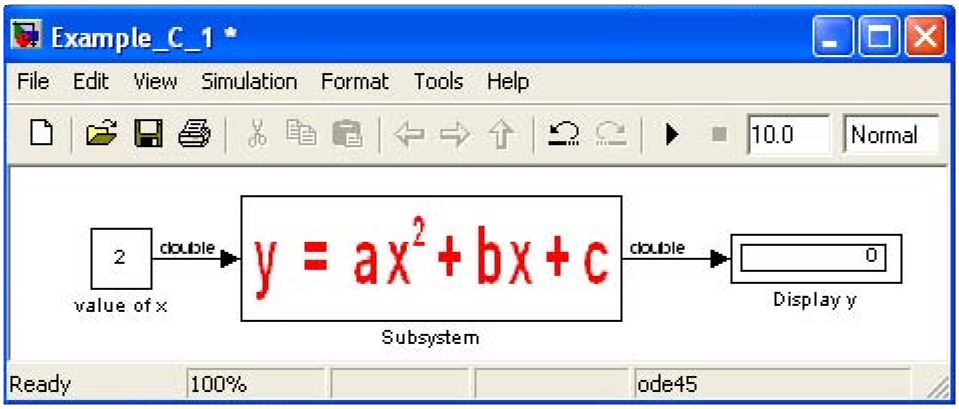


Figure B.10.

The **Mask Editor** also contains the **Initialization** tab that allows us to enter MATLAB commands that initialize the masked subsystem, and the **Documentation** tab that lets us define or modify the type description and help text for a masked subsystem. These tabs are shown in Figures B.11 and B.12, and are not used in this example.

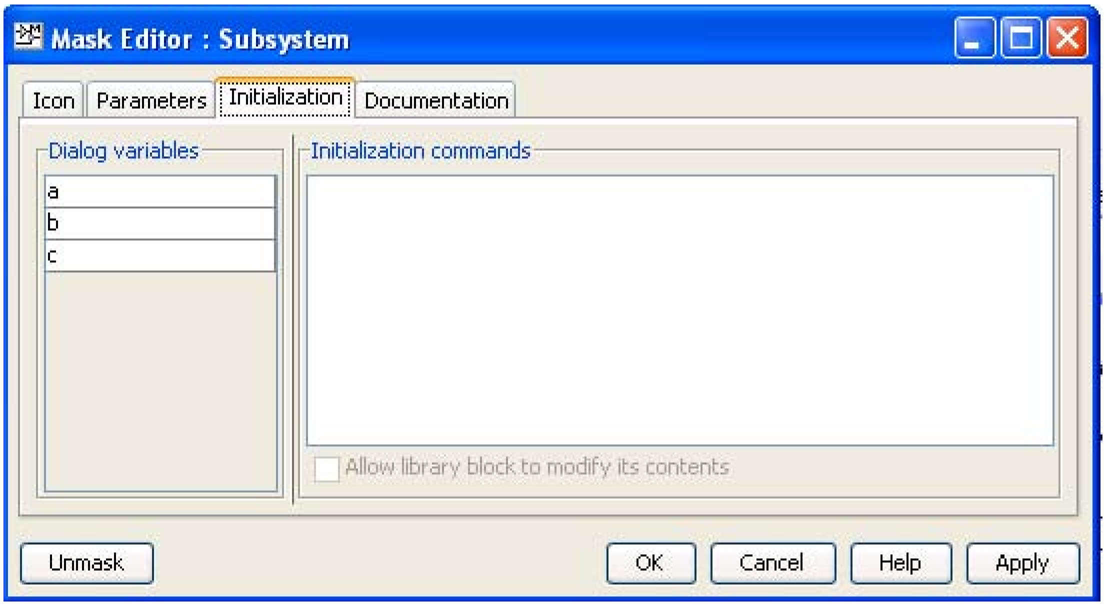


Figure B.11. The Initialization tab for the Mask Editor Window

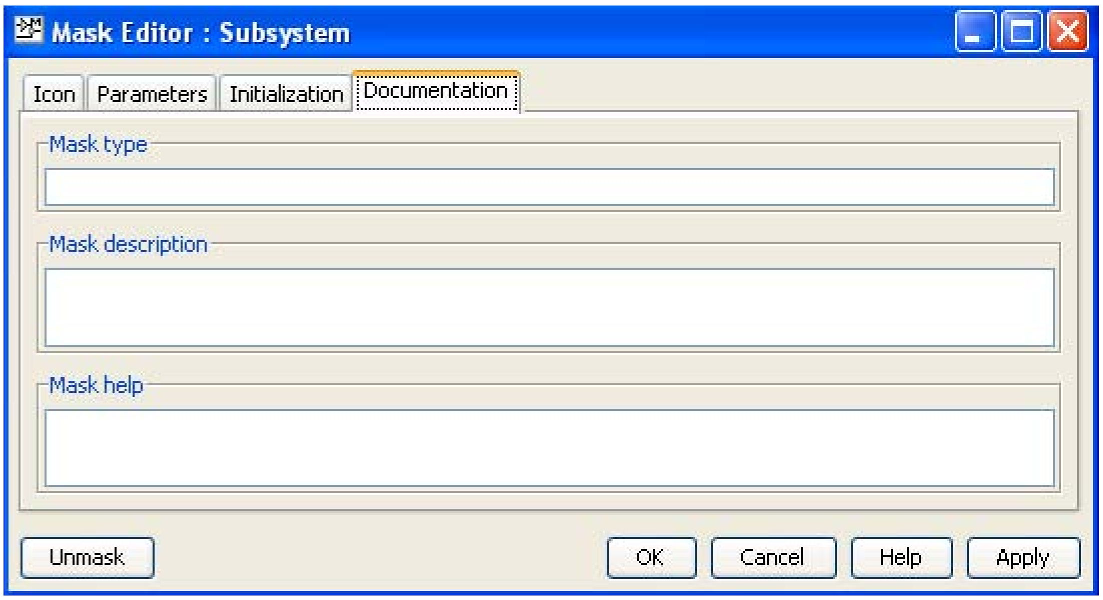


Figure B.12. The Documentation tab for the Mask Editor window.

Appendix C

Random Number Generation

This appendix is a short tutorial on Random Number Generation. An example is presented to illustrate the sequence which most random generators use.

C.1 Random Numbers

Random numbers are used in many applications. Random number generation is the production of an unpredictable sequence of numbers in which no number is any more likely to occur at a given time or place in the sequence than any other. Truly random number generation is generally viewed as impossible. The process used in computers would be more properly called **pseudorandom number generation.**

C.2 An Example

A typical random number generator creates a sequence in accordance with the following recurrence:

$$x_{n+1} = P_1x_n + P_2 \quad (\text{mod } N) \quad n=0,1,2,\ldots \qquad x_0 = \text{seed} \tag{C.1}$$

where $\text{mod } N$ is used to indicate that the sum $P_1x_n + P_2$ is divided by N and then is replaced by the remainder of that division. The values of x_0 (seed), P_1, P_2, and N must be specified. As an example, let

$$x_0 = 1 \qquad P_1 = 281 \qquad P_2 = 123 \qquad N = 75$$

then, in MATLAB notation

```
x0=1, P1=281, P2=123, N=75
x1=P1*x0+P2, y1=mod(x1,N)
x2=P1*y1+P2, y2=mod(x2,N)
.............
xn=P1*y(n-1)+P2, yn=mod(xn,N)
```

To find the sequence of numbers for the random number generator, we use the following MATLAB script:

```
P1=281; P2=123; N=75; x=1:100; y=zeros(100,2);
y(:,1)=x'; y(:,2)=mod((P1.*x+P2),N)'; fprintf('  x    y \n'); disp('  ------');
fprintf('%3.0f\t %3.0f\n',y')
```

MATLAB outputs the following table:

```
   x   y
  ------
   1  29
   2  10
   3  66
   4  47
   5  28
   6   9
   7  65
   8  46
   9  27
  10   8
  11  64
  12  45
  13  26
  14   7
  15  63
  16  44
  17  25
  18   6
  19  62
  20  43
  21  24
  22   5
  23  61
  24  42
  25  23
  26   4
  27  60
  28  41
  29  22
  30   3
  31  59
  32  40
  33  21
  34   2
  35  58
  36  39
  37  20
  38   1
```

```
39  57
40  38
41  19
42   0
43  56
44  37
45  18
46  74
47  55
48  36
49  17
50  73
51  54
52  35
53  16
54  72
55  53
56  34
57  15
58  71
59  52
60  33
61  14
62  70
63  51
64  32
65  13
66  69
67  50
68  31
69  12
70  68
71  49
72  30
73  11
74  67
75  48
76  29
77  10
78  66
79  47
80  28
81   9
```

```
 82  65
 83  46
 84  27
 85   8
 86  64
 87  45
 88  26
 89   7
 90  63
 91  44
 92  25
 93   6
 94  62
 95  43
 96  24
 97   5
 98  61
 99  42
100  23
```

We observe that for `x = 1`, `y = 29`, and for `x = 76`, `y = 29` also. This indicates that the sequence repeats. For this reason, this generator is referred to as a pseudo-random generator. For a true random number generator[*] all numbers from 0 to 99 should be included in the sequence, of course, in a random manner.

If we wanted to transform the above sequence in the interval 0 to 1, we would divide the original sequence of numbers again by N.

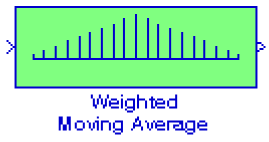
* *Truly random number generation is considered as impossible.*

Appendix D

The Weighted Moving Average

This appendix describes the **Weighted Moving Average** block which is no longer used in the latest revision of Simulink. It has been replaced by the **Digital FIR filter** block described in the **Discrete Blocks** Library, Chapter 5. It is presented here as an introduction to the concept of moving average, and for the benefit of those readers who are working with previous versions of the Simulink package.

D.1 The Weighted Moving Average Block



The **Weighted Moving Average** block samples and holds the N most recent inputs, multiplies each input by a specified value (given by the Weights parameter), and stacks them in a vector. This block supports both single–input / single–output (SISO) and single–input / multi–output (SIMO) modes. For a detailed discussion please refer to the Help menu for this block.

The following discussion will help us understand the meaning of a weighted moving average.

Suppose that the voltages displayed by an electronic instrument in a 5-day period, Monday through Friday, were $23.5, 24.2, 24.0, 23.9 \text{ and } 24.1$ volts respectively. The average of those five readings is

$$\frac{23.5 + 24.2 + 24.0 + 23.9 + 24.1}{5} = 23.94$$

Now, suppose that on the following Monday the reading was found to be 24.2 volts. Then, the new 5–day average based on the last five days, Tuesday through Monday is

$$\frac{24.2 + 24.0 + 23.9 + 24.1 + 24.2}{5} = 24.08$$

We observe that the 5–day average has changed from 23.94 to 24.08 volts. In other words, the average has "moved" from 23.94 to 24.08 volts. Hence, the name **moving average**.

However, a more meaningful moving average can be obtained if we assign weights to each reading where the most recent reading carries the most weight. Thus, using a 5–day moving average we could take the reading obtained on the 5th day and multiply it by 5, the 4th day by 4, the 3rd day by 3, the 2nd day by 2, and the 1st day by 1. We could now add these numbers and divide the sum by the sum of the multipliers, i.e., 5+4+3+2+1=15. Thus, the 5–day weighted moving average would be

$$\frac{1\times 24.2+2\times 24.0+3\times 23.9+4\times 24.1+5\times 24.2}{15} = 24.09$$

and the value 24.09 is referred to as the **Weighted Moving Average (WMA)**.

An **Exponential Moving Average (EMA)** takes a percentage of the most recent value and adds in the previous value's exponential moving average times 1 minus that percentage. For instance, suppose we wanted a 10% EMA. We would take the most recent value and multiply it by 10% then add that figure to the previous value's EMA multiplied by the remaining percent, that is,

$$\text{Most Recent Value}\times 0.1+\text{Previous Value's EMA}\times(1-0.1) \tag{D.1}$$

Alternately, we can use the following formula to determine the percentage to be used in the calculation:

$$\text{Exponential Percentage} = \frac{2}{\text{Time Periods}+1} \tag{D.2}$$

For example, if we wanted a 20 period EMA, we would use

$$\frac{2}{20+1} = 9.52\ \% \tag{D.3}$$

Example D.1

The price of a particular security (stock) over a 5–day period is as follows:

77 80 82 85 90

where the last value is the most recent. We will create single-input / single output (SISO) model with a **Weighted Moving Average** block to simulate the weighted moving average over this 5–day period.

For this example, we will represent the SISO output as follows:

$$y_1(k) = a_1u(k)+b_1u(k-1)+c_1u(k-2)+d_1u(k-3)+e_1u(k-4) \tag{D.4}$$

where

$$u(k) = 5/15 \quad u(k-1)=4/15 \quad u(k-2)=3/15 \quad u(k-3)=2/15 \quad u(k-4)=1/15 \tag{D.5}$$

The model is shown in Figure 5.25 where in the **Function Block Parameters** dialog box for the **Weighted Moving Average** block we have entered:

Weights:

$$[5/15 \quad 4/15 \quad 3/15 \quad 2/15 \quad 1/15]$$

Initial conditions:

$$[85 \;\; 82 \;\; 80 \;\; 77]$$

Constant block – Output scaling value: $[1.25 \;\; 3]$

Weighted Moving Average block – Parameter data types: $\mathtt{sfix(16)}$, Parameter scaling: 2^{-4}

Signal data types: $\mathtt{sfix(16)}$, Parameter scaling: 2^{-6}

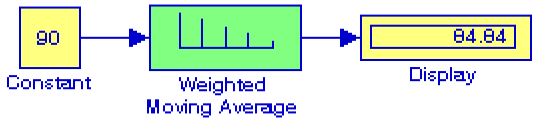


Figure D.1. Model for Example D.1

References and Suggestions for Further Study

A. The following publications by The MathWorks, are highly recommended for further study. They are available from The MathWorks, 3 Apple Hill Drive, Natick, MA, 01760, www.mathworks.com.

1. *Getting Started with MATLAB*
2. *Using MATLAB*
3. *Using MATLAB Graphics*
4. *Using Simulink*
5. *Sim Power Systems*
6. *Fixed–Point Toolbox*
7. *Simulink Fixed–Point*
8. *Real–Time Workshop*
9. *Signal Processing Toolbox*

10. *Getting Started with Signal Processing Blockset*

10. *Signal Processing Blockset*

11. *Control System Toolbox*

12. *Stateflow*

For the complete list of all of The MathWorks products and MATLAB / Simulink based books, please refer to:

http://www.mathworks.com/index.html?ref=pt

B. Other references indicated in footnotes throughout this text, are listed below.

1. *Introduction to Stateflow with Applications*, ISBN 978–1–934404–07–2

2. *Signals and Systems with MATLAB Computing and Simulink Modeling, Third Edition*, ISBN 978–0–9744239–9–9

3. *Digital Circuit Analysis and Design with Simulink Applications and Introduction to CPLDs and FPGAs, Second Edition*, ISBN 978–1–934404–05–8

4. *Electronic Devices and Amplifier Circuits with MATLAB Applications*, ISBN 978–0–9709511–7–5

5. *Circuit Analysis I with MATLAB Applications*, ISBN 978–0–9709511–2–0

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Steven T. Karris is the founder and president of Orchard Publications, has undergraduate and graduate degrees in electrical engineering, and is a registered professional engineer in California and Florida. He has more than 35 years of professional engineering experience and more than 30 years of teaching experience as an adjunct professor, most recently at UC Berkeley, California. His area of interest is in The MathWorks, Inc. ™ products and the publication of MATLAB® and Simulink® based texts.

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