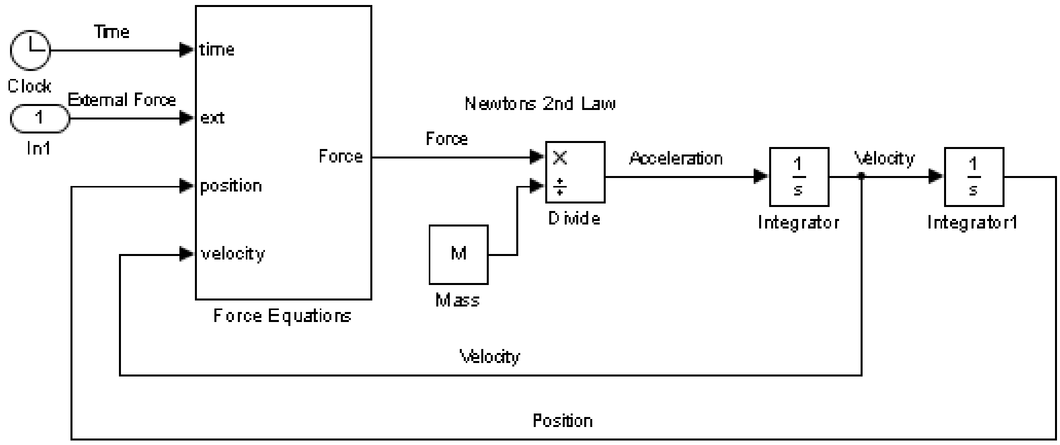
An Introduction to Using Simulink



COURSE NOTES

Eric Peasley, Department of Engineering Science, University of Oxford

Adapted and updated by Dr I. F. Mear using MATLAB 2017b and MATLAB 2018b

version 5.0, 2018

Table of Contents

Introduction

This document is part of the "Introduction to Using Simulink" seminar. This seminar is designed for people that have never used Simulink. There are two components to the seminar. There are exercises in a separate document that will take you step by step through the tasks required to build and use a Simulink model. Once you get started using Simulink, you will find a lot of the functionality is self-intuitive. Inevitably, there are things that need a bit more explanation. So the other part of the Seminar is a talk and demonstration. This document contains the notes for the talk.

It would be impossible to put everything about Simulink into such a short document, so this document concentrates on the parts of the package that are considered the most useful. It also aims to highlight features that are not obvious to the casual user. The intention is that you use these notes as a reference when carrying out the exercises and when building your own models. Although these notes have their limits, I hope that they should be sufficient to get you started using the package and that they cover most of your modelling needs.

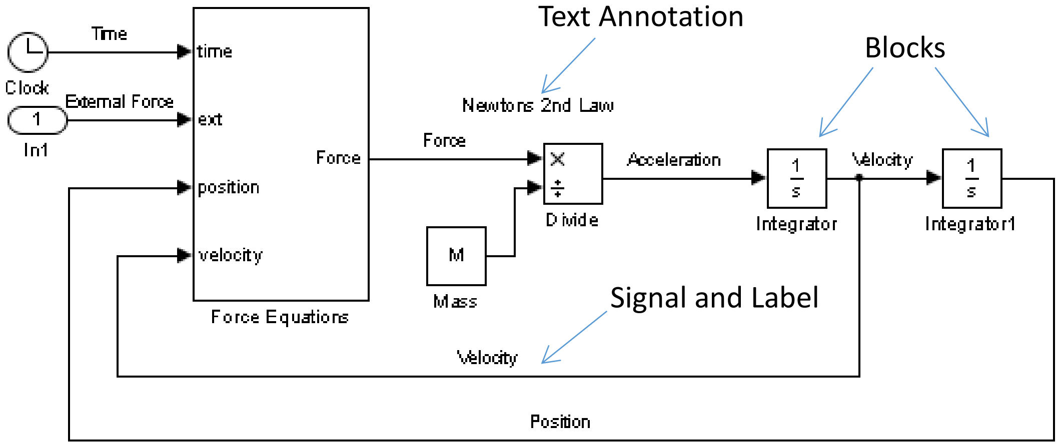
This is not a Simulink manual. Sooner or later you will need to know more detail about something within Simulink. This document is intended to be used in conjunction to the documentation available within the package. Mathworks, creators of MATLAB & Simulink, provide extensive online documentation for Simulink that can be accessed using the MATLAB help system. There is so much online documentation that not many people have the time or inclination to read all of it. So an aim of the Seminar is to emphasize the things that you ought to know about Simulink and to give you some idea about where you can find any other information that you require.

What is Simulink?

Simulink is a visual programming interface designed to make modelling systems intuitive. It offers a way to solve equations numerically using a graphical user interface, rather than requiring code.

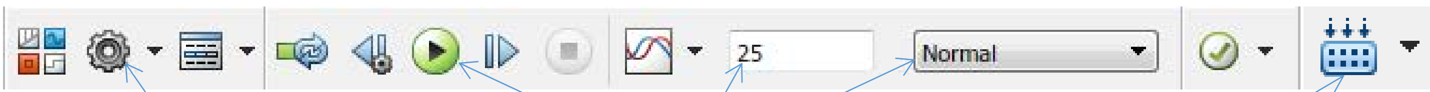
Models contain **blocks**, **signals** and **annotation** on a background:.

- **Blocks** are mathematical functions, they can have varying numbers of inputs and outputs.
- **Signals** are lines connecting blocks, transferring values between them. Signals are different data types, for example numbers, vectors or matrices. Signals can be **labelled**.
- **Annotations** of text or images can be added to the model, and while not used in the calculations they can make it easier for others to understand design decisions in the model.



The Simulink Toolbar

Above the main canvas of a Simulink model, is the **toolbar.**



Model Settings

All of the settings related to how to numerically solve the equations of the model are found in "Model Configuration Parameters" Cog.

Run Model

To run the simulation, press the green arrow. Be aware there are different modes e.g. 'Normal'. If you are working with hardware the mode will be 'External'.

The textbox is how many seconds you want the simulation to run for.

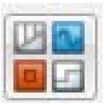
Build Model

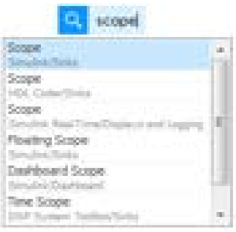
If your model is interacting with hardware, you will need to *build* the model before it can run. The current status is shown in the lower left of the Simulink window.

Working with Blocks

Adding Blocks to Model

There are two ways to add blocks to a model: the **Library Browser** or the **Quick Search**:



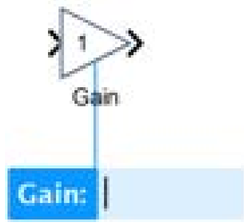


- **Library Browser**
  Shows all blocks available in Simulink, sorted by folders such as ‘Math Operations’ or ‘Signal Routing’. There is a search bar on the top left. Drag blocks from the library straight onto your model canvas.

- **Quick Search**
  Directly search for blocks by single clicking on the background of your model and typing in a search term. Select a block from the search results to quickly add it to your model.

Automatic Block Input Box

When adding a block to a model for the first time, the most common parameter will often pop up automatically for a value to be specified. e.g. *If you add a Gain Block it will ask you to specify the gain value. Interacting with this can save time opening the Block Parameters menu*



Positioning Blocks

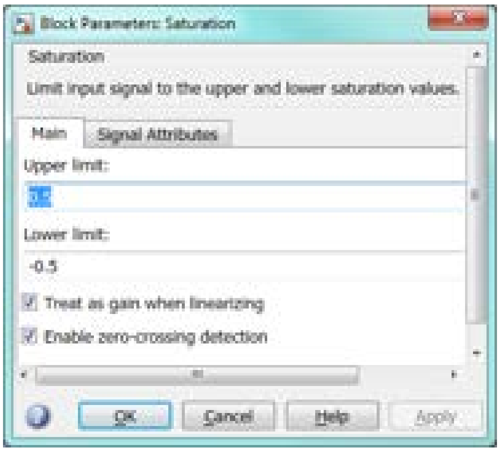
- Blocks can be moved by simply clicking and dragging.
- Connect blocks by clicking **output** of one block and dragging it **to an input** of another block.
- Once a signal connects two blocks, it can be clicked and dragged to be repositioned.
- To create a branch from an existing signal, hold ctrl while clicking and dragging.
- Blocks can be rotated/flipped for better positioning: Right click block, select “Rotate & Flip”.

Overview of Libraries

Library Name	**Type of Blocks**	**Examples of Blocks**
Sources	Provide inputs to your model	Constant, Sine Wave, Step
Sinks	Provide ways to view or export data	Scope, XY Graph, To Workspace
Math Operations	Common mathematical functions to apply to data.	Add, Divide, Abs
Ports & Subsystems	Create different subsystems (resettable, triggered etc)	Subsystem, Enable port, Inputs and Outputs: In1 and Out1
User Defined Functions	Implement custom functions	Fcn, MATLAB Fcn
Lookup Tables	Use functions defined as discrete data	1-D Lookup Table
Signal Routing	Organise signals from blocks	Mux, BusCreator, Goto, Switch
Continuous	Systems with continuous states	Integrator, Derivative
Discrete	Systems with discrete states	Unit Delay, Discrete Derivative
Logical and Bit Operations	Boolean operators for comparisons	Compare To Zero, Logical Operator

Block Settings

Each block has its own settings in **Block Parameters** and **Block Properties**.

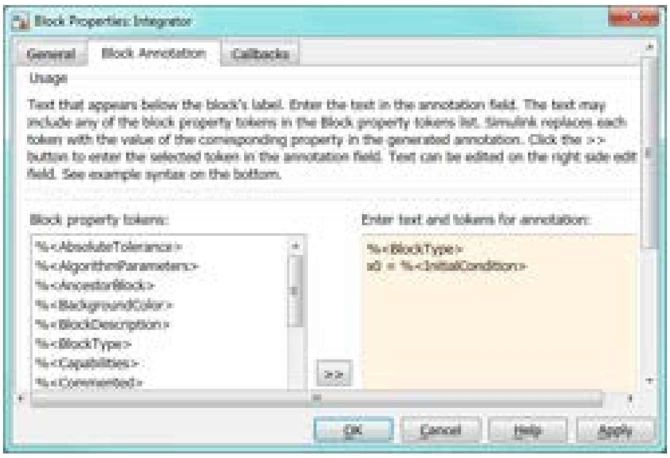


Block Parameters

Double click on a block to open Block Parameters, where you change the settings for that specific block.
e.g. In a Saturation Block, you can set the upper and lower limit.

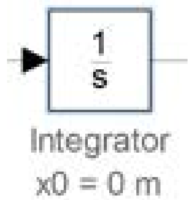
Block Properties

Right click and select "Properties…" to open the Block Properties. This contains settings to do with how the block works as part of the larger model.



You can change what information is displayed about the block in the Block Annotation tab. For properties to be displayed under a block in your model, move properties from the left to the right by using the double arrow (>>). You can also add your own text around the various %< Properties>

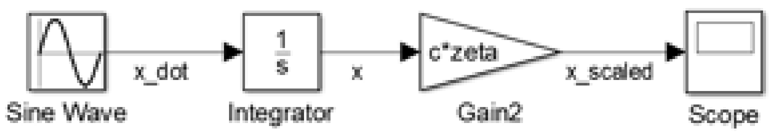
%<BlockType>
x0 = %<InitialCondition> m



The example above shows how to display the block type and initial condition to under an Integration Block.

Simulink Models & MATLAB Variables

Simulink blocks can contain MATLAB variables. These variables need to be defined in the MATLAB workspace before you run the Simulink model, otherwise an error will state there is an undefined function or variable. Below `c` and `zeta`, in the gain block, are defined in the MATLAB workspace.



It is good practice to design a MATLAB script that sets up all the parameters needed in your model. It is easier to change a variable in a script than to open many block parameter menus in Simulink. It allows you to set up loops to run a simulation for many values of `c` for example (see page 17).

Model Annotation

Text and Image Annotation

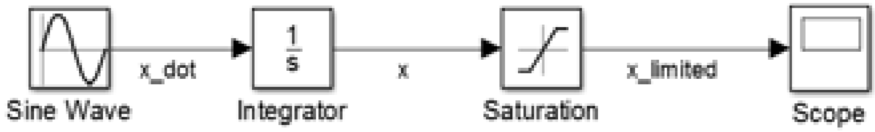
You can double click anywhere on the background of your model and type a comment. Pressing Enter will select the "Create Annotation" option of the quick menu.

You can also use the shortcuts on the left to bring up the **annotation tool**. There are many formatting options. You can insert

- Text and images
- **Greek letters:** use backslash (e.g. \alpha for α).
- TeX typesetting: Right click text box, select Properties… and tick Enable TeX Commands.

Signal Labelling

The lines connected the blocks are called signals. By double-clicking directly on a signal you can label it. This makes it easier to recall what the signals are, gives useful legend labels on scopes and can be used when importing data into MATLAB (see page 17).



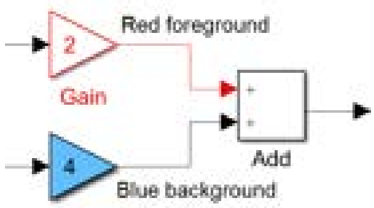
Display Menu – Useful for Debugging Errors

The Display Menu allows you to easily toggle on and off information about your signals.

- **Display > Signals & Ports > Port Data Types**
  Shows you the data type on each signal e.g. double or logical
- **Display > Signals & Ports > Signal Dimensions**
  Shows you the dimensions of each signal e.g. [3 4] vector
  Useful if you have a dimension mismatch error.
- **Display > Sample Time > All**
  Colours each block to show the different sample times, this is particularly useful when you obtain a sample time mismatch error.
- **Display > Signals & Ports > Wide Non-scalar Lines**
  Gives different thicknesses to each signal that is actually a combination of signals. Useful if you have a dimension mismatch error. This visualises Mux and Bus signals (see page 14).

Format Menu – Block Annotation

By right-clicking on any block, you can select the **Format menu** to:



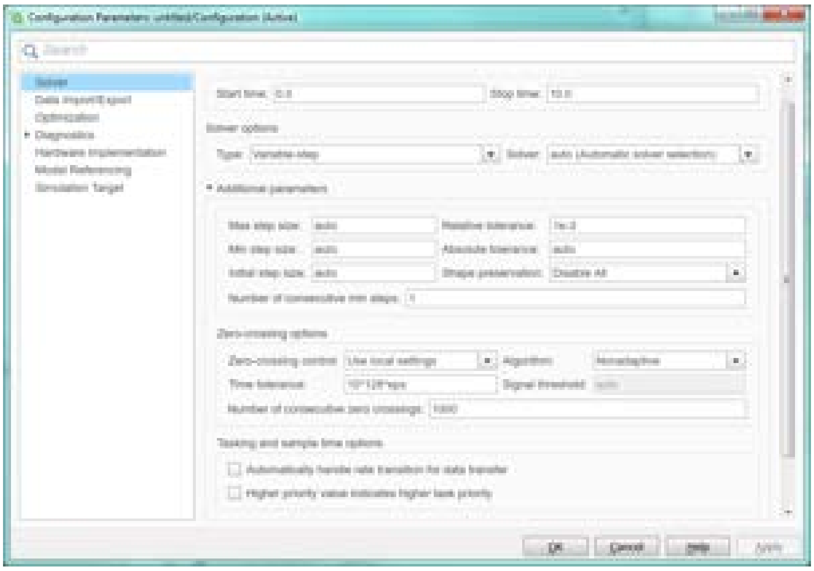
- Show/Hide Block Name
- Add foreground and background colours
- Add shadows to blocks

The Solver

Most of the time, you can just use the default settings to run your model. However you will sometimes find that you will want the model to use smaller steps, or fixed width steps. This is all configurable on the **Solver** page of the **Configuration Parameters**.

From the menu bar on your model select **Simulation ► Model Configuration Parameters**

Or simply use the shortcut on the toolbar 



Once opened, select **Solver**. There are many configurable settings.

- **Start/Stop time:** It is suggested that you leave the start time as zero.
  The stop time is same as in the toolbar at the top of your model.

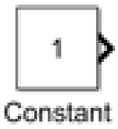
- There are two **types of solver**:
  - A **variable step** solver (the default): This will automatically adjust the step size as the model runs. If you are using variable step generally keep the default solver (**ode45**). Set the **Max step size** to a small fixed value to improve the smoothness of any plots.
  - A **fixed step** solver will be necessary for models with discrete components. If it also has no continuous components, change the solver to *Discrete (no continuous states)* and set the step size to a known value. The fixed solvers are numbered in order of simplicity, **ode1** being the simplest.

- **Zero-crossing options:** Under "Additional Parameters" you will find the Zero-crossing options. Further details about zero-crossing are found on page 27.

For more information about solvers, click on the **Help** button at the bottom of the configuration parameters window, while you are viewing the solver section.

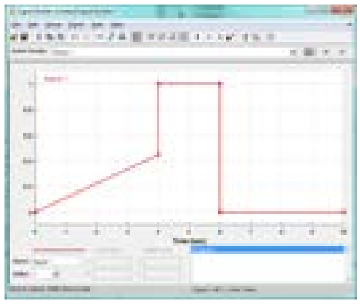
Sources Library

Source blocks provide **different signals** for your model.

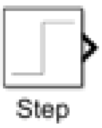


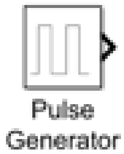
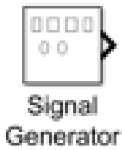
The simplest source is simply a **Constant**.
A block that outputs a constant value.

The **Signal Builder** allows custom signals to be built using a graphical user interface (see right).

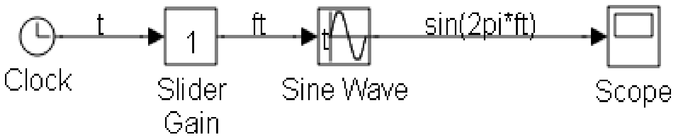


For more typical periodic functions, see the table below with key blocks from this library:

Block	Key Block Parameters
 Sine Wave	• Amplitude and Frequency • Bias and Phase Time can be input as external signal
 Step	• Step Time • Initial Value • Final Value

Block	Key Block Parameters
 Pulse Generator	• Amplitude • Period (seconds) • Pulse Width (% of period) • Phase Delay (seconds)
 Signal Generator	• Waveform: Sine, Square, Sawtooth or Random • Amplitude • Frequency • Units (rad/sec or Hertz)

Assume we want to use the sine wave block to look at the frequency response of a system. Repeatedly editing the block parameters to change the frequency of the sine wave is tedious. The alternative is to use an external time input to the block.

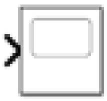


To do this, in the Sine Wave block parameters you set the **Time** parameter to **Use external signal** and set the **frequency** to 2*pi. You then connect a clock to the new input via a slider gain. The slider then sets the frequency of the sine wave.

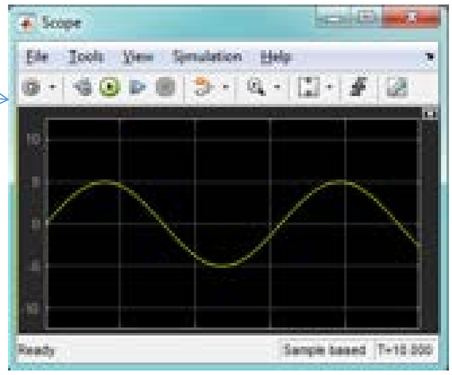
Sinks Library

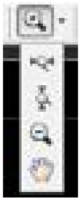
The blocks in this library are mostly used for viewing data from the model.

Scope



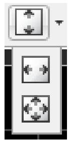
Scope plots **inputs against time**.
It has an extensive toolbar.





The **magnifying glass** icon allows you to zoom in and out in the x and y direction simultaneously and individually.

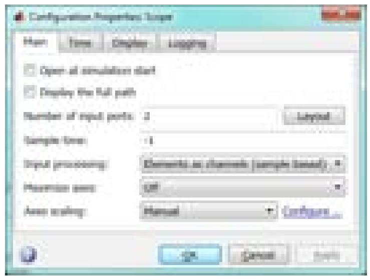
The **hand** allows you to pan or drag the plot around.



The **scaling** icons allow you to automatically scale axes individually or simultaneously in the x and y directions.

The **Cog** icon opens a **Configuration Menu**. This allows you to set the:

- number of input ports
- layout of the plots
- ranges of the axes
- legend
- enable data logging (see below)

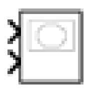


The **Logging Tab** contains a tick box to 'Log data to workspace'. If this is enabled then whenever the simulation is run, a variable is automatically populated in the MATLAB workspace. You can name the variable and set the datatype.

Data Logging without Scope: To Workspace Block

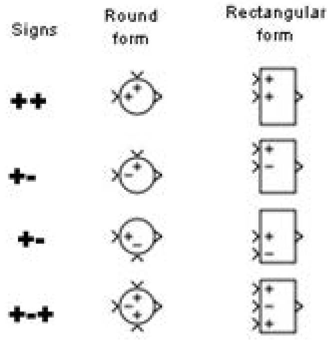
Data can also be sent to the MATLAB workspace using a **To Workspace** block. Any input to the block is sent to the MATLAB workspace after the model has been run. The variable name by default is 'simout' but can be changed along with data type. See page 17 for more details.

Other Blocks in the Sinks Library

 Display	Displays values in a textbox while the simulation is running.
 XY Graph	Plots the top **input X** against lower **input Y** in a figure within Simulink. Cannot easily change the axis labels or titles, so it is better to use the To Workspace block to send data to MATLAB, then plot there.
 STOP Stop Simulation	Halts the simulation

Math Operations Library

The blocks in this library relate to common mathematical functions.

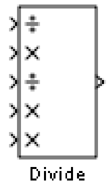


Add, Subtract and Sum Blocks

The **Add**, **Subtract** and **Sum** blocks are all essentially the same. By changing the **Icon shape** and **List of signs** in the block parameter you can convert one into the other (see right).

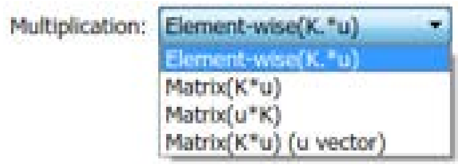
Product and Divide Blocks

The **Product** and **Divide** blocks are also interchangeable. You can use a list of asterisks and forward slashes in the **number of inputs** block parameter to define operations needed *e.g. Block to the right was created by number of inputs =* ***/*/****

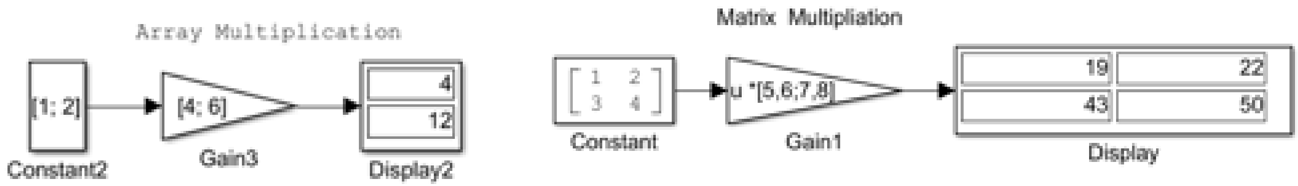


Gain Block

The **Gain** block can be used to multiply a signal by a constant value. You must configure the Block Parameters to perform matrix or element-wise (array) multiplication.



Array and Matrix Multiplication:

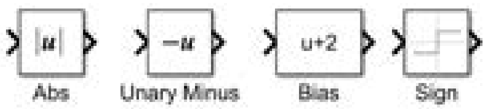


Array multiplication with column vector $K = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$ *and Matrix multiplication where* $K = \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix}$

Both examples have Gain block configured to do Matrix(u*K) multiplication. For a Gain block to contain a matrix or vector, simply use MATLAB notation. For example $\begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix}$ is entered as [5, 6; 7, 8] – commas separate row elements and semi colons separate columns.

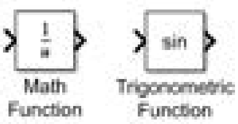
Mathematical Functions

There are lots of blocks for **specific mathematical functions**:



The **Abs** block finds the magnitude or absolute value of a signal, the **Unary Minus** block negates a signal and the **Bias** block adds a constant to a signal. The **Sign** block outputs +/- 1 depending on the sign of the input.

There are also blocks **with multiple functions to choose from**:



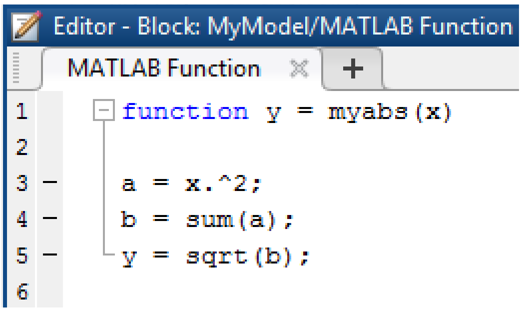
The **Math Function** block can perform many different functions: square, square root, log, reciprocal etc. A block parameter allows you to select which particular function you want. The **Trigonometric Function** block operates in a similar manner but for cos, sin, $\tan^{-1}$ etc.

User Defined Functions & Lookup Tables

User Defined Functions

Sometimes you cannot find the exact function that you want. If this is the case, then try the block called **Fcn**. This allows you to enter a mathematical expression using a restricted set of operators and functions:

To see what is allowed, click on the Help in the block parameters. If you need something a bit more complicated then you can write your own MATLAB function and use the block **MATLAB Fcn**:



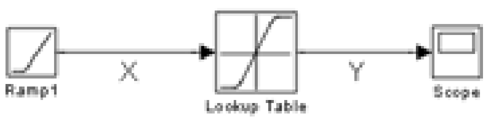
This block has been configured to call the MATLAB function myabs, shown left. *x* is the input and *y* is the output.

Notice that the MATLAB function is not stored as a .m file in the working directory, instead you are editing code stored within the block itself. This can be seen from *Block: MyModel/MATLAB Function.*

If you are using Simulink to create a program using the Real Time Workshop, then you will need to use the Embedded Matlab Function or an S Function. S functions are used to embedded Matlab, C or Fortran into your model.

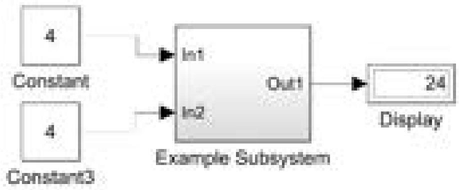
Look Up Tables

If all else fails, then you can use a look up table to define your function.



You need two vectors to do this. A vector of input values and a vector containing the table of corresponding output values. You enter these in to the appropriate block parameter. For intermediate values, the output is calculated using interpolation. Extrapolation is used to calculate values beyond the specified input range. There are a range of look up tables to suit different needs (e.g. 1-D Lookup Table, 2-D Lookup Table), see the documentation for further details.

Ports & Subsystems



A subsystems is a collection of blocks grouped together to carry out a particular task. They help to keep models organised and easier to understand. The example subsystem on right takes two inputs. It doubles the first input, quadruples the second input and outputs the sum.

Creating a Subsystem

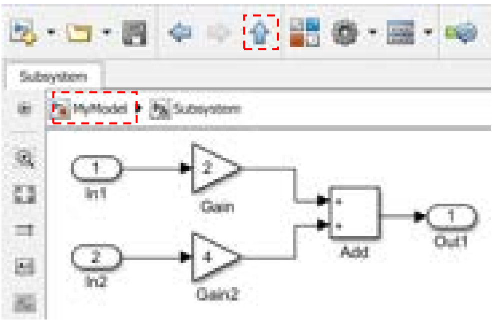
- Drag in a **Subsystem block** from the Ports and Subsystems library

OR

- Select the blocks that you want to put into a subsystems and right click then select **Create Subsystem from Selection** in the menu that appears**.**

You can have many nested subsystem (i.e. a subsystem in a subsystem).

Once you have a subsystem, you can open it by **double clicking** the block. This opens a new tab showing the blocks of the subsystem. Exit the subsystem and return to the top page by:



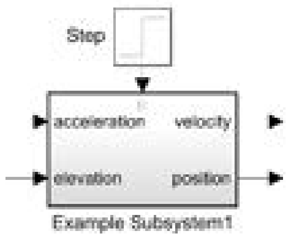
- Selecting the **'Up to Parent' arrow** 

OR

- Selecting the home tab, e.g. 'MyModel'

Input and output ports are called **In** and **Out**. If you need extra input/output ports, they can be found in the Ports and Subsystems library or the relevant Source / Sink library.

Trigger, Reset and Enable Inputs to Subsystems



You may need a part of your model to only occur when an appropriate signal is applied, or for blocks to reset at certain time intervals. For this you place an **Enable**, **Trigger** or **Reset** block inside the subsystem. These will create an appropriate input port on the subsystem.

There is extensive documentation on the MathWorks website giving comparisons of each of these subsystems. A summary is given below:

Enabled Subsystems: Subsystem only runs when signal is 1 through the enable input, a 0 will disable it. The block parameters of the output ports allow configuration to either hold the current value or reset to a specified value when the subsystem is disabled.

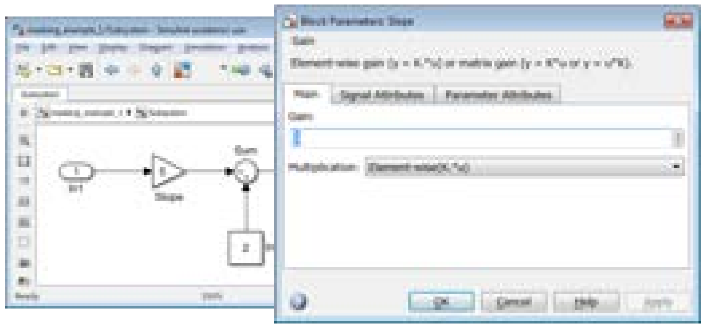
Triggered Subsystems: Executes one step each time the appropriate signal is applied to the trigger input. You can configure the trigger input to react to a rising edge, a falling edge or both edges.

Resettable Subsystems: Executes at every time step but conditionally resets the states of blocks within it to their initial conditions when a trigger event occurs at the reset port.

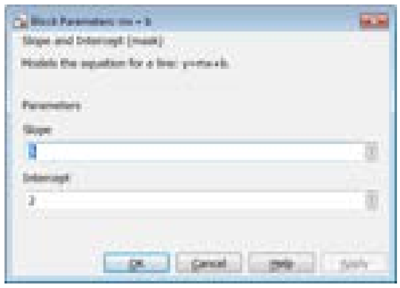
Masked Subsystems

A **mask** is special type of subsystem. It offers a custom interface for a subsystem and hides the content, making it appear as a built in ‘base’ block with **its own icon and custom parameter dialog box**. It simplifies the graphical appearance of a model and controls access to the block content.

Consider an example subsystem below which simply produces a straight line $y = mx + c$ where x is the simulation time steps and m and c are defined by Gain and Constant blocks respectively. To edit m and c you would normally have to open the subsystem, and interact with each of the block parameters (this involved multiple windows and clicks).



If we instead turn this subsystem into a **mask** (right click -> Mask -> Create Mask) then we could create a custom dialog block. Whenever we click on this new masked susbsytem, we would get ***one*** dialog box where we can conveniently set m and c.



For information on creating your own masks, see this video:
https://uk.mathworks.com/videos/creating-a-mask--masking-fundamentals-1480968643715.html

Program Control: For, While, If and Case

Within the Ports and Subsystems library, you will see subsystems that perform the Simulink equivalent of **For** and **While** loops and **If** and **Case** statements. The **For** and **While** loops will perform a number of loops for each step of the simulation. They each contain a control block that allows you to configure how many loops are performed. It takes two sorts of block to implement an **If** statement:

- The **If** block itself is used to perform the test that determines what is going to happen. It produces two control signals: one for true the other for false.
- The control signals go to **If Action** subsystems. You put the blocks required for each condition into the appropriate Action subsystem.

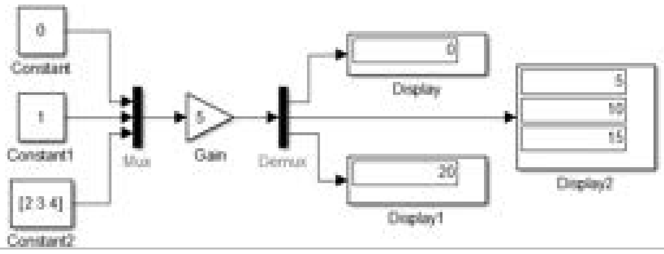
The case statement is performed in a similar way. There are two different blocks. The **Case** block itself determines which of the **Case Action** subsystems to perform.

Signal Routing & Logicals

Mux & Demux : Group signals of <u>same</u> type

A **mux** block **groups multiple signals of the same type.** In Block Parameters you specify the **Number of Inputs** to group**.** You can feed a mux output directly into a mathematical block so that the block will operate on all signals at once.

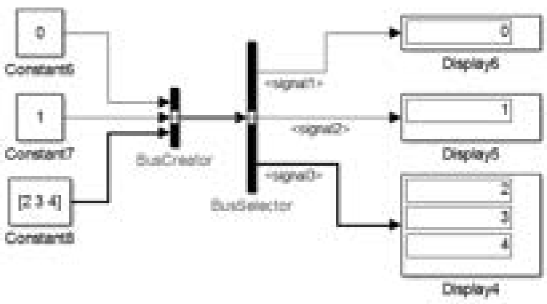
A **demux** block **separates out individual signals**. Specify the **Number of Outputs** in block parameters - this can be a single integer or a vector. Each number in the vector specifies the number of signals in a particular output.



Example: A **mux** groups 3 signals and multiplies them all by a gain 5. The **demux**, with Number of Outputs = [1 3 1], separates the signals into 3 outputs: The first and last outputs are single wires, and the middle output is a mux group with 3 signals.

Buses : Grouping signals of different types

A **bus** is like cable tidy: a convenient way keeping things organised and not having a lots of wires running everywhere.

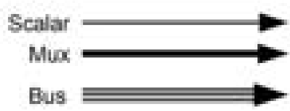


Buses contain **signals of <u>different</u> types and sizes**. That means that it is **not** always possible to feed a bus into a mathematical block.

Create bus signals using the **BusCreator** block (analogous to Mux). Unpack bus signals using **BusSelector** (analogous to demux).

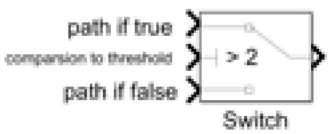
To overcome possible dimension mismatch errors created by using buses and mux blocks in the same model, it is helpful to visualise Mux and Bus signals. To give a different style to each signal type set:

Display > Signals & Ports > Wide Nonscalar Lines



Switches

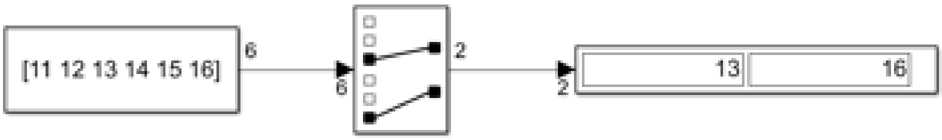
The simplest is the **Manual Switch**.
A user double clicks the block to divert the signal between two paths.



The output of the **Switch** block is determined by the centre pin. A comparison is carried out between the centre input and a threshold value. You can select the threshold value and for the comparison to be $\geq, \leq, =$, etc. If the comparison is true, the output is switch to the top input, else the output is connected to the bottom input.

Selectors : Accessing specific signals

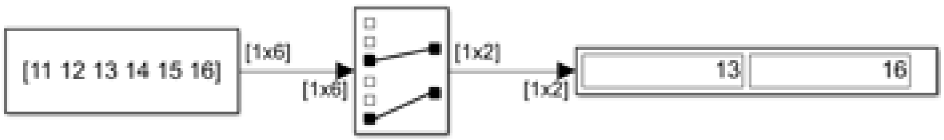
In MATLAB to access the 3rd and 6th elements of a vector, **V** say, we would use index notation: **V([3 6])**. Selectors are the Simulink equivalent of these indices in MATLAB:



Constant source with "Interpret vector parameters as 1-D" option checked

The selector above has been configured to extract the 3rd and the 6th element of the input vector. This has been done by setting: Number of Inputs = 6 and Index Vector = [3 6]. You can also configure selectors so that the Index Vector is obtained via an external input (select “Index Vector (port)” in the drop down menu).

Selectors will also work higher dimensional arrays. It is important to note the dimensions of the quantities you are working with. Untick the box in the Selector Block Parameters “Interpret vector as 1-D” to change how the constant is interpreted. By setting Display > Signals & Ports > Signal Dimensions to *on*, we now see that the constant has been interpreted as a 2-D vector.



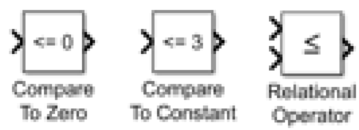
Constant source with "Interpret vector parameters as 1-D" option ***not*** checked;

Goto / From Blocks : Move signals without connecting wires

Another way to move signals around is to use **Goto** and **From** blocks. Send a signal to a **Goto** block, where it is given a unique tag. Then a **From** block can be configured to use this same tag and access the signal. A simple example is given below. These blocks can be used to avoid complex signals crossing, and even work to get signals out of subsystems.

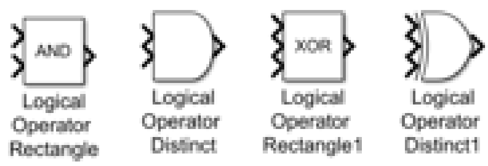
Compare To…

These blocks compare a signal with either zero, a constant or another signal. The particular operation (greater than, equals to etc) is selected by a block parameter. The output is a Boolean.



Logic Operator

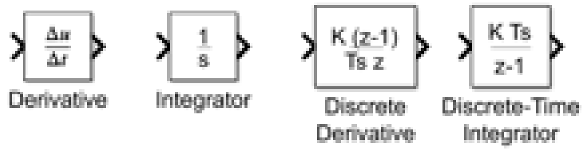
The **Logical Operator** block carries out the same operation as a Boolean logic gate. The logic operation e.g. AND, OR, NOT etc is selected from block parameters.



The first two blocks (above) are AND blocks with different block parameter settings. The first has default rectangular icon shape, the second has the icon shape set to distinctive. The last two are XOR with three inputs (rectangular and distinctive shape).

Integration and Differentiation

There are continuous and discrete integrator and derivative blocks.



Continuous Integrator

There are various ways of configuring integrators with extra functionality using block parameters:

- By default, the Initial Condition is set within the block, however it can be set as a block input. (set *Initial Condition Source* to *External*)
- Limit the output to a maximum and minimum value (tick *Limit Output*, adds saturation icon to block).
- You can add an external reset signal, to force the output of the integrator back to its initial condition. You can configure the reset pin to act on a rising edge, falling edge or both.

Discrete Integrator

For the discrete integrator block, you can specify whether to use forward or backward Euler, or the Trapezoidal method. As with the continuous integrator block you can specify in the block parameters if you want to define initial conditions externally or internally, set upper and lower limits and set up a reset condition. You can also define an input gain value.

Continuous Derivative

The **derivative** block approximates the derivative of the input signal u with respect to the time t, by computing a numerical difference. Here Δu is the change in input value and Δt is the change in time since the previous simulation (major) time step:

$$y(T_{current}) = \frac{\Delta u}{\Delta t} = \frac{u(T_{current}) - u(T_{previous})}{T_{current} - T_{previous}}$$

The initial output for the block is zero.

Discrete Derivative

The discrete derivative block computes an optionally scaled discrete time derivative with output:

$$y(T_{current}) = \frac{Ku(T_{current})}{T_s} - \frac{Ku(T_{previous})}{T_s}$$

where T_s is the fixed simulation time step.

Note on accuracy of derivatives: It is best practice to structure your models to use Integrators instead of Derivative blocks, as Integrator blocks have states that allow solvers to adjust step size and improve accuracy of the simulation. The derivative block output might be very sensitive to the dynamics of the entire model. The accuracy of the output signal depends on the size of the time steps taken in the simulation. Smaller steps allow a smoother and more accurate output, however unlike with blocks that have continuous states, the solver does not take smaller steps when the input to this block changes rapidly.

MATLAB & Simulink Working Together

While Simulink is useful for modelling and visualising processes such as feedback loops, detailed data analysis and generation of good quality figures is still best completed within MATLAB. You can run Simulink models and export the results to MATLAB or run Simulink models from MATLAB.

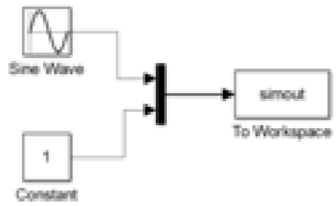
Exporting Simulink Data to MATLAB

There are multiple ways to get data from a Simulink to MATAB:

- **Scope Block:** You can enabling data logging from a Scope block within the Configuration Menu Logging tab (see page 9).

- **To Workspace block:** Once this block is used in your model, each time you run your model two variables are created in the MATLAB workspace:
  `tout` – column vector of time steps
  `simout` – variable storing simulation data

  Use a Mux if you need more than one output.



The simulation data can be of type *timeseries*, *array* or *structure*, as set in 'Save Format' in Block Parameters. Accessing your data in MATLAB depends on the variable type you set.
After running the simulation command above, you can define the vector of time steps as:

```
t = s.get('tout')
```

and the columns of signal data as:

`y = s.get('simout')`	if 'Save Format' is **array**
`y = s.get('simout').Data`	if 'Save Format' is **structure**
`y = s.get('simout').signals.values`	if 'Save Format' is **timeseries**

Running Simulations from MATLAB

You can also run your Simulink models using commands from MATLAB. The most basic way is to use the `sim` command with two outputs and one input (the model file name as a string):

```
[t,y]=sim('model')
```

where `t` is a column vector of time steps and `y` is a corresponding matrix with columns of signal data. The **sim** command can also be used with other inputs that allow the control of simulation run time for example, but only one output must be assigned. The extra inputs are known as 'name-valued pairs' as a condition is specified and then the value set. For example:

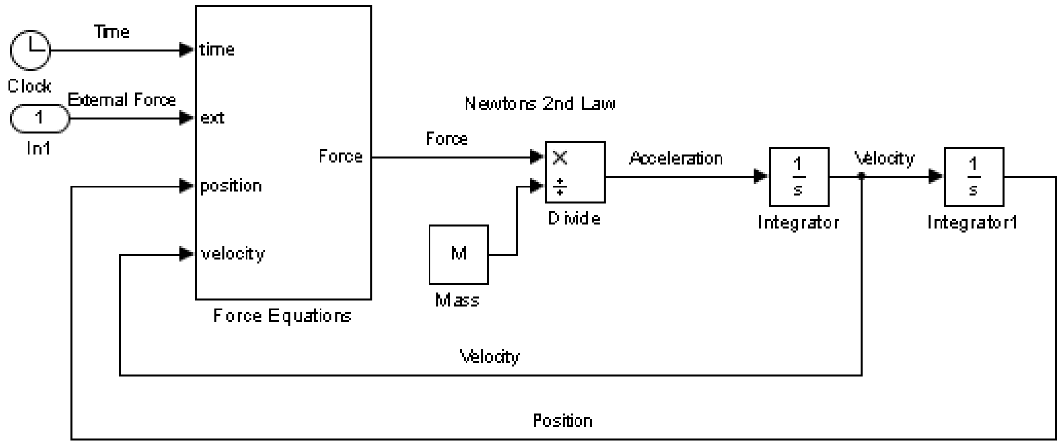
```
s = sim('model','StopTime','10','MaxStep','0.1')
```

When using a single output, the Simulink model must also be set up to export data in some way, otherwise s will only give a vector of timesteps. This can be done by adding a 'To Workspace' Block, as described above, or adding Output Ports to the Simulink model.

Examples Models

The following examples will hopefully give ideas for the best way to lay out models. While there is no right or wrong way, always prioritise readability.

Example 1: Dynamic Systems



The above shows the general approach to modelling dynamic systems. You calculate the force, use Newton's 2^{nd} law to calculate the acceleration, integrate to get the velocity and then integrate again to obtain the position.

The above model is a general guide, it can get a bit more complicated. For example, the mass is required to calculate gravitational forces. It is also possible that the mass will be a function. For example, a rocket losses most of its mass as the fuel is burnt off.

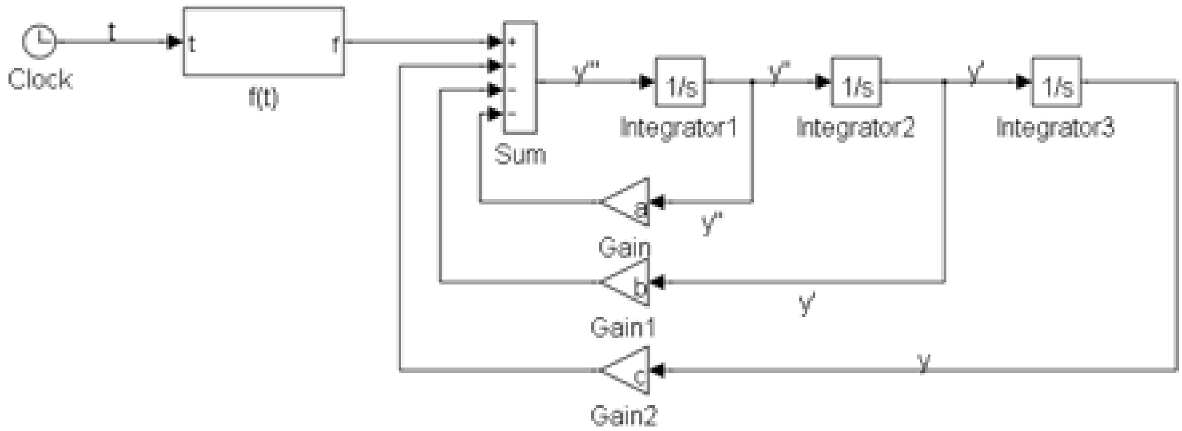
Example 2: Ordinary Differential Equations (ODE)

The general rule for solving differential equations is to write the equation in terms of the highest differential. For example, consider the general second order equation below.

$$\dddot{y} + a\ddot{y} + b\dot{y} + cy = f(t) \tag{1}$$

$$\dddot{y} = f(t) - a\ddot{y} - b\dot{y} - cy$$

You then use integrators to obtain lower terms:

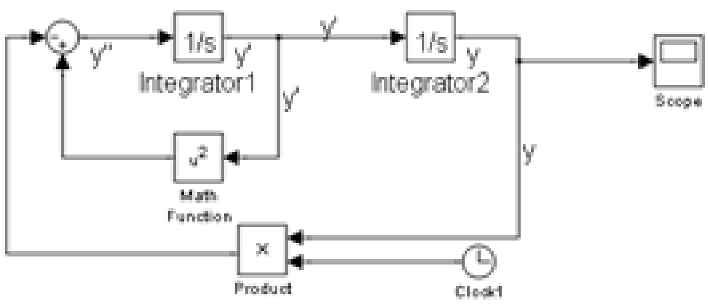


The right hand side of the equations is formed by feeding back these terms to form the expression required.

Notice that the model contains no differentiators, even though we are modelling a differential equation. Models with differentiators tend to produce a lot of noise, so are avoided if possible.

The next example is not linear or time invariant:

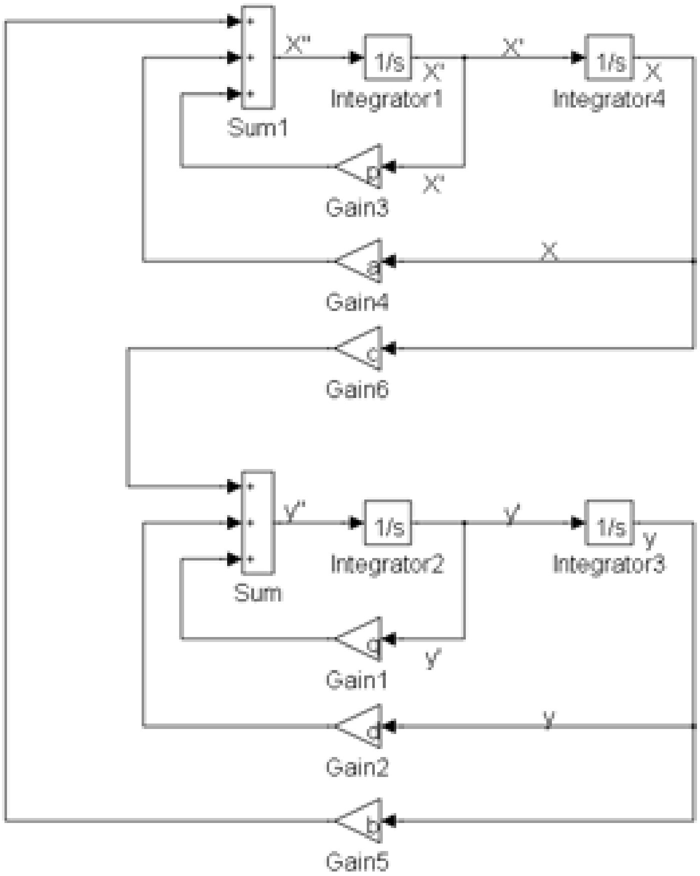
$$\ddot{y} = \dot{y}^2 - ty \tag{2}$$



Example 3: Simultaneous Ordinary Differential Equations

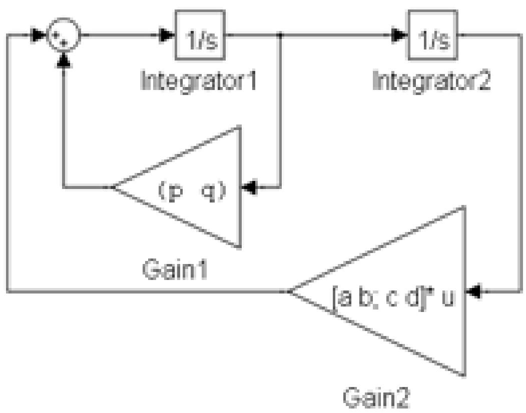
Of course Simulink is not limited to equations in one variable.
Consider the simultaneous equation below:

$$\begin{aligned} \ddot{x} &= p\dot{x} + ax + by \\ \ddot{y} &= q\dot{y} + cx + dy \end{aligned} \tag{3}$$



This can be simplified by using matrices:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} p\dot{x} \\ q\dot{y} \end{bmatrix} + \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{4}$$



Example 4: Linear Systems

Many systems can be modelled by linear, time invariant (LTI) differential equations, such as equation 5 below.

$$a_3\dddot{y} + a_2\ddot{y} + a_1\dot{y} + a_0 y = b_2\ddot{x} + b_1\dot{x} + b_0 x \tag{5}$$

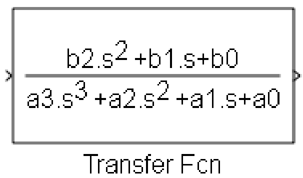
where *y* is the output and *x* the input.

LTI systems can be represented by a transfer function:

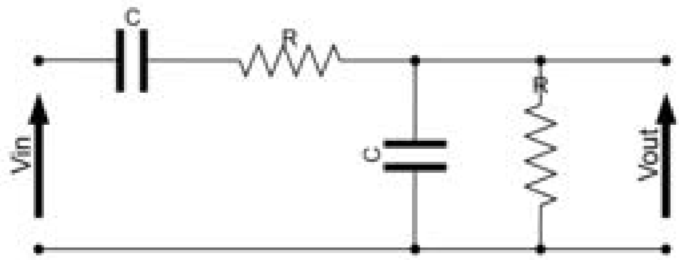
$$H(s) = \frac{Y(s)}{X(s)} = \frac{b_2 s^2 + b_1 s + b_0}{a_3 s^3 + a_2 s^2 + a_1 s + a_0}$$

$$H(j\omega) = \frac{b_2 (j\omega)^2 + j\omega b_1 + b_0}{a_3 (j\omega)^3 + a_2 (j\omega)^2 + j\omega a_1 + a_0}$$

It is the convention in MATLAB to represent polynomial expressions with row vectors of the coefficients. So the numerator of the above transfer function is represented by [b_2 b_1 b_0] and the denominator by [a_3 a_2 a_1 a_0]. Entering these two vectors to the appropriate block parameters of a transfer function block will produce the following block:

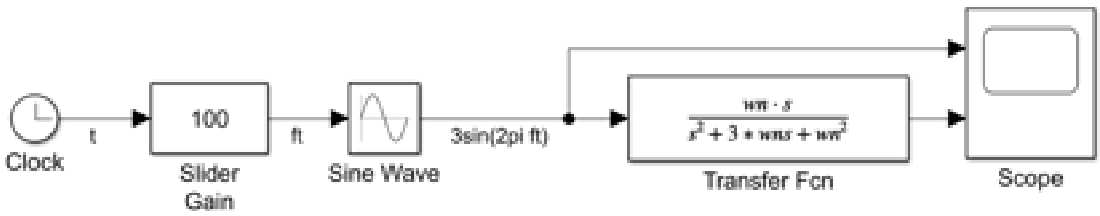


LTI transfer functions are used extensively in electronics to represent idealized electronic circuits. Take for example this circuit and its transfer function representation below:



$$H(s) = \frac{Vout(s)}{Vin(s)} = \frac{s\omega_n}{s^2 + 3s\omega_n + \omega_n^2} \tag{6}$$

The following model can be used to observe the behaviour in Simulink:



In the Transfer Function block parameters values are set with `wn` being a predefined variable in the MATLAB workspace: **numerator** = `[wn 0]` and **denominator** = `[1 3*wn wn^2]`

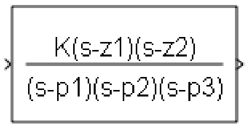
Poles and Zeros

An alternative way of representing a transfer functions is to use the pole-zero description. If you solve the numerator polynomial you get the zeros. So called because the transfer function is zero at that value. If you solve the denominator polynomial, you get the poles. They are called poles because if you plot the absolute value of a transfer function, it looks a bit like a tent, with the poles being the location of the tent poles.

The transfer function from the circuit example can then be represented in its pole zero form:

$$H(s) = K\frac{(s-z_1)(s-z_2)}{(s-p_1)(s-p_2)(s-p_3)} \tag{7}$$

Where p_i is a pole and z_i is a zero and K is a constant.
You can model the transfer function in this form using a zero-pole block:



Zero-Pole

To configure this block you provide a vector for the numerator and the denominator. In this case the numerator is [***z1 z2***] and the denominator is [***p1 p2 p3***] and the gain is ***K***.

Useful MATLAB functions:

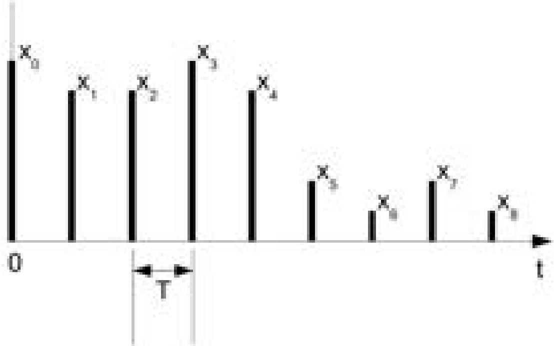
- The MATLAB function **`roots`** will solve a polynomial, given the coefficients of the polynomial. The function **`poly`** does the opposite. Given the roots of a polynomial, it will return the coefficients of the polynomial.

- The Signal Processing toolbox provides a number of functions to provide the coefficients required to implement various filters. See help for butter, cheby1, cheby2 and besself.

- The function **`freqs(B,A)`** will plot the frequency response of a system, where **`B`** is a vector of the numerator coefficients and **`A`** is a vector of the denominator coefficients.

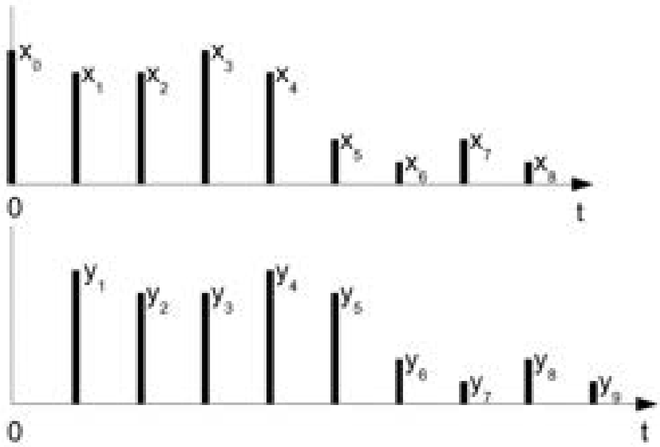
Example 5: Modelling Discrete Systems

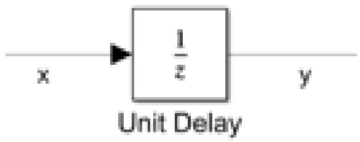
A discrete signal has values only at discrete points in time. A sampled signal is always discrete. The sample period, **T**, is the time between two successive samples and sample frequency, f_s, is $1/T$.



You will need to set the Sample Time in Block Parameters for many of the blocks in the discrete library. Most blocks use '-1' which is simply the inherited value from the model. Unfortunately, inherited sample time does not work for discrete models. If you find that you model is sampling at one second, regardless of the solver settings, then check the sample time of your blocks.

The fundamental component of a discrete system is a Unit delay. This delays the signal by one time period. In general, $y_n = x_{n-1}$, as seen in the example below.



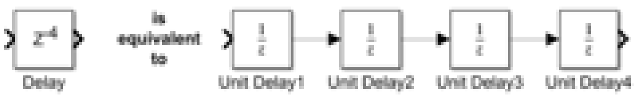


The Z transform replaces each delay by one sample with a multiplication by $\mathbf{z}^{-1}$:

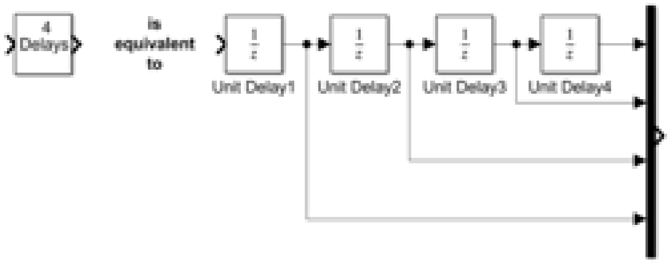
$$Y(z) = z^{-1}X(z)$$

$$H(z) = \frac{Y(z)}{X(z)} = \frac{1}{z}$$

There are other blocks in the discrete library that contain combinations of unit delays.



You can also use the Tapped Delay block:



Discrete Transfer Functions

Continuous systems are described by differential equations, discrete systems are described by recurrence equation. Equation 8 below is a typical recurrence equation:

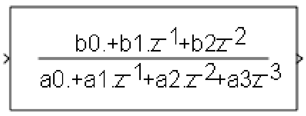
$$a_0 y_n + a_1 y_{n-1} + a_2 y_{n-2} + a_3 y_{n-3} = b_o x_n + b_1 x_{n-1} + b_2 x_{n-2} \tag{8}$$

where x is the input and y the output. Each unit delay is replace by $\mathbf{z}^{-1}$ in the Z transform.

$$(a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3})Y(z) = (b_o + b_1 z^{-1} + b_2 z^{-2})X(z)$$

$$H(z) = \frac{Y(z)}{X(z)} = \frac{b_o + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3}} \tag{9}$$

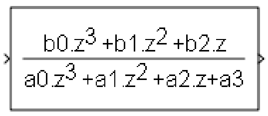
which is the transfer function of a digital filter and is **defined in terms of $\mathbf{z}^{-1}$.** This can be represented in a Simulink model by the **discrete filter block**.



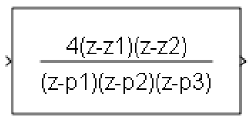
Discrete Filter

This block was produced by setting:
numerator = [**b0 b1 b2**] and **denominator** = [**a0 a1 a2 a3**]
in the block parameters.
Do not forget to set the sample time too.

An alternative form is to write the **transfer function in terms of z**. If we multiply top and bottom of equation 9 by $\mathbf{z}^3$ we get equation (10). You can represent this with the Transfer Function block or if you have the poles and zeros, the Zero-Pole block.



Discrete
Transfer Fcn



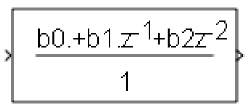
Discrete
Zero-Pole

$$H(z) = \frac{b_o z^3 + b_1 z^2 + b_2 z}{a_0 z^3 + a_1 z^2 + a_2 z^1 + a_3} \tag{10}$$

Finite Impulse Response (FIR) digital filters do not have any poles. The recurrence equation:

$$y_n = b_o x_n + b_1 x_{n-1} + b_2 x_{n-2} \tag{11}$$

gives the following Z transform and can be represented by the block especially for FIR filters:



Discrete FIR Filter

$$Y(z) = (b_o + b_1 z^{-1} + b_2 z^{-2})X(z)$$

$$H(z) = \frac{Y(z)}{X(z)} = b_o + b_1 z^{-1} + b_2 z^{-2} \tag{12}$$

Simulink Shortcuts

This section contains the short cut keys that can be used to build and edit your model.
For more details select from the model menu bar **Help ► Keyboard Shortcuts**

OBJECT SELECTION SHORTCUTS	
Select an object	Click
Select more objects	**Shift**+click
Select all objects	Ctrl+A
Copy object	Drag with right mouse button **Ctrl**+drag
Delete selected object	Delete *or* Backspace
Cut	Ctrl+X
Paste	Ctrl+V
Undo	Ctrl+Z
Redo	Ctrl+Y

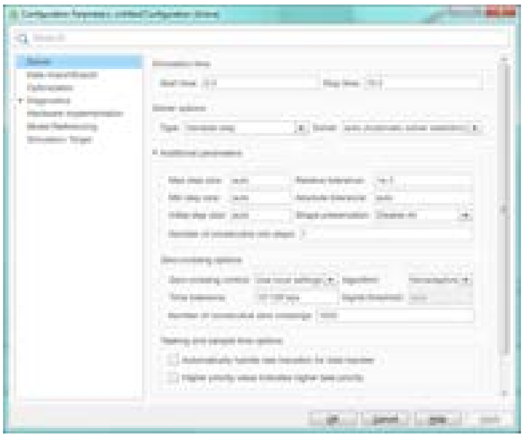
BLOCK SHORTCUTS	
Search for blocks	Click and type
Add text to model	Double click and type
Move block	Drag *or* Arrow keys
Resize block	Drag handles in corners
Resize block, keeping same ratio of width and height	**Shift** + drag handle
Resize block from the center	**Ctrl** + drag handle
Rotate block counterclockwise	Ctrl + Shift + R
Flip block	Ctrl+I
Rotate block clockwise	Ctrl+R
Rotate block counterclockwise	Ctrl+Shift+R
Connect blocks	Drag from port to port
	Select first block, **Ctrl**+click second block
Draw branch line	**Ctrl**+drag line Right-mouse button+drag
Create subsystem from selected blocks	Ctrl+G
Open selected subsystem	**Enter** *or* Double click
Go to parent of selected subsystem	Esc

SIMULATION SHORTCUTS	
Open Configuration Parameters dialog box	Ctrl+E
Update diagram	Ctrl+D
Start simulation	Ctrl+T
Stop simulation	Ctrl+Shift+T
Build model (for code generation)	Ctrl+B

SIGNALS SHORTCUTS	
Name a signal line	Double-click signal and type name
Delete signal label and name	Delete characters in label or delete name in Signal Properties dialog box.
Delete signal label only	Right-click label and select **Delete Label**.
Open signal label text box for edit	Double-click signal line Click label
Move signal label	Drag label to a new location on same signal line
Copy signal label	**Ctrl**+drag signal label
Change the label font	Select the signal line (not the label) and use **Diagram** > **Format** > **Font Style**

ZOOMING SHORTCUTS	
Zoom in	Ctrl + +
Zoom out	Ctrl + -
Zoom to normal (100%)	Ctrl + 0 or Alt + 1
Zoom with mouse	**Ctrl** + scroll wheel
Zoom in on object	Drag the **Zoom** button  from the palette to the object
Fit diagram to screen	Spacebar
Scroll view	Arrow keys *or* **Shift** + arrow for larger pans
Scroll with mouse	Spacebar + drag Hold the scroll wheel down and drag the mouse

The Solver: Zero-Crossing Options



A variable-step solver dynamically adjusts the time step size, causing it to increase when a variable is changing slowly and to decrease when the variable changes rapidly. This behaviour causes the solver to take many small steps in near a discontinuity because the variable is rapidly changing in this region. This improves accuracy but can lead to excessive simulation times.

Simulink uses a technique known as zero-crossing detection to accurately locate a discontinuity without resorting to tiny time steps. Usually this technique improves simulation run time, but it can cause some simulations to halt before the intended completion time. Understanding how Simulink's zero-crossing detection algorithms, adaptive and non-adaptive, work is beyond the scope of the course.

The table below should help you overcome some errors associated with zero-crossing, particularly a halting model. Implementing most of the changes, involves using the **Model Configuration Parameters dialog (MCP) box**, accessed via the Cog symbol. 

Possible Change...	How to make this change...	Rationale for making this change...
Increase the number of allowed zero crossings	Increase the **Number of consecutive zero crossings** on the **Solver** pane in the MCP box.	This may give your model enough time to resolve the zero crossing.
Disable zero-crossing detection for a specific block	First, clear the **Enable zero-crossing detection** check box on the block's parameter dialog box. Then, select Use local settings from the **Zero-crossing control** pull down on the **Solver** pane of the MCP box.	Locally disabling zero-crossing detection prevents a specific block from stopping the simulation because of excessive consecutive zero crossings. All other blocks continue to benefit from the increased accuracy that zero-crossing detection provides.
Disable zero-crossing detection for the entire model	Select Disable all from the **Zero-crossing control** pull down on the **Solver** pane of the MCP box.	This prevents zero crossings from being detected anywhere in your model.
Reduce the maximum step size	Enter a value for the Max step size option on the **Solver** pane of the MCP box.	This can insure the solver takes steps small enough to resolve the zero crossing. However, reducing the step size can increase simulation time, and is seldom necessary when using the Adaptive algorithm.
Use the Adaptive Algorithm	Select **Adaptive** from the **Algorithm** pull down on the **Solver** pane in the MCP box.	This algorithm dynamically adjusts the zero-crossing threshold, which improves accuracy and reduces the number of consecutive zero crossings detected. You can now specify **Time tolerance** and **Signal threshold**.
Relax the Signal threshold	Select **Adaptive** from the **Algorithm** pull down and increase the value of the **Signal threshold** option on the **Solver** pane in the MCP box.	The solver requires less time to precisely locate the zero crossing. This can reduce simulation time and eliminate an excessive number of consecutive zero-crossing errors. However, relaxing the **Signal threshold** may reduce accuracy.

Simulink Online Documentation

The full Simulink documentation is available from the help menu. You can obtain this from the MATLAB help, or you can go directly to the Simulink help. From the model menu bar select

Help ► Simulink ► Simulink Help

Block Documentation

The easiest way of obtaining the documentation for a particular block is to hit the help button in the block parameters. An alternative is to select the block and then select

Help ► Simulink ► Blocks & Blocksets Reference

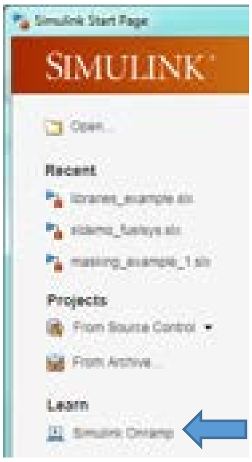
from the model menu bar. If no block is selected when you do this, then you will be given a list of all the blocks. You can then select the documentation you want from this list. At the top of the list, on the right hand side you can choose to display by Category or in Alphabetic order.

In the Help Menu you will also find links to Web Resources

Help ► Web Resources

Particularly useful MATLAB Central which is the hub for the online MATLAB and Simulink community. Here you will find “MATLAB Answers” where people ask for support on MATLAB & Simulink. Once you become confident with MATLAB and Simulink you may wish to explore the File Exchange, where people upload custom files.

Further Examples



Simulink Onramp

In MATLAB 2018b, you can complete the Simulink Onramp course created by MathWorks. It is around 3 hours of good quality content designed to introduce you to Simulink. It will give you more practice at a similar level to the exercises in this course.
You can access this by installing MATLAB 2018b (see instructions on final pages of notes) and then downloading a toolbox available at

bit.ly/SimulinkOnRamp

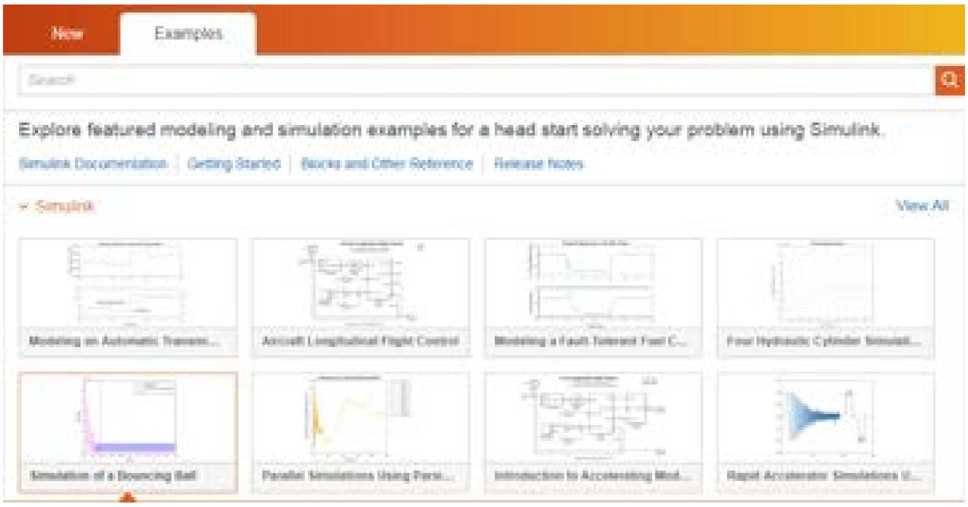
OR

https://uk.mathworks.com/matlabcentral/fileexchange/69056-simulink-onramp

Once installed, restart MATLAB, launch Simulink and click the link under **Learn**

Explore Simulink Examples

Use the Examples Tab to explore different Simulink models
(File > New > Model…)



There is even a bouncing ball example so you can see a different approach to one you might have taken in the final exercise.

Experiment with Simulink Dashboard Blocks

Open the Fuel System Demo with the command:

```
open_system([matlabroot '\toolbox\simulink\simdemos\automotive\fuelsys\sldemo_fuelsys'])
```

Read through the documentation, so that you understand how the model works:
https://uk.mathworks.com/help/simulink/ug/tune-and-visualize-your-model-with-dashboard-blocks.html

Explore the blocks by double clicking them to get a better understanding of how they work.
Follow the instructions in the section **Tune Parameters During Simulation** to try editting the model.

Oxford University MATLAB Installation

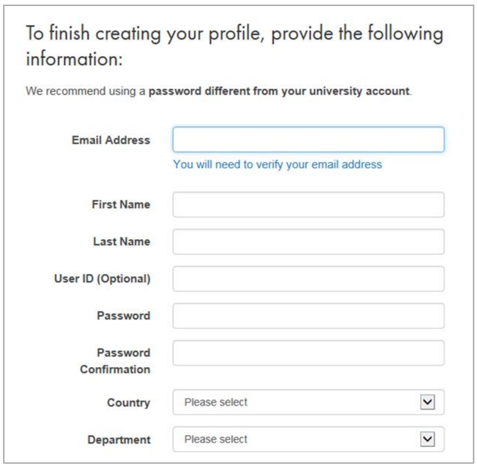
1. VISIT UNIQUE WEB ADDRESS

To install MATLAB onto your computer, go to the web page http://bit.ly/OxUniMatlab OR https://www.mathworks.com/login/identity/university?entityId=https://registry.shibboleth.ox.ac.uk/idp

Use your University of Oxford, single sign-on username and password.

2. CREATE UNIVERSITY LINKED MATHWORKS ACCOUNT

Then click on **Create** to make **a MathWorks Account:**



To register to use MATLAB, you need an Oxford University e-mail address such as firstname.lastname@eng.ox.ac.uk.

Fill in the rest of the form. The system will send you an e-mail, with a link you must click to verify.

You can access your e-mail at https://outlook.office.com/owa/

Now you can access many resources:
e.g. MATLAB Online, Mobile or Academy.

You can also download and install MATLAB for your personal computer.
See the next page for details.

3. DOWNLOAD CHOOSEN MATLAB VERSION

After verification you will be taken directly to the MATLAB download page.
(Also accessible by “My Account” and the Download Icon:)

Choose the most recent release (mac users see the table for guidance).

4. SELECT THE CORRECT INSTALLATION METHOD AND LICENSE

When you run the installer, you will be asked to select an **Installation Method**.

*Select **Log in** with a MathWorks Account.*

Later, you will be asked enter an **e-mail address** and **password.**

*Use the **e-mail address** and **password** that you for your MathWorks account*

When asked to **Select a license**, choose the license with the **Individual** Label.

Toolboxes: When asked to select the products, there are over 80 toolboxes available to install. If you are using a standard broadband network connection at home, it will take many hours to download all the toolboxes. To save time, select just MATLAB and the toolboxes you need. We suggest MATLAB, Symbolic Math Toolbox and Simulink. You can run the installer again later to add additional toolboxes.

Which MATLAB version for mac?

Use the table on the right to choose the correct MATLAB release for your operating system.

To find which version of OSX you are using. On the Mac, Click on the apple in the far top left.

Select **About this MAC**

If you have any problems or queries, have a look at the MATLAB FAQ page: http://users.ox.ac.uk/~engs1643/matlab-faq.html

Mac Operating System		MATLAB
High Sierra	macOS 10.13	R2018a
Sierra	macOS 10.12	R2018a
El Capitan	OS X 10.11	R2018a
Yosemite	OS X 10.10	R2017a
Mavericks	OS X 10.9.5	R2015b
	OS X 10.9	R2014b
Mountain Lion	OS X 10.8	R2014b
Lion	OS X 10.7.4 & above	R2014b
	OS X 10.7	R2012a or b
Snow Leopard	OS X 10.6.4 & above	R2012a or b
	OS X 10.6.x	R2010b
Leopard	OS X 10.5.8 & above	R2010b
	OS X 10.5.5 & above	R2010a
	OS X 10.5.x	R2008b