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Matlab/Simulink Tutorial

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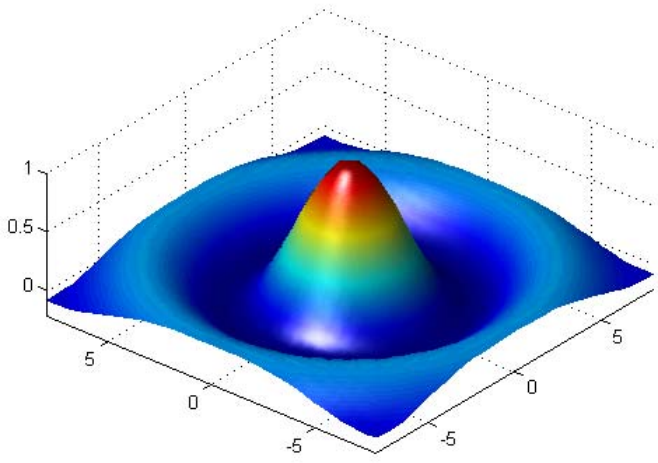


Contents

CHAPTER 1: The Basics

1.1 Introduction

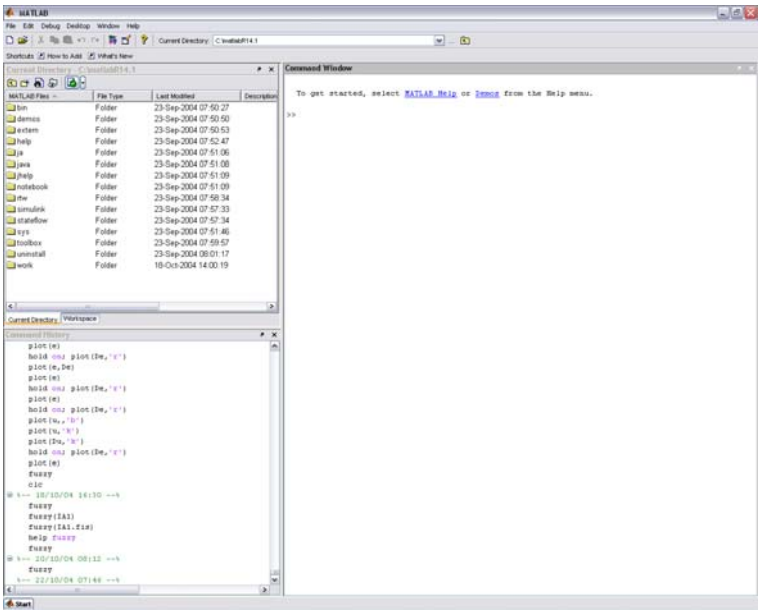
Matlab stands for **Matrix Laboratory**. The very first version of Matlab, written at the University of New Mexico and Stanford University in the late 1970s was intended for use in Matrix theory, Linear algebra and Numerical analysis. Later and with the addition of several toolboxes the capabilities of Matlab were expanded and today it is a very powerful tool at the hands of an engineer.

Typical uses include:

- Math and Computation
- Algorithm development
- Modelling, simulation and prototyping
- Data analysis, exploration and visualisation
- Scientific and engineering graphics
- Application development, including graphical user interface building.

Matlab is an interactive system whose basic data element is an **ARRAY**. Perhaps the easiest way to visualise Matlab is to think it as a full-featured **calculator**. Like a basic calculator, it does simple math like addition, subtraction, multiplication and division. Like a scientific calculator it handles square roots, complex numbers, logarithms and trigonometric operations such as sine, cosine and tangent. Like a programmable calculator, it can be used to store and retrieve data; you can create, execute and save sequence of commands, also you can make comparisons and control the order in which the commands are executed. And finally as a powerful calculator it allows you to perform matrix algebra, to manipulate polynomials and to plot data.

To run Matlab you can either double click on the appropriate icon on the desktop or from the start up menu. When you start Matlab the following window will appear:



Initially close all windows except the “Command window”. At the end of these sessions type “Demo” and choose the demo “Desktop Overview” for a full description of all windows. The command window starts automatically with the symbol “>>” In other versions of Matlab this symbol may be different like the educational version: “EDU>>”. When we type a command we press ENTER to execute it.

1.2 Simple math

The first thing that someone can do at the command window is simple mathematic calculations:

```
» 1+1

ans =

    2

» 5-6

ans =

   -1

» 7/8

ans =

    0.8750

» 9*2

ans =

   18
```

The arithmetic operations that we can do are:

Operation	Symbol	Example
Addition, a+b	+	5+3
Subtraction, a-b	-	5.05-3.111
Multiplication, a*b	*	0.124*3.14
Left division, a\b	\	5\3
Right division, b/a	/	3/5(=5\3)
Exponentiation, a^b	^	5^2

The order of this operations follows the usual rules: Expressions are evaluated from left to right, with exponentiation operation having the highest order of precedence, followed by both multiplication and division, followed by both addition and subtraction. The order can change with the use of parenthesis.

1.3 Matlab and variables

Even though those calculations are very important they are not very useful if the outcomes cannot be stored and then reused. We can store the outcome of a calculation into variables by using the symbol "=":

```
» a=5

a =

    5
```

```
» b=6

b =

    6

» newcastle=7

newcastle =

    7

» elec_elec_sch=1

elec_elec_sch =

    1
```

We can use any name for our variables but there are some rules:

- The maximum numbers of characters that can be used are 63
- Variable names are case sensitive, thus the variable “A” is different from “a”.
- Variable names must start with a letter and they may contain letters, numbers and underscores but NO spaces.

Also at the start of Matlab some variables have a value so that we can use them easily. Those values can be changed but it is not wise to do it. Those variables are:

Special variable	**Value**
ans	The default variable name used for results
pi	3.14…
eps	The smallest possible number such that, when added to one, creates a number greater than one on the computer
flops	Count of floating point operations. (Not used in ver. 6)
inf	Stands for infinity (e.g.: 1/0)
NaN	Not a number (e.g: 0/0)
i (and) j	i=j= $\sqrt{-1}$
nargin	Number of function input arguments used
nargout	Number of function output arguments used
realmin	The smallest usable positive real number
realmax	The largest usable positive real number

Also there are names that you cannot use: for, end, if, function, return, elseif, case, otherwise, switch, continue, else, try, catch, global, persistent, break.

If we want to see what variables we have used, we use the command “who”:

```
» who

Your variables are:

a               b               newcastle
ans             elec_elec_sch
```

To see the value of a variable we type its name:

```
» a

a =

    5
```

To erase a variable we use the command “clear”

```
» clear a
```

Now if we check our variables:

```
» who

Your variables are:

ans             elec_elec_sch
 b               newcastle
```

Current versions of Matlab allow us to use a new window called “Workspace” that shows all the necessary information about our variables.

1.4 Variables and simple math

The variables that we have just defined can be used, exactly like the numbers:

```
» d=a+b

d =

   11

» f=a*newcastle

f =

   35
```

1.5 Complex numbers

One of the characteristics that made Matlab so popular is how easily we can use complex numbers. To define a complex number we have to use the variable i (or j):

```
» z=1+j

z =

   1.0000 + 1.0000i

» z1=5.36-50i

z1 =

    5.3600 -50.0000i
```

Complex numbers and variables can be used exactly like real numbers and variables.

To transform a complex number from its rectangular form to its polar we use the commands “abs” and “angle”:

```
» zamp=abs(z)

zamp =

    1.4142

» zphase=angle(z)

zphase =

    0.7854
```

At this point we must note that Matlab ALWAYS uses radians for angles and not degrees.

To find the real and the imaginary part of a complex number we use the commands “real” and “imag”:

```
» zreal=(real(z1))

zreal =

    5.3600

» zimaginary=(imag(z1))

zimaginary =

       -50
```

1.6 Common mathematical functions

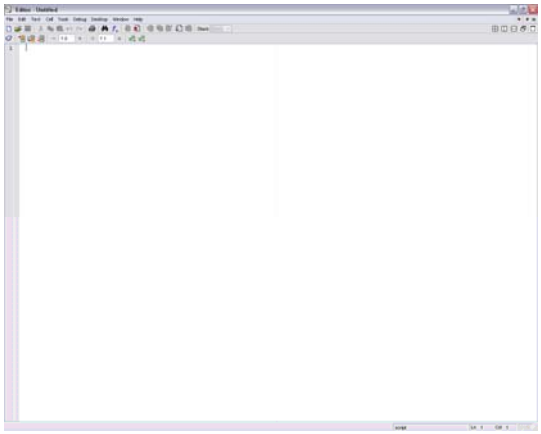
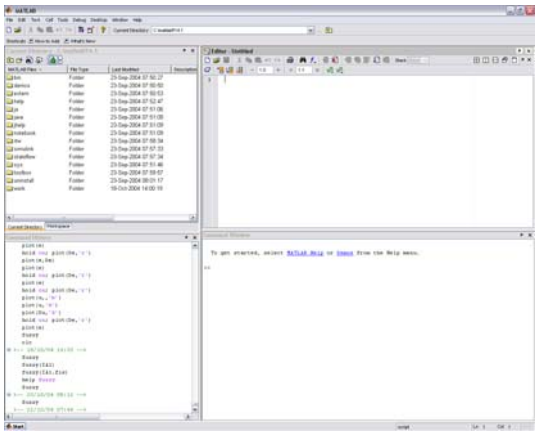
Like most scientific calculators, Matlab offers many common functions important to mathematics, engineering and the sciences. The number of those functions is more than 1000 just in the basic Matlab. And every function may take different forms depending on the application. So it is impossible in this text to analyse all of them. Instead we will give a table of the most common that we think that will be useful.

Matlab name	**Comments**
abs(x)	Absolute value or magnitude of complex number.
acos(x)	Inverse cosine.
angle(x)	Angle of complex number.
asin(x)	Inverse sine.
atan(x)	Inverse tan.
conj(x)	Complex conjugate.
cos(x)	Cosine.
exp(x)	e^x.
imag(x)	Complex imaginary part.
log(x)	Natural logarithm.
log10(x)	Common logarithm.
real(x)	Complex real part.
rem(x,y)	Remainder after division: x/y
round(x)	Round toward nearest integer.
sqrt(x)	Square root.
tan(x)	Tangent

One useful operation of the command prompt is that we can recall previous commands by using the cursor keys (↑,↓). Also with the use of the mouse we can copy and paste commands.

1.7 M-files

For simple problems, entering the commands at the Matlab prompt is fast and efficient. However as the number of commands increases, or when you wish to change the value of a variable and then re-valuate all the other variables, typing at the command prompt is tedious. Matlab provides for this a logical solution: place all your commands in a text file and then tell Matlab to evaluate those commands. These files are called script files or simple M-files. To create an M-file, chose form the File menu the option NEW and then chose M-file. Or click at the appropriate icon at the command window. Then you will see this window:

After you type your commands save the file with an appropriate name in the directory “work”. Then to run it go at the command prompt and simple type its name or in the M-file window press F5. Be careful if you name your file with a name that has also used for a variable, Matlab is going to give you the value of that variable and not run the M-file. When you run the M-file you will not see the commands (unless you would like to) but only the outcomes of the calculations. If you want to do a calculation either at the command prompt or in an M-file but not to see the outcome you must use the symbol “;” at the end of the command. This is very useful and makes the program very fast. E.g.:

```
» a=10
a =

    10

» b=5

b =

    5

» c=a+b

c =

   15
```

With this code you actually want only the value of the variable “c” and not “a” and “b” so:

```
» a=10;
» b=5;
» c=a+b

c =

    15
```

Even though now this seems a littlie bit unnecessary you will find it imperative with more complex programs.

Because of the utility of M-files, Matlab provides several functions that are particularly useful:

Matlab name	**Comments**
disp(ans)	Display results without identifying the variable names
disp('Text')	Display Text
input	Prompt user for input
keyboard	Give control to keyboard temporally. (type return to quit)
pause	Pause until user presses any keyboard key
pause(n)	Pause for n seconds
waitforbuttonpress	Pause until user presses mouse button or keyboard key.

When you write an M-file it is useful to put commends after every command. To do this use the symbol "%":

```
temperature=30 % set the temperature
temperature =

    30
```

1.8 Workspace

All the variables that you have used either at the command prompt or at an M-file are stored in the Matlab **workspace**. But if you type the command "clear" or you exit Matlab all these are lost. If you want to keep them you have to save them in "mat" files. To do this go from the File menu to the option: "save workspace as…". Then save it as the directory "work". So the next time you would like to use those variables you will load this "mat" file. To do this go at the File menu at chose "Load workspace…". To see the workspace except from the command who (or whos) you can click at the appropriate icon at the command window.

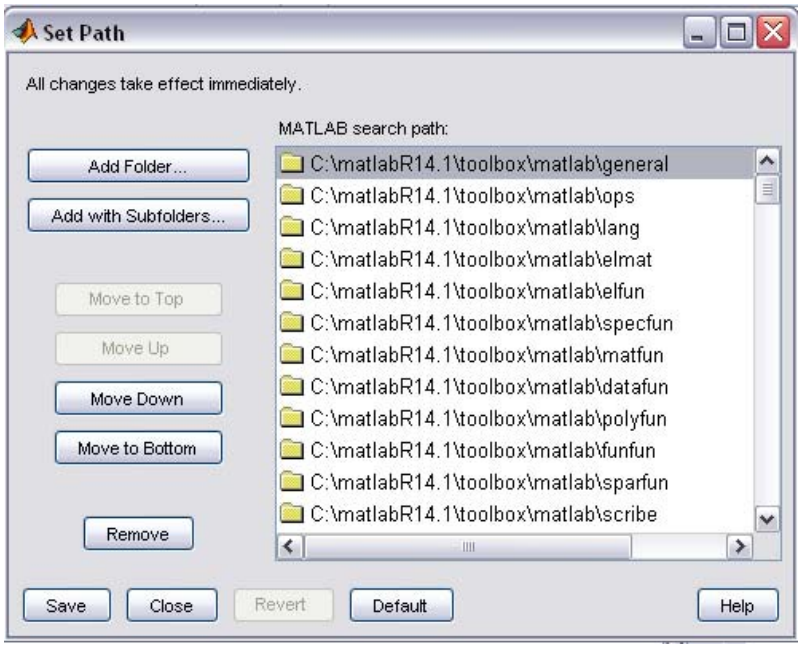
1.9 Number display formats

When Matlab displays numerical results it follows some rules. By default, if a result is an integer, Matlab displays it as an integer. Likewise, when a result is a real number, Matlab displays it with approximately four digits to the right of the decimal point. You can override this default behaviour by specifying a different numerical format within the preferences menu item in the File menu.

The most common formats are the short (default), which shows four digits, and the format long, which shows 15 digits. Be careful in the memory the value is always the same. Only the display format we can change.

1.10 Path Browser

Until now we keep say save the M-file or the workspace to the "work" directory. You can change this by changing the Matlab path. To see the current path type the command "path". If you wish to change the path (usually to add more directories) from the File menu chose "Set Path…". The Following window will appear:



After you added a directory you have to save the new path if you want to keep it for future uses.

1.11 Toolboxes.

To expand the possibilities of Matlab there are many libraries that contain relevant functions. Those libraries are called **Toolboxes**. Unfortunately because of the volume of those toolboxes it is impossible to describe all of these now.

1.12 Help…….

As you have realised until now Matlab can be very complicated. For this reason Matlab provides two kinds of help. The first one is the immediately help. When you want to see how to use a command type “help *commandname*”. Then you will see a small description about this command. The second way to get help is to get to from the help menu in the command window.

CHAPTER 2: Arrays

2.1 Array construction

Consider the problem of computing values of the sine function over one half of its period, namely: y=sin(x), x E [0,π]. Since it is impossible to compute sin(x) at all points over this range (there are infinite number of points), we must choose a finite number of points. In doing so, we are sampling the function. To pick some number, let's say evaluate every 0.1π in this range, i.e.

let x={0, 0.1π, 0.2π, 0.3π, 0.4π, 0.5π, 0.6π, 0.7π, 0.8π, 0.9π, π}. In Matlab to create this vector is relative easy:

```
» x=[0 0.1*pi 0.2*pi 0.3*pi 0.4*pi 0.5*pi 0.6*pi 0.7*pi 0.8*pi
0.9*pi pi]

x =

  Columns 1 through 7

  0    0.3142    0.6283    0.9425    1.2566    1.5708    1.8850

  Columns 8 through 11

2.1991    2.5133    2.8274    3.1416
```

To evaluate the function y at these points we type:

```
» y=sin(x)

y =

  Columns 1 through 7

  0    0.3090    0.5878    0.8090    0.9511    1.0000    0.9511

  Columns 8 through 11

  0.8090    0.5878    0.3090    0.0000
```

To create an array in Matlab, all you have to do is to **start with a left bracket enter the desired values separated by comas or spaces, then close the array with a right bracket**. Notice how Matlab finds the values for "x" and stores them in the array "y".

2.2 Array addressing

Suppose that we have the array "x" and we want to find the value of the third element. To do this we type:

```
» a=x(3)

a =

    0.6283
```

Or we want the first five elements:

```
» b=x(1:5)

b =

  0    0.3142    0.6283    0.9425    1.2566
```

Notice that, in the first case the variable “a” is a scalar variable and at the second the variable “b” is a vector.

Also if we want the elements from the seventh and after we type:

```
» c=x(7:end)

c =

    1.8850    2.1991    2.5133    2.8274    3.1416
```

Here the word “end” specifies the last element of the array “x”. There are many other ways to address:

```
» d=y(3:-1:1)

d =

    0.5878    0.3090         0
```

These are the third, second and first element in reverse order. The term 3:-1:1 says “start with 3, count down by 1 and stop at 1.

Or:

```
» e=x(2:2:7)

e =

   0.3142    0.9425    1.5708
```

These are the second, fourth and sixth element of x. The term 2:2:7 says, ”start with 2 count up by two and stop when seven”. In this case adding 2 to 6 gives 8, which is greater than 7, so the eighth element is not included.

Or:

```
» f=y([8 2 9 1])

f =

    0.8090    0.3090    0.5878         0
```

Here we used the array [8 2 9 1] to extract the elements of the array “y” in the order we want them.

2.3 Array Construction

Earlier we entered the values of "x" by typing each individual element in "x". While this is fine when there are only 11 values of "x", what if there are 111 values? So we need a way to automatically generate an array.

This is:

```
» x=(0:0.1:1)*pi

x =

  Columns 1 through 7

  0    0.3142    0.6283    0.9425    1.2566    1.5708    1.8850

  Columns 8 through 11

2.1991    2.5133    2.8274    3.1416
```

Or:

```
» x=[0:0.1:1]*pi

x =

  Columns 1 through 7

  0    0.3142    0.6283    0.9425    1.2566    1.5708    1.8850

  Columns 8 through 11

 2.1991    2.5133    2.8274    3.1416
```

The second way is not very good because it takes longer for Matlab to calculate the outcome.

Or:

```
» x=0:0.1:1

x =

  Columns 1 through 7

  0    0.1000    0.2000    0.3000    0.4000    0.5000    0.6000

  Columns 8 through 11

    0.7000    0.8000    0.9000    1.0000

» xa=x*pi

xa =
```

```
  Columns 1 through 7

    0    0.3142    0.6283    0.9425    1.2566    1.5708    1.8850

  Columns 8 through 11

    2.1991    2.5133    2.8274    3.1416
```

Or we can use the command “linspace”:

```
» x=linspace(0,pi,11)

x =

  Columns 1 through 7

    0    0.3142    0.6283    0.9425    1.2566    1.5708    1.8850

  Columns 8 through 11

    2.1991    2.5133    2.8274    3.1416
```

In the first cases the notation “0:0.1:1” creates an array that starts at 0, increments by 0.1 and ends at 1. Each element then is multiplied by π to create the desire values in “x”. In the second case, the Matlab function “linspace” is used to create “x”. This function’s arguments are described by:

linspace(first_value, last_value, number_of_values)

The first notation allows you to specify the increment between data points, but not the number of the data points. “linspace”, on the other hand, allows you to specify directly the number of the data points, but not the increment between the data points.

For the special case where a logarithmically spaced array is desired, Matlab provides the “logspace” function:

```
» a=logspace(0,2,11)

a =

  Columns 1 through 7

    1.0000    1.5849    2.5119    3.9811    6.3096   10.0000
15.8489

  Columns 8 through 11

   25.1189   39.8107   63.0957  100.0000
```

Here the array starts with 10^0, ending at 10^2 and contains 11 values.

Also Matlab provides the possibility to combine the above methods:

```
» a=1:5

a =

    1     2     3     4     5

» b=1:2:9

b =

    1     3     5     7     9

» c=[a b]

c =

    1     2     3     4     5     1     3     5     7     9
```

2.4 Array Orientation

In the preceding examples, arrays contained one row and multiple columns. As a result of this row orientation, they are commonly called **row vectors**. It is also possible to have a **column vector**, having one column and multiple rows. In this case, all of the above array manipulation and mathematics apply without change. The only difference is that results are displayed as columns, rather than as rows.
To create a column vector we use the symbol ";":

```
» c=[1;2;3;4]


c =

    1
    2
    3
    4
```

So while spaces (and commas) separate columns, semicolons separate rows.

Another way to create a column vector is to make a row vector and then to transpose it:

```
» x=linspace(0,pi,11);
» x1=x'


x1 =

    0
    0.3142
    0.6283
    0.9425
    1.2566
    1.5708
    1.8850
    2.1991
    2.5133
```

```
    2.8274
    3.1416
```

If the vector x contained complex numbers then the operator "'" would also give the conjugate of the elements:

```
» k=[0 1+2i 3+0.5465i];
» l=k'

l =

   0
   1.0000 - 2.0000i
   3.0000 - 0.5465i
```

To avoid this we can use the dot-transpose:

```
» l=k.'

l =

   0
   1.0000 + 2.0000i
   3.0000 + 0.5465i
```

Since we can make column and row vectors is it possible to combine them and to make a matrix? The answer is yes. By using spaces (or commas) to separate columns and semicolons to separate rows:

```
» A=[1 2 3; 4 5 6]

A =

    1     2     3
    4     5     6
```

Or we can use the following notation:

```
» A=[1 2 3
4 5 6]

A =

    1     2     3
    4     5     6
```

2.5 Array – Scalar Mathematics

When we use scalar and arrays we have to be careful. For example the expression g-2, where g is a matrix would mean g-2*I, where "I" is the unitary matrix. In Matlab this does not apply. The above expression would mean subtract from all the elements in the matrix g the number 2.:

```
» g=[1 2 3;4 5 6];
» g1=g-2
```

```
g1 =

    -1     0     1
    2     3     4
```

Otherwise we can do everything that we can do with the scalar variables.

2.6 Array-Array mathematics

Here we can do any operation we want as long as it is mathematically correct. For example we cannot add matrices that have different number of rows and columns.

```
» A=[1 2 3 4;5 6 7 8;9 10 11 12];
» B=[1 1 1 1;2 2 2 2;3 3 3 3];
» C=A+B

C =

    2     3     4     5
    7     8     9    10
    12    13    14    15

» D=C-A

D =

    1     1     1     1
    2     2     2     2
    3     3     3     3

» F=2*A-D

F =

    1     3     5     7
    8    10    12    14
   15    17    19    21
```

The multiplication and division with matrices can be done with 2 different ways.
The first is the classical "* or /" and follows the laws of the matrix algebra:

```
» M=[1 2;3 4];
» N=[5 6;7 8];
» K=M*N

K =

    19    22
    43    50
```

The second way is to do those arithmetic operations element by element, and so we do need to care about the dimensions of the matrices. To do this we use the symbols "*" and "/" but with a dot in front of them ".*" and "./" :

```
» K=M.*N

K =

     5    12
    21    32
```

The same procedure with division and multiplication can be done with array powers:

```
» N1=N^2

N1 =

    67    78
    91   106

» N2=N.^2

N2 =

    25    36
    49    64

» M1=M.^(-1)

M1 =

    1.0000    0.5000
    0.3333    0.2500
```

2.7 Zeros, Ones, …

Because of their general utility, Matlab provides functions for creating arrays:
The command “eye” creates the unitary matrix:

```
» g=eye(2,3)

g =

     1     0     0
     0     1     0
```

The command “zeros” creates the zero matrix:

```
» f=zeros(5)

f =

     0     0     0     0     0
     0     0     0     0     0
     0     0     0     0     0
     0     0     0     0     0
     0     0     0     0     0
```

The command “ones” makes an array where all the elements are equal to 1:

```
» h=ones(3,3)

h =

     1     1     1
     1     1     1
     1     1     1
```

The command "rand" makes an array where the elements are uniformly distributed random numbers:

```
» l=rand(5,6)

l =

    0.9501    0.7621    0.6154    0.4057    0.0579    0.2028
    0.2311    0.4565    0.7919    0.9355    0.3529    0.1987
    0.6068    0.0185    0.9218    0.9169    0.8132    0.6038
    0.4860    0.8214    0.7382    0.4103    0.0099    0.2722
    0.8913    0.4447    0.1763    0.8936    0.1389    0.1988
```

The command "randn" makes an array where all the elements are normally distributed random numbers:

```
» p=randn(7,1)

p =

   -0.4326
   -1.6656
    0.1253
    0.2877
   -1.1465
    1.1909
    1.1892
```

2.8 Array Manipulation

Since arrays and matrices are fundamental to Matlab, there are many ways to manipulate them. Once matrices are formed, Matlab provides tools to insert, extract and rearrange subsets of them. Knowledge of these features is key to using Matlab efficiently. There are many ways to do these manipulations so here we can only give some examples:

```
» A=[1 2 3;4 5 6;7 8 9];
» A(3,3)=0

A =

     1     2     3
     4     5     6
     7     8     0
```

Set the element (3,3) equal to zero.

```
» A(2,6)=1

A =

     1     2     3     0     0     0
     4     5     6     0     0     1
     7     8     0     0     0     0
```

Here because the number of columns of A is 3 Matlab places 1 at the element (2,6) and the rest of the elements that were added are equal to zero.

```
» A(:,4)=20

A =

     1     2     3    20     0     0
     4     5     6    20     0     1
     7     8     0    20     0     0
```

Here Matlab sets all the elements of the fourth column equal to 20.

```
» A=[1 2 3;4 5 6;7 8 9];
» B=A(3:-1:1,1:3)

B =

     7     8     9
     4     5     6
     1     2     3
```

Here it creates a matrix “B” by taking the rows of “A” in reversed order.
The previous manipulation can also be done with the following way:

```
» B=A(3:-1:1,:)

B =

     7     8     9
     4     5     6
     1     2     3
```

If we want to erase a column then we type:

```
» A(:,2)=[]

A =

     1     3
     4     6
     7     9
```

If we want to reshape a matrix we type:

```
» A=[1 2 3;4 5 6];
» B=reshape(A,1,6)
```

```
B =

     1     4     2     5     3     6
```

2.9 Array Searching and Comparison

Many times, it is desirable to know the indices or subscripts of those elements of an array that satisfy some relational expression. In Matlab, this task is performed by the function “find”, which returns the subscripts where a relational expression is true:

```
» x=-3:3

x =

    -3    -2    -1     0     1     2     3

» k=find(abs(x)>1)

k =

   1     2     6     7
```

And if we want to find those numbers then:

```
» y=x(k)

y =

    -3    -2     2     3
```

The command “find” also works with matrices:

```
» A=[1 2 3;4 5 6;7 8 9];
» [i,j]=find(A>5)

i =

    3
    3
    2
    3
j =

    1
    2
    3
    3
```

At times it is desirable to compare two arrays. For example:

```
» B=[1 5 6;9 0 0;4 5 1];
» A=[1 2 3;4 5 6;7 8 9];
» isequal(A,B)

ans =

    0
```

```
» isequal(A,A)

ans =

    1
```

2.10 Array Size

There are cases where the size of a matrix in unknown but is needed for some manipulation, Matlab provides two utility functions “size” and “length”:

```
» A=[1 2 3 4;5 6 7 8];
» B=size(A)

B =

    2     4
```

With one output argument, the “size” function returns a row vector whose first element is the number of rows and whose second element is the number of columns.

```
» [r,c]=size(A)

r =

    2


c =

    4
```

With two output arguments, “size” returns the number of rows in the first variable and the number of columns in the second variable.

If we want to see which number is bigger (i.e. if the array has more rows than columns) we use the command “length”:

```
» C=length(A)

C =

    4
```

Actually the function “length” is doing: “max(size(A)”

2.11 Matrix operations

There are various matrix functions that we can do in Matlab, some of them are:

To find the determinant:

```
» A=[1 2 3;4 5 6;7 8 9];
```

```
» a=det(A)

a =

     0
```

To find the inverse:

```
» A=[1 5 3;4 5 10;7 8 50];
» b=inv(A)

b =

   -0.3476    0.4622   -0.0716
    0.2658   -0.0593   -0.0041
    0.0061   -0.0552    0.0307
```

Command	**Commends**
det(a)	Determinant.
eig(a)	Eigenvalues.
[x,d]=eig(a)	Eigenvectors.
expm(a)	Matrix exponential.
inv(a)	Matrix inverse.
norm(a)	Matrix and vectors norm.
norm(a,1)	1-norm
norm(a,2)	2-norm (Euclidean)
norm(a,inf)	Infinity
norm(a,p)	P-norm (vectors only)
norm(a,'fro')	F-norm
poly(a)	Characteristic polynomial
rank(a)	Rank
sqrtm(a)	Matrix square root
trace(a)	Sum of diagonal elements

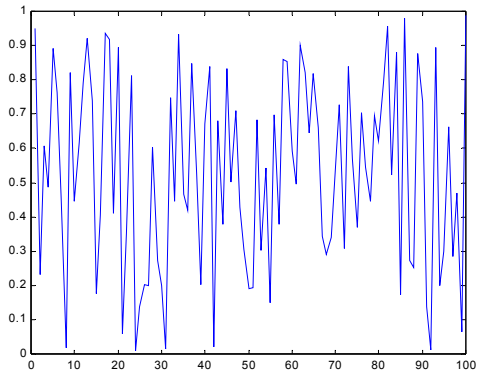
CHAPTER 3: Plots

3.1 2DPlots

One of the most useful abilities of Matlab is the ease of plotting data. In Matlab we can plot two and three-dimensional graphics. Here we will only study two-dimensional plots. Assume that in vector "x" we have the data from an experiment. To plot those we use the command "plot" like this:

```
» z=rand(1,100);
» plot(z)
```

Then we will see a new window that contains the following figure:



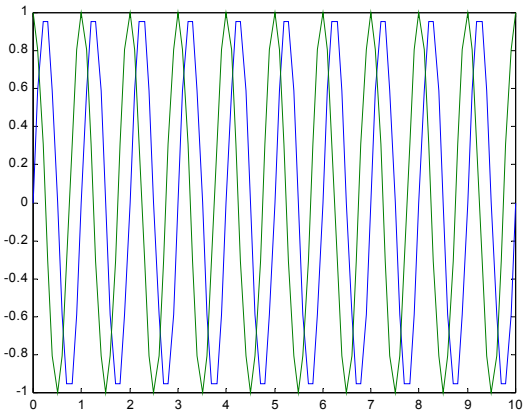
As we can see the command "plot" created a graph where the elements of the "y" axis are the values of the vector "z" and at the "x" axis we have the number of the index inside the vector.

Another way to use the command "plot" is like this:

```
» t=0:0.1:10;
» z=sin(2*pi*t);
» plot(t,z)
```

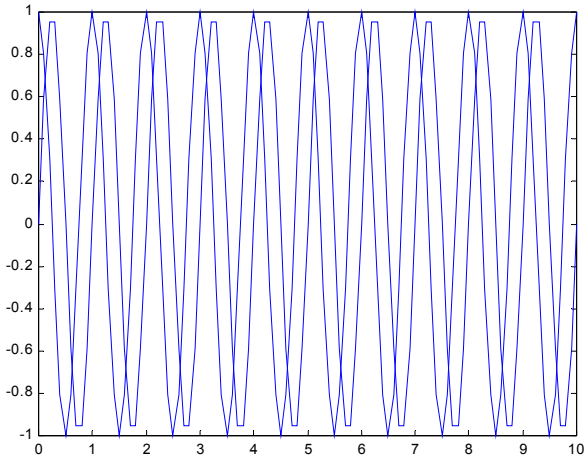
Also we can combine two graphs at the same figure:

```
» t=0:0.1:10;
» z1=sin(2*pi*t);
» z2=cos(2*pi*t);
» plot(t,z1,t,z2)
```



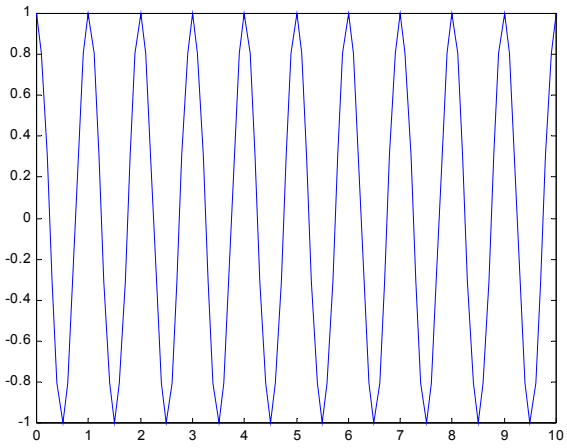
Or:

```
» t=0:0.1:10;
» z1=sin(2*pi*t);
» z2=cos(2*pi*t);
» plot(t,z1)
» hold
Current plot held
» plot(t,z2)
```



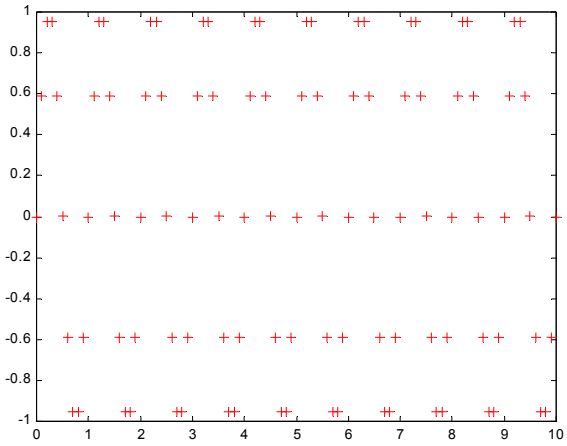
ATTENTION: If we do not use the command “hold” the second graph will overwrite the first one:

```
» t=0:0.1:10;
» z1=sin(2*pi*t);
» z2=cos(2*pi*t);
» plot(t,z1)
» plot(t,z2)
```

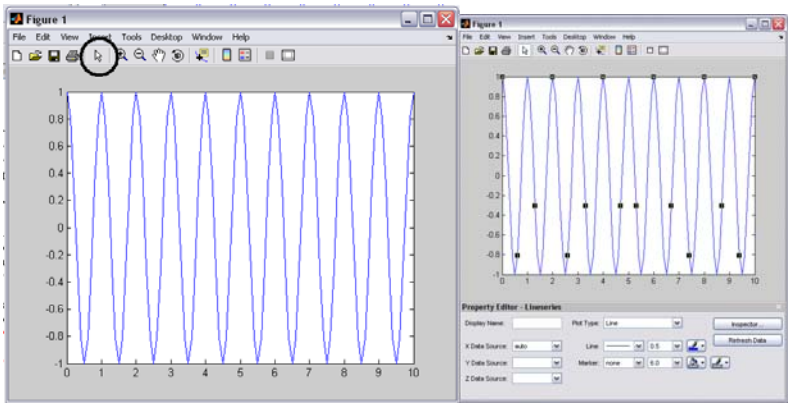


Also we can change the colour and the line style of the graph. This can be done either by typing the command plot like this:

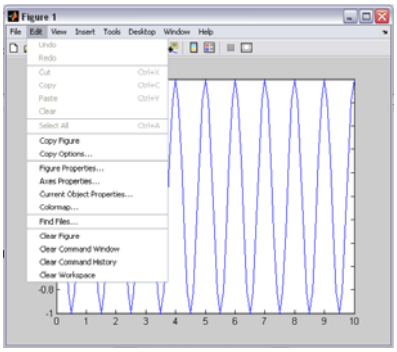
```
» t=0:0.1:10;
» z1=sin(2*pi*t);
» plot(t,z1,'r+’)
```



Or after the plot has been created by double clicking on the graph.



Finally to insert a figure in “Word” we chose from the menu “Edit” the “Copy Figure” choice:



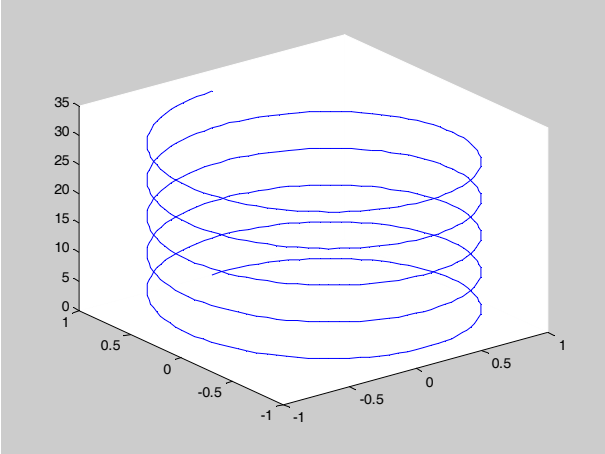
And then simply “paste” on the “Word” file.

Note: An interesting plotting command is *comet* that will gradually plot the curve.

3.2 3DPlots

Three dimensional plots can created in a similar way using the command *plot3*:

```
t = 0:pi/50:10*pi;
plot3(sin(t),cos(t),t)
```



As before this plot can be edited. Other plotting commands include mesh, surf…

3.3 Object Handles

In our everyday life we give different properties to various people, objects to identify them, for example the “red vase is on the table”. So for that object we defined its colour and location. Obviously we need to be more specific and define things like size, orientation…

Matlab is doing exactly that, the most basic (graphical object) is the screen. So if we type in the command window *findobj* we get:

```
>>h= findobj

ans =

     0
```

This means that Matlab found only one object, it gave it the number (label) 0. This number is called a handle. To see the properties of this object we can type:

```
>> get(h)
 CallbackObject = []
 CommandWindowSize = [62 24]
 CurrentFigure = []
 Diary = off
 DiaryFile = diary
 Echo = off
 FixedWidthFontName = Courier New
 Format = short
 FormatSpacing = loose
 Language = english
 MonitorPositions = [ (2 by 4) double array]
 More = off
 PointerLocation = [420 165]
 PointerWindow = [0]
 RecursionLimit = [500]
 ScreenDepth = [32]
 ScreenPixelsPerInch = [96]
 ScreenSize = [1 1 900 1440]
 ShowHiddenHandles = off
 Units = pixels

 BeingDeleted = off
 ButtonDownFcn =
 Children = []
 Clipping = on
 CreateFcn =
 DeleteFcn =
 BusyAction = queue
 HandleVisibility = on
 HitTest = on
 Interruptible = on
 Parent = []
 Selected = off
 SelectionHighlight = on
 Tag =
```

```
Type = root
UIContextMenu = []
UserData = []
Visible = on
```

Now we see a whole set of properties which can help us identify the object and even to modify it. These are the properties of your monitor. A more interesting case appears if we create a figure:

```
>> figure
>> h=findobj

h =

     0
     1
```

As it can bee seen now we have 2 objects. The monitor and the figure (notice that the figure is empty). The monitor always will have the handle zero and the figures 1, 2, 3…

Let's see the properties now of the figure:

```
>> get(h(2))
 Alphamap = [ (1 by 64) double array]
 BackingStore = on
 CloseRequestFcn = closereq
 Color = [0.8 0.8 0.8]
 Colormap = [ (64 by 3) double array]
 CurrentAxes = []
 CurrentCharacter =
 CurrentObject = []
 CurrentPoint = [0 0]
 DockControls = on
 DoubleBuffer = on
 FileName =
 FixedColors = [ (3 by 3) double array]
 IntegerHandle = on
 InvertHardcopy = on
 KeyPressFcn =
 MenuBar = figure
 MinColormap = [64]
 Name =
 NextPlot = add
 NumberTitle = on
 PaperUnits = centimeters
 PaperOrientation = portrait
 PaperPosition = [0.634517 6.34517 20.3046 15.2284]
 PaperPositionMode = manual
 PaperSize = [20.984 29.6774]
 PaperType = A4
 Pointer = arrow
 PointerShapeCData = [ (16 by 16) double array]
 PointerShapeHotSpot = [1 1]
 Position = [170 918 560 420]
 Renderer = None
 RendererMode = auto
```

```
Resize = on
ResizeFcn =
SelectionType = normal
ShareColors = on
ToolBar = auto
Units = pixels
WindowButtonDownFcn =
WindowButtonMotionFcn =
WindowButtonUpFcn =
WindowStyle = normal
WVisual = 00 (RGB 32  GDI, Bitmap, Window)
WVisualMode = auto

BeingDeleted = off
ButtonDownFcn =
Children = []
Clipping = on
CreateFcn =
DeleteFcn =
BusyAction = queue
HandleVisibility = on
HitTest = on
Interruptible = on
Parent = [0]
Selected = off
SelectionHighlight = on
Tag =
Type = figure
UIContextMenu = []
UserData = []
Visible = on
```

The default colour is gray (Color = [0.8 0.8 0.8]). We can see this clearer by typing:

```
>> get(h(2),'color')


ans =


   0.8000    0.8000    0.8000
```

Note*: Be careful this is American English.*

We can easily change that by typing:

```
>> set(h(2),'color',[0.1 0.9 0.8])
```

Similarly we can change all these properties. The Matlab help files explain these properties and how they can be changed.

Let's add now a 2D axes system:

```
>> h=findobj

h =

         0
    1.0000
  153.0016
```

Note: *The number for the axes is random so you may see a different number.*

Again we can see the properties of the axes by typing:

```
>> get(h(3))
 ActivePositionProperty = outerposition
 ALim = [0 1]
 ALimMode = auto
 AmbientLightColor = [1 1 1]
 Box = off
 CameraPosition = [0.5 0.5 9.16025]
 CameraPositionMode = auto
 CameraTarget = [0.5 0.5 0.5]
 CameraTargetMode = auto
 CameraUpVector = [0 1 0]
 CameraUpVectorMode = auto
 CameraViewAngle = [6.60861]
 CameraViewAngleMode = auto
 CLim = [0 1]
 CLimMode = auto
 Color = [1 1 1]
 CurrentPoint = [ (2 by 3) double array]
 ColorOrder = [ (7 by 3) double array]
 DataAspectRatio = [1 1 1]
 DataAspectRatioMode = auto
 DrawMode = normal
 FontAngle = normal
 FontName = Helvetica
 FontSize = [10]
 FontUnits = points
 FontWeight = normal
 GridLineStyle = :
 Layer = bottom
 LineStyleOrder = -
 LineWidth = [0.5]
 MinorGridLineStyle = :
 NextPlot = replace
 OuterPosition = [0 0 1 1]
 PlotBoxAspectRatio = [1 1 1]
 PlotBoxAspectRatioMode = auto
 Projection = orthographic
 Position = [0.13 0.11 0.775 0.815]
 TickLength = [0.01 0.025]
 TickDir = in
 TickDirMode = auto
```

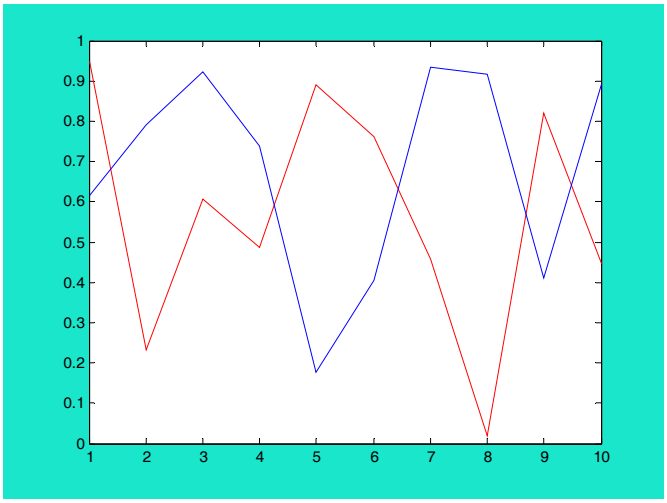
```
TightInset = [0.0392857 0.0380952 0.00892857 0.0190476]
Title = [154.002]
Units = normalized
View = [0 90]
XColor = [0 0 0]
XDir = normal
XGrid = off
XLabel = [158.001]
XAxisLocation = bottom
XLim = [0 1]
XLimMode = auto
XMinorGrid = off
XMinorTick = off
XScale = linear
XTick = [ (1 by 11) double array]
XTickLabel = [ (11 by 3) char array]
XTickLabelMode = auto
XTickMode = auto
YColor = [0 0 0]
YDir = normal
YGrid = off
YLabel = [159.001]
YAxisLocation = left
YLim = [0 1]
YLimMode = auto
YMinorGrid = off
YMinorTick = off
YScale = linear
YTick = [ (1 by 11) double array]
YTickLabel = [ (11 by 3) char array]
YTickLabelMode = auto
YTickMode = auto
ZColor = [0 0 0]
ZDir = normal
ZGrid = off
ZLabel = [160.001]
ZLim = [0 1]
ZLimMode = auto
ZMinorGrid = off
ZMinorTick = off
ZScale = linear
ZTick = [0 0.5 1]
ZTickLabel =
ZTickLabelMode = auto
ZTickMode = auto

BeingDeleted = off
ButtonDownFcn =
Children = []
Clipping = on
CreateFcn =
DeleteFcn =
BusyAction = queue
HandleVisibility = on
HitTest = on
Interruptible = on
```

```
Parent = [1]
Selected = off
SelectionHighlight = on
Tag =
Type = axes
UIContextMenu = []
UserData = []
Visible = on
```

Now let's add two plots:

```
>> plot(rand(1,10),'red')
>> hold on
>> plot(rand(1,10),'blue')
```




```
>> h=findobj

h =

         0
    1.0000
  153.0016
  155.0011
  154.0029
```

The analysis now is trickier as we cannot tell which object is for each handle. To answer that we can type:

```
>> get(h,'type')

ans =

    'root'
    'figure'
    'axes'
    'line'
    'line'
```

Hence we can isolate an object by:

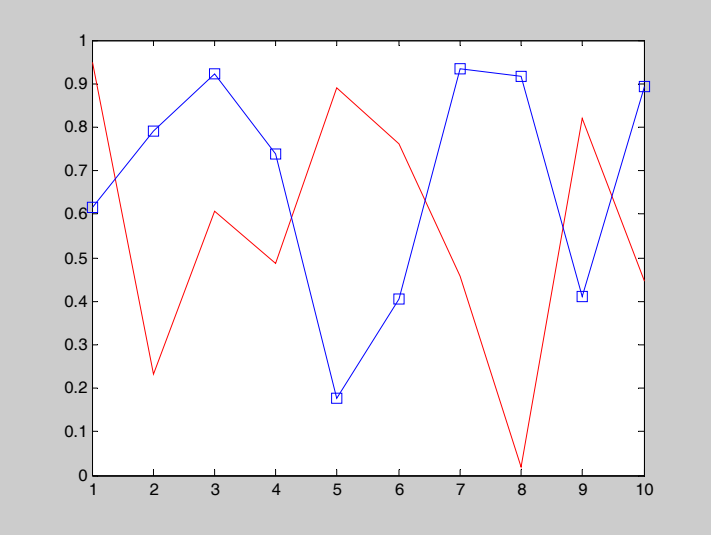
```
>> findobj('type','line')

ans =

  158.0013
  154.0029
```

If we want we can refine our search:

```
>> h_line_blue=findobj('type','line','color','blue');
>> set(h_line_blue,'Marker','square')
```



There are many things that we can do with these handles but this will be outside the scope of these sessions. Nevertheless sometimes we have created in the past a figure from an experiment and then we lost the data. The next commands retrieve the data of the red line:

```
>> h_line_red=findobj('type','line','color','red');
>> x=get(h_line_blue,'XData')

x =
     1     2     3     4     5     6     7     8     9    10

>> y=get(h_line_blue,'YData')

y =

  Columns 1 through 6

    0.6154    0.7919    0.9218    0.7382    0.1763    0.4057

  Columns 7 through 10

    0.9355    0.9169    0.4103    0.8936
```

CHAPTER 4: Strings, Cells and Structures

4.1 Strings

The true power of Matlab is its ability to crunch numbers. However it is desirable sometimes to manipulate text. In Matlab, text variables are referred to as **character strings**, or simple **strings**.

Character strings in Matlab are arrays of ASCII values that are displayed as their character string representation:

```
» t='how about this character string'

t =

how about this character string

»size(t)
ans =
 1 31
```

A character string is simple a text surrounded by single quotes.

The function “disp” allows you to display a string without printing its variable name:

```
» disp(t)
    how about this character string
```

It is possible to combine 2 strings and hence to create a matrix:

```
>> x='this is'

x =

this is

>> y=' a course'

y =

 a course

>> z=[x y]

z =

this is a course
```

A string can be converted back to a number by:

```
>> double(x)

ans =

   116   104   105   115    32   105   115
```

And a number to a string:

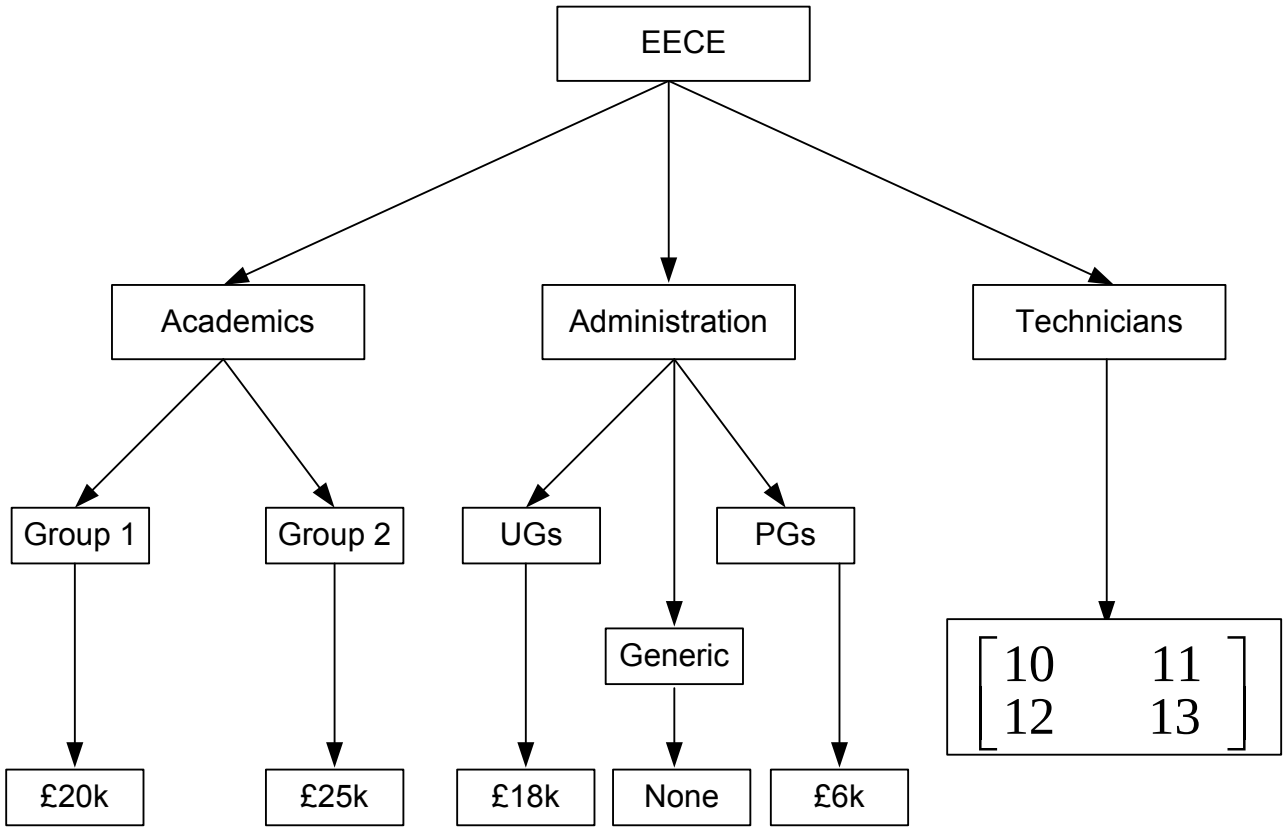
```
>> char([72])

ans =

H
```

4.2 Structures

Another common Matlab object is the structure which is nothing more than a tree diagram. Lets see for example the following tree diagram:



In Matlab this will be created as:

```
>> EECE.Academics.Group1=20
EECE.Academics.Group2=25
EECE.Administration.UGs=18
EECE.Administration.Generic='None'
EECE.Administration.PGs=6
EECE.Technicians=[10 11;12 13]

EECE =

    Academics: [1x1 struct]


EECE =

    Academics: [1x1 struct]
```

```
EECE =

         Academics: [1x1 struct]
    Administration: [1x1 struct]


EECE =

         Academics: [1x1 struct]
    Administration: [1x1 struct]


EECE =

         Academics: [1x1 struct]
    Administration: [1x1 struct]


EECE =

         Academics: [1x1 struct]
    Administration: [1x1 struct]
       Technicians: [2x2 double]
```

Hence we can combine different objects. To extract a value:

```
>> EECE.Academics.Group1

ans =

    20

>> EECE.Administration

ans =

        UGs: 18
    Generic: 'None'
        PGs: 6
```

4.3 Cell Arrays

Up to now we have seen various Matlab objects like variables, vectors (row/column), strings… In the previous section we saw a nice way to combine these objects. Sometimes though it is better to have them in one array:

$$ar = \begin{bmatrix} \begin{bmatrix} 1 \\ 2 \\ \vdots \\ 100 \end{bmatrix} & 2 & Newcastle \\ \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} & 3j & EECE \\ \begin{bmatrix} 0 & 0 & \ldots & 0 \end{bmatrix} & \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} & [] \end{bmatrix}$$

>> ar={[1:100]' 2 'Newcaste'; [1 2;3 4], 3*j, EECE; zeros(1,10), ones(10,1), []}

ar =

```
[100x1  double]   [       2]   'Newcaste'
[  2x2  double]   [0 + 3.0000i]   [1x1 struct]
[  1x10 double]   [10x1 double]          []
```

Hence to create an array we use curly brackets and we follow the same rules as with the matrix construction.

The arrays can be accessed just like matrices:

```
>> ar{2,1}
ans =
     1     2
     3     4
>> ar{2,2}
ans =
        0 + 3.0000i
>> ar{3,3}
ans =
     []
>> ar{2,3}
ans =
         Academics: [1x1 struct]
    Administration: [1x1 struct]
       Technicians: [2x2 double]

>> ar{2,3}.Academics

ans =

    Group1: 20
    Group2: 25
```

CHAPTER 5: Logic and Control Flow

5.1 Relational and Logical Operations

5.1.1 Relational Operators

Matlab relational operators include:

Relational Operator	Description
<	Less than
<=	Less than or equal to
>	Greater than
>=	Greater than or equal to
==	Equal to
~=	Not equal to

General a relational operator returns one for true and zero for false:

```
» A=1:9;
» B=9-A;
» tf=A>4

tf =

    0     0     0     0     1     1     1     1     1
```

Here we see that after the fourth element the values of A are greater than 4.

```
» tf=A==B

tf =

    0     0     0     0     0     0     0     0     0
```

Finds element of A that are equal to those of B. The symbol "==" compares two variable and returns one where they are equal and zeros when they are not.

5.1.2 Logical Operators

Logical operators provide a way to combine or negate relational expressions. Matlab logical operators include:

Logical Operator	Description
&	AND
|	OR
~	NOT

Examples:

```
» tf=~(A>4)

tf =

    1     1     1     1     0     0     0     0     0

» tf=(A>2)&(A<6)

tf =

    0     0     1     1     1     0     0     0     0
```

Other relational and logical operators are:

Operator	Description
xor(x,y)	Exclusive OR operation. Returns ones where either x or y is nonzero (True). Returns zeros if both x and y are zero (False) or nonzero (True)
any(x)	Return one if any element of the vector x is nonzero. Return one for each column in a matrix x that has nonzero elements.
all(x)	Return one if all elements are nonzero

5.2 Control flow

5.2.1 "for" loops

"for" loops allow a group of commands to be repeated a fixed, predetermined number of times. The general form of a "for" loop is:

```
for x=array

    commands…

end
```

The commands… between the "for" and "end" statements are executed once every column in "array". At each interaction, "x" is assigned to the next column of "array", i.e. during the n^{th} time through the loop, x=array.

Example:

```
» for n=1:10
x(n)=sin(n*pi/10);
end;
» x

x =

  Columns 1 through 7
```

```
    0.3090    0.5878    0.8090    0.9511    1.0000    0.9511
0.8090

  Columns 8 through 10

0.5878    0.3090    0.0000
```

Also the “for” loops can be nested as desired:

```
clear all
for k=1:10
    for l=1:5
       x(l,k)=5*sqrt(k*l);
    end;
end;

» x

x =

  Columns 1 through 7

    5.0000    7.0711    8.6603   10.0000   11.1803   12.2474
13.2288
    7.0711   10.0000   12.2474   14.1421   15.8114   17.3205
18.7083
    8.6603   12.2474   15.0000   17.3205   19.3649   21.2132
22.9129
   10.0000   14.1421   17.3205   20.0000   22.3607   24.4949
26.4575
   11.1803   15.8114   19.3649   22.3607   25.0000   27.3861
29.5804

  Columns 8 through 10

   14.1421   15.0000   15.8114
   20.0000   21.2132   22.3607
   24.4949   25.9808   27.3861
   28.2843   30.0000   31.6228
31.6228   33.5410   35.3553
```

Sometimes it is possible to avoid “for” loops. This is very good because we make the program faster. For example the first example on this paragraph can be also done:

```
» n=1:10;
» x=sin(n*pi/10)

x =

  Columns 1 through 7

    0.3090    0.5878    0.8090    0.9511    1.0000    0.9511
0.8090
```

```
  Columns 8 through 10

0.5878    0.3090    0.0000
```

5.2.2 "while" Loops

While a "for" loop evaluates a group of commands a fixed number of times, a "while" loop evaluates a group of commands an identified number of times. The general form of a "while" loop is:

while expression

    Commands

end

The command between the "while" and "end" statements are executed as long as all elements in expression are true. For example:

```
» a=10;
» while a>0
y(a)=a*10;
a=a-1;
end;
» y

y =

   10    20    30    40    50    60    70    80    90   100
```

5.2.3 if-else-end Constructions

Many times sequences of commands must be conditionally evaluated based on a relational test. This can be accomplished by the if-else-then construction. The simplest form is:

if expression

    commands…

end

The commands... between the "if" and "end" statements are evaluated if all elements in expression are true (nonzero). The following M-file gives an example:

```
k=input('Give me your age ');

if k<0| k>100
   disp('you are a liar')
end;
```

If there are two alternatives we can use:

```
l=input('Give me the value of the product ');
k=input('Give me the discound (%)');

if k<10 | k>50
   disp('Discound value unacceptable ')
```

```
else Cost=l-l*k/100
end;
```

When there are more than two alternatives then we can use:

```
l=input('Give me the value of the product ');
k=input('Give me the discound (%)');

if k<0
   disp('Wrong discound value ')
elseif k<10 & k>=0
   disp('Discound value too small ')
elseif k>50 & k<=80
   disp('Discound value too big ')
elseif k>80
   disp('Are you crazy??? ')
else
 Cost=l-l*k/100
end;
```

CHAPTER 6: Polynomials, Integration, Differentiation & Functions

6.1 Polynomials

Finding the roots of a polynomial is a problem that arises in many disciplines. Matlab solves this problem and provides other polynomial manipulation tools as well. In Matlab, a polynomial is represented by a row vector of its coefficients in descending order. For example the polynomial $x^4 - 12x^3 + 25x + 116$ is entered as:

```
» p=[1 -12 0 25 116]

p =

    1   -12     0    25   116
```

Note that terms with zero coefficients must be included.

The roots of a polynomial can be found by the function “roots”:

```
» q=roots(p)

q =

  11.7473
   2.7028
  -1.2251 + 1.4672i
  -1.2251 - 1.4672i
```

If we have the roots we can find the polynomial by using the function “poly”:

```
» p1=poly(q)

p1 =

    1.0000  -12.0000   -0.0000   25.0000  116.0000
```

To multiply two polynomials we use the command “conv”:

```
» p=[1 -12 0 25 116];
» r=[1 1];
» pr=conv(p,r)

pr =

    1   -11   -12    25   141   116
```

To divide two polynomials we use the command “deconv”:

```
» a=[1 1 2];
» b=[2 0 0 1];
» [q,r]=deconv(b,a)

q =
```

```
     2    -2


r =

     0     0    -2     5
```

The result says that the quotient of the division is “q” and the remainder is “r”.
The differentiation of a polynomial is found by using the function “polyder”:

```
» pd=polyder(p)

pd =

     4   -36     0    2
```

To evaluate a polynomial at a specific point we use the function “polyval”:

```
» polyval(p,-1+j)

ans =

  63.0000 + 1.0000i
```

If we have the ratio of two polynomials we manipulate them as two different polynomials:

```
» num=[1 -10 100];  % numerator
» den=[1 10 100 0]; % denominator
» zeros=roots(num)

zeros =

   5.0000 + 8.6603i
   5.0000 - 8.6603i

» poles=roots(den)

poles =

 0
  -5.0000 + 8.6603i
  -5.0000 - 8.6603i
```

But if we want to find the derivative of this ratio we use the command “polyder” in the next form:

```
» [numd,dend]=polyder(num,den)

numd =

   -1        20      -100     -2000      -10000
```

```
dend =

  Columns 1 through 6

    1        20       300      2000     10000         0

  Column 7

    0
```

Finally the command “residue” finds the partial fractions of the ratio:

» [r,p,k]=residue(num,den)

```
r =

   0.0000 + 1.1547i
   0.0000 - 1.1547i
   1.0000


p =

  -5.0000 + 8.6603i
  -5.0000 - 8.6603i
   0


k =

   []
```

where :

$$\frac{num(s)}{den(s)} = \frac{r_1}{s-p_1} + \frac{r_2}{s-p_2} + \frac{r_3}{s-p_3} ... + k(s)$$

6.2 Numerical Integration

The integral, or the area under a function, is yet another useful attribute. Matlab provides three functions for numerically computing the area under a function over a **finite** range: “trapz”, “quad” and “quad8”:

```
» x=(0:0.1:1)*pi;
» y=sin(x);
» area=trapz(x,y)

area =

    1.9835

» x=(0:0.1:2)*pi;
» y=sin(x);
» area=trapz(x,y)

area =
```

```
    -1.3878e-016
```

The function “trapz’ approximates the area under the function “sin” as trapezoids. If we want better approximation we have to reduce the size of those trapezoids. We can clearly see that, this approximation calculation inserts an error. This is obvious in the second example where the “area” is equal to a very small number but not to zero. The functions “quad” and “quad8” are used in a different format and give better approximation than trapz:

```
» area=quad('sin',0,2*pi)

area =

0
```

6.3 Numerical Differentiation

Compared to integration, numerical differentiation is much more difficult. Integration describes an overall or macroscopic property of a function, whereas differentiation describes the slope of a function at a point, which is a microscopic property of a function. As a result, integration is not sensitive to minor changes in the shape of a function, whereas differentiation is. Any small changes in a function can easily create large changes in its slope in the neighbourhood of the change.

Because of this inherent difficulty with differentiation, numerical differentiation is avoided wherever it is possible, especially if the data are obtained experimentally. In this case it is best to perform a least squares curve fit to data and then find the resulting polynomial. To find a polynomial that fits at a set of data we use the command “polyfit(x,y,n)”, where “x” are the data of the x-axis, “y” are the data for the y-axis and “n” are the order of the polynomial that we want to fit. So to find the derivative at a specific point we use:

```
» x=0:0.1:1;
» y=[-0.447 1.978 3.28 6.16 7.08 7.34 7.66 9.56 9.48 9.30 11.2];
» p=polyfit(x,y,2)

p =

   -9.8108   20.1293   -0.0317

» pd=polyder(p)

pd =

  -19.6217   20.1293

» slope_of_p=polyval(pd,0.5)

slope_of_p =

  10.3185
```

Matlab provides on the other hand a function that computes, very rough, the derivative of the data that describe a function. This is the function “diff” :

```
» dy=diff(y)./diff(x)

dy =

  Columns 1 through 7

   24.2500    13.0200    28.8000     9.2000     2.6000     3.2000
19.0000

  Columns 8 through 10

   -0.8000   -1.8000   19.0000
```

Note the last function is well to be avoided and to be used only when it is necessary.

6.4 Functions

When you use in Matlab functions such as: “inv”, “abs”, “angle”… Matlab takes the variables you pass it, computes the required results using your input, and then passes those results back to you. Functions are a very powerful tool inside Matlab and can reduce the size and the complexity of a program. The next example helps us to understand the use of functions:

Suppose we want to add two arrays and give back only the outcome. To do this we need as inputs the two arrays and as output Matlab will return the sum. We chose the name of our function as “fun1”. We go to the same place as the M-file and we type:

```
function z=fun1(x,y)
% This is a demo
% of how to use functions
% This function finds the sum of two matrices (x,y)
% and stores the outcome at the matrix "z"

z=x+y;
```

Later at the command prompt we type:

```
» a=[1 1;2 2];
» b=[3 3;4 4];
» outcome=fun1(a,b)

outcome =

4     4
6     6
```

If we want to see the help of this function we type:

```
» help fun1

  This is a demo
  of how to use functions
  This function finds the sum of two matrices (x,y)
  and stores the outcome at the matrix "z"
```

6.4.1 Rules and Properties

1) The function name and file name are IDENTICAL.
2) Comment lines up to the first noncomment line in a function M-file are the help text returned when you request help.
3) Each function has each own workspace separate from the Matlab workspace. The only connections between the variables within a function and the Matlab workspace are the function's input and output variables. If a function changes the value of a variable this appear only inside the function. If a variable is created inside a function does NOT appear at the Matlab workspace.
4) Functions can share the same variables if we use the command "global":

```
  function z=fun1(x,y)
% This is a demo
% of how to use functions
% This function finds the sum of two matrices (x,y)
% and stores the outcome at the matrix "z"
global g1;
g1=10;
z=x+y;

function z=fun2(x)
% This is a demo
% of how to use functions
% This function finds the product of a matrix and
% the global variable g1
% and stores the outcome at the matrix "z"
global g1
z=g1*x;
» outcome1=fun2(a)
outcome1 =

    10    10
    20    20
```

Finally inside a function can be used other functions as well:

```
function z=fun3(x)
% This is a demo
% of how to use functions
% This function finds the product of a matrix and
% the global variable g1, then it finds the square root of the
% elements
% and stores the outcome at the matrix "z"
global g1
z1=g1*x;
z=sqrt(z1);

» outcome2=fun3(a)

outcome2 =

    3.1623    3.1623
    4.4721    4.4721
```

CHAPTER 7: Symbolic Manipulation

7.1 Symbolic variables

Up to this point we have used numerical variables like:

```
>> x=10

x =

    10
```

But sometimes we want to do symbolic manipulations. For example to symbolically solve $ax=10$ for x:

```
>> xsol=solve('a*x=10',x)

xsol =

10/a
```

For more complicated manipulations we can define many symbolic variables and use them as any other variables:

```
>> syms x y z
>> d=x^2+cos(y)-sqrt(49*z)

d =

x^2+cos(y)-7*z^(1/2)
```

Matlab effectively calls Maple to handle these symbolic variables. Hence we can do with Matlab almost what we can do with Maple. Maple is a very powerful program that obviously cannot be fully covered here. Instead only a small description will be "attempted".

7.2 Symbolic solution of algebraic/differential equations

If we want to solve a system of linear equations we use the command solve:

```
>> sol=solve('x+y=10','x-y=5')

sol =

    x: [1x1 sym]
    y: [1x1 sym]

>> sol.x
```

```
ans =

15/2


>> sol.y

ans =

5/2
```

Alternatively:

```
>> f1=x+y;
>> f2=x-y;
>> f1=x+y-10;
>> f2=x-y-5;
>> sol=solve(f1,f2)

sol =

    x: [1x1 sym]
    y: [1x1 sym]

>> sol.x

ans =

15/2


>> sol.y

ans =

5/2
```

Nonlinear equation can be solved (assuming that this is possible):

```
>> sol=solve('x^2+y^2=10','x-y=5')

sol =

    x: [2x1 sym]
    y: [2x1 sym]

>> sol.x

ans =

 5/2+1/2*i*5^(1/2)
```

```
 5/2-1/2*i*5^(1/2)


>> sol.y

ans =

 -5/2+1/2*i*5^(1/2)
 -5/2-1/2*i*5^(1/2)
```

Differential equations can also easily be solved using the command dsolve:

```
>> dsolve('Dx=3*x')

ans =

C1*exp(3*t)


>> sol=dsolve('Dx=3*x+y','Dy=4*x+2*y')

sol =

    x: [1x1 sym]
    y: [1x1 sym]

>> sol.x

ans =

C1*exp(1/2*(5+17^(1/2))*t)+C2*exp((5/2-1/2*17^(1/2))*t)


>> sol.y

ans =

-
1/2*C1*exp(1/2*(5+17^(1/2))*t)+1/2*C1*exp(1/2*(5+17^(1/2))*t)
*17^(1/2)-1/2*C2*exp((5/2-1/2*17^(1/2))*t)-1/2*C2*exp((5/2-
1/2*17^(1/2))*t)*17^(1/2)


>> sol=dsolve('Dx=3*x+y','Dy=4*x+2*y','x(0)=1', 'y(1)=2')

sol =

    x: [1x1 sym]
    y: [1x1 sym]

>> sol.x
```

```
ans =

(4*exp(1/2*17^(1/2))+exp(5/2)+exp(5/2)*17^(1/2))/exp(5/2)/(-
exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp(1/2*(5+1
7^(1/2))*t)+(-exp(5/2)*exp(17^(1/2))-
4*exp(1/2*17^(1/2))+exp(5/2)*exp(17^(1/2))*17^(1/2))/exp(5/2)
/(-exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp((5/2-
1/2*17^(1/2))*t)


>> sol.y

ans =

-
1/2*(4*exp(1/2*17^(1/2))+exp(5/2)+exp(5/2)*17^(1/2))/exp(5/2)
/(-
exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp(1/2*(5+1
7^(1/2))*t)+1/2*(4*exp(1/2*17^(1/2))+exp(5/2)+exp(5/2)*17^(1/
2))/exp(5/2)/(-
exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp(1/2*(5+1
7^(1/2))*t)*17^(1/2)-1/2*(-exp(5/2)*exp(17^(1/2))-
4*exp(1/2*17^(1/2))+exp(5/2)*exp(17^(1/2))*17^(1/2))/exp(5/2)
/(-exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp((5/2-
1/2*17^(1/2))*t)-1/2*(-exp(5/2)*exp(17^(1/2))-
4*exp(1/2*17^(1/2))+exp(5/2)*exp(17^(1/2))*17^(1/2))/exp(5/2)
/(-exp(17^(1/2))+exp(17^(1/2))*17^(1/2)+1+17^(1/2))*exp((5/2-
1/2*17^(1/2))*t)*17^(1/2)
```

Note: The last two expressions are big because Maple (that is called by Matlab) uses "exact arithmetic", i.e. it prefers to display a number like 0.3333… as 1/3.

7.3 Other operations

The symbolic math toolbox allows us to make a number of basic calculus operations like to differentiate or integrate a function, to find the Taylor Series expansion…

```
>> syms x
f=cos(x)
diff(f)
int(f,x)
int(f,x,0,1)
pi/2

f =

cos(x)
```

```
ans =

-sin(x)

 ans =

sin(x)

ans =

sin(1)

ans =

    1.5708
>> TS=taylor(f,3)

TS =

1-1/2*x^2
```

Also, there is a great number of matrix operations where we can use symbolic variables:

```
>> A=[x 1; 2*x exp(x)]

A =

[      x,      1]
[    2*x, exp(x)]


>> inv(A)

ans =

[ exp(x)/x/(exp(x)-2),     -1/x/(exp(x)-2)]
[       -2/(exp(x)-2),        1/(exp(x)-2)]


>> det(A)

ans =

x*exp(x)-2*x
>> syms x y
>> f=[x^2+y; cos(y*x)];
>> jacobian(f)

ans =
```

```
[         2*x,           1]
[ -sin(y*x)*y, -sin(y*x)*x]
```

The command “subs” can replace a symbolic variable with another one that can be symbolic and/or numeric:

```
>> syms z
>> f=[x^2+y; cos(y*x)]

f =

    x^2+y
 cos(y*x)


>> subs(f,x,z)

ans =

    z^2+y
 cos(y*z)


>> subs(f,x,10)

ans =

     100+y
 cos(10*y)
```

Finally Matlab has some very powerful commands that can help us to simplify symbolic expressions:

```
>> f=(x-1)^2

f =

(x-1)^2

>> simple(f)

simplify:

(x-1)^2
```

```
radsimp:

(x-1)^2


combine(trig):

x^2-2*x+1


factor:

(x-1)^2


expand:

x^2-2*x+1


combine:

(x-1)^2


convert(exp):

(x-1)^2


convert(sincos):

(x-1)^2


convert(tan):

(x-1)^2


collect(x):

x^2-2*x+1

 mwcos2sin:
 (x-1)^2

ans =

(x-1)^2
```

CHAPTER 8: Introduction to Simulink

8.1 Introduction

Simulink is a time based software package that is included in Matlab and its main task is to solve Ordinary Differential Equations (ODE) numerically. The need for the numerical solution comes from the fact that there is not an analytical solution for all DE, especially for those that are nonlinear.
The whole idea is to break the ODE into small time segments and to calculate the solution numerically for only a small segment. The length of each segment is called "step size". Since the method is numerical and not analytical there will be an error in the solution. The error depends on the specific method and on the step size (usually denoted by h).
There are various formulas that can solve these equations numerically. Simulink uses Dormand-Prince (ODE5), fourth-order Runge-Kutta (ODE4), Bogacki-Shampine (ODE3), improved Euler (ODE2) and Euler (ODE1). A rule of thumb states that the error in ODE5 is proportional to h^5, in ODE4 to h^4 and so on. Hence the higher the method the smaller the error.
Unfortunately the high order methods (like ODE5) are very slow. To overcome this problem variable step size solvers are used. When the system's states change very slowly then the step size can increase and hence the simulation is faster. On the other hand if the states change rapidly then the step size must be sufficiently small.
The variable step size methods that Simulink uses are:

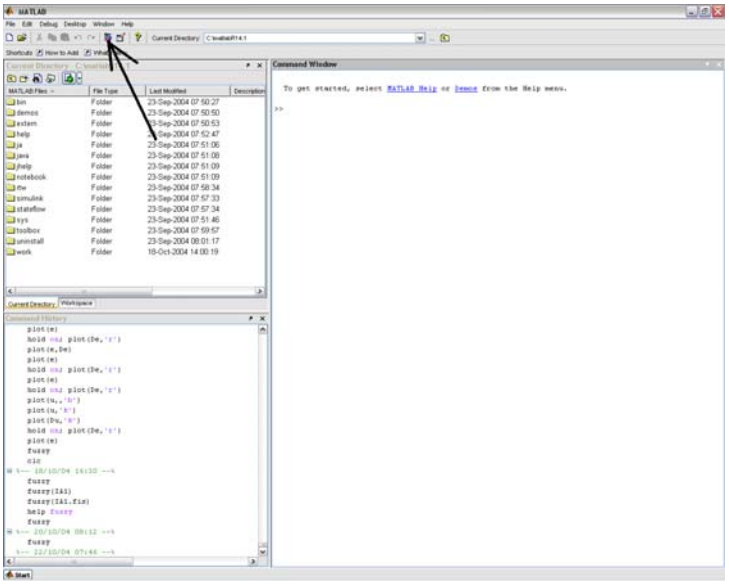
- An explicit Runge-Kutta (4,5) formula, the Dormand-Prince pair (ODE45).
- An explicit Runge-Kutta (2,3) pair of Bogacki and Shampine (ODE23).
- A variable-order Adams-Bashforth-Moulton PECE solver (ODE113).
- A variable order solver based on the numerical differentiation formulas (NDFs) (ODE15s).
- A modified Rosenbrock formula of order 2 (ODE23s).
- An implementation of the trapezoidal rule using a "free" interpolant (ODE23t).
- An implementation of TR-BDF2, an implicit Runge-Kutta formula with a first stage that is a trapezoidal rule step and a second stage that is a backward differentiation formula of order two (ODE23tb).

Note the solvers that contain the letter 's' are stiff solvers. For more information about stiff solvers and ODE in general you can look at the Simulink help file files or at some specialised books about numerical solutions.

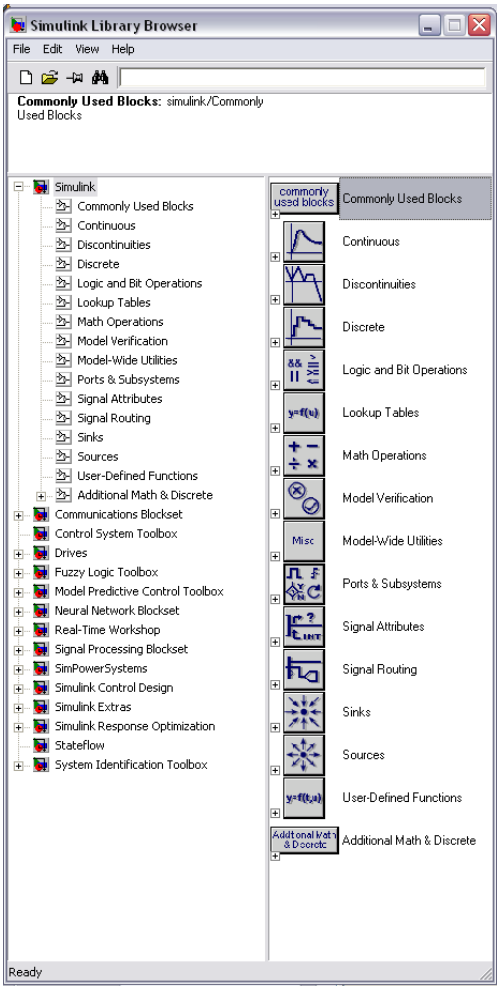
To summarise the best method is ODE5 (or ODE45), unless you have a stiff problem, and a smaller the step size is better, within reason.

8.2 Solving ODE

Since the key idea of Simulink is to solve ODE let us see an example of how to accomplish that. Through that example many important features of Simulink will be revealed.
To start Simulink click on the appropriate push button from the command window:

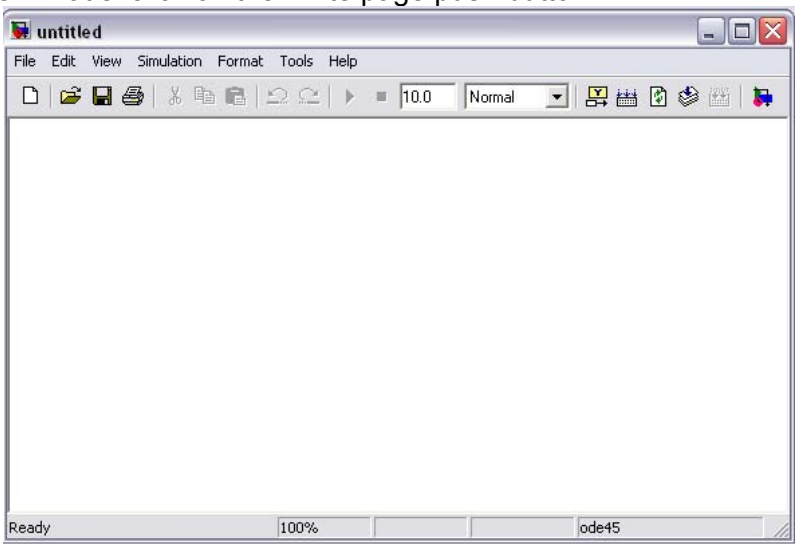


The next window will appear:

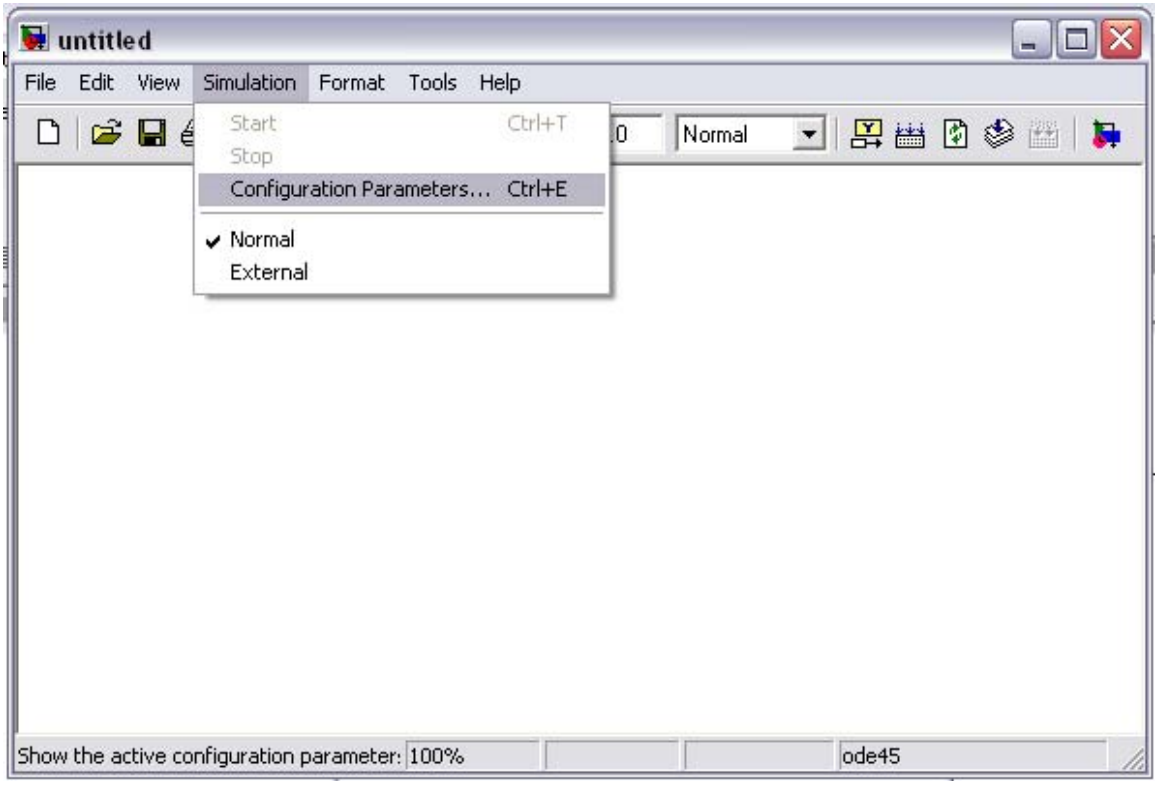


These are the libraries of Simulink. As it can be seen there are many of them and even more sub-libraries. In order to be able to find the appropriate blocks you must spend some time in looking in those libraries. After some time you will be able to find quickly any blocks that you may need.

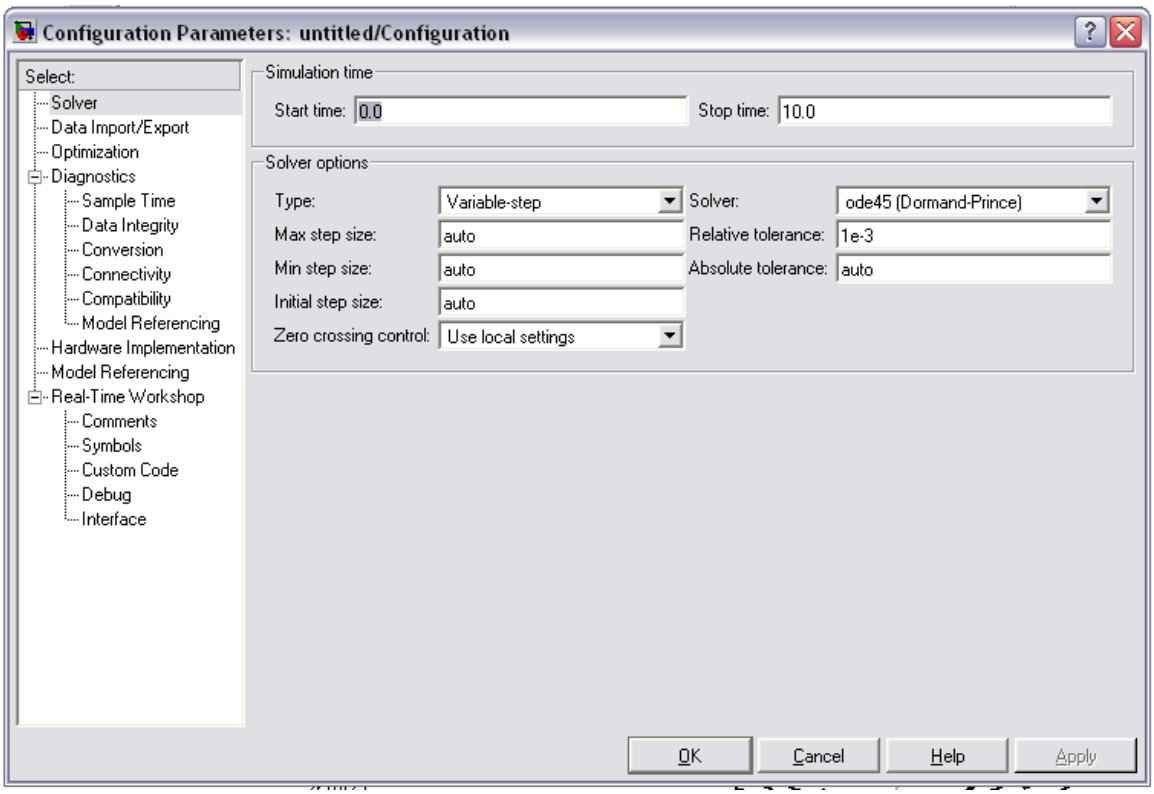
To create a new model click on the white page push button:



The most important menu that you must know is the parameters menu which can be found:



Then this window will appear:

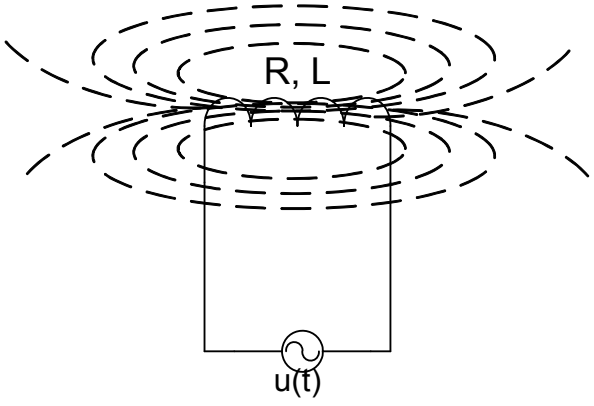


Here you can define the start and stop time of the simulation and the solver options where you can choose variable or fixed step size, the solver method and the step size. If you choose a variable step size, remember that the minimum step size must be less than the maximum.
Let's solve now a very easy ODE.

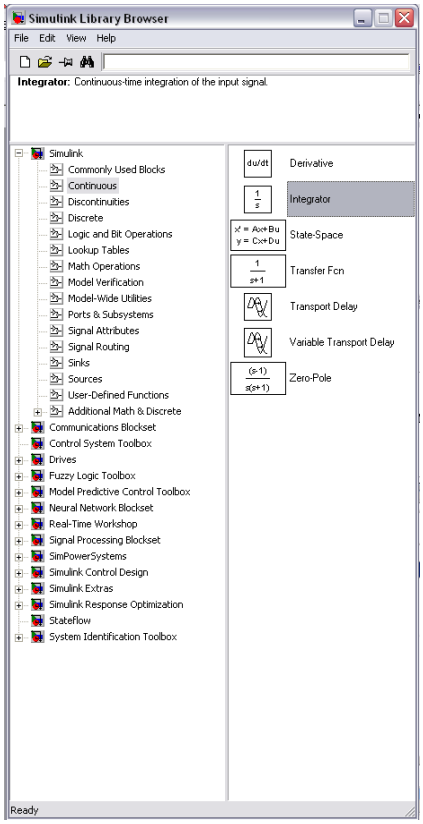
8.2.1 Examples

Example A

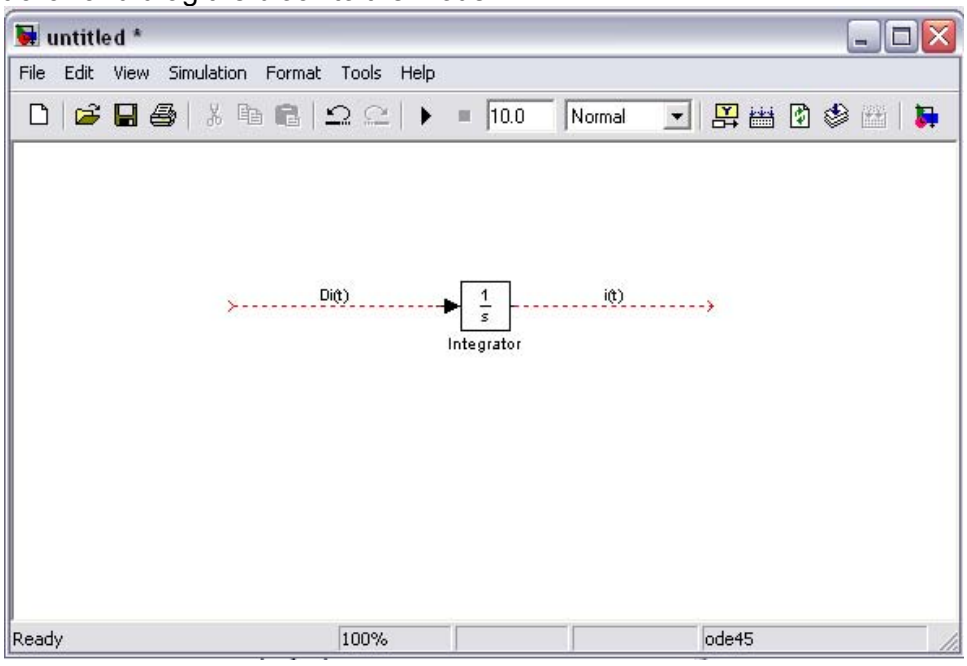
Consider the coil shown in the next figure. The voltage supply is equal to: $u(t) = i(t)R + \frac{d\psi(t)}{dt}$. Assuming that the inductance of the coil is constant the above equation is: $u(t) = i(t)R + L\frac{di(t)}{dt}$. This is a linear 1st order ODE. What is the response of the current to a sudden change of the voltage, assuming zero initial conditions? To answer this we must solve the above ODE. There are various ways to solve it (Laplace...). Here we will try to solve it numerically with Simulink.



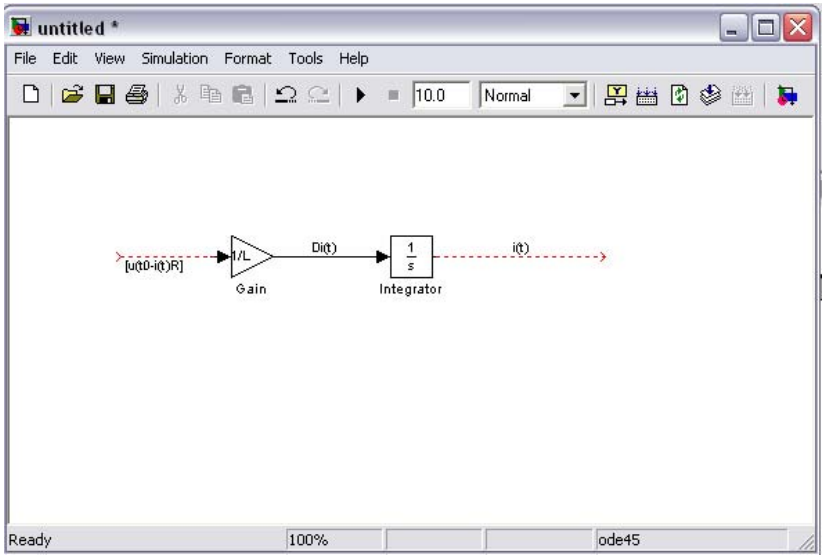
- Step 1: First of all we must isolate the highest derivative: $\frac{di(t)}{dt} = \frac{1}{L}(u(t) - i(t)R)$
- Step 2: We will use as many integrators as the order of the DE that we want to solve: The integrator block is in:



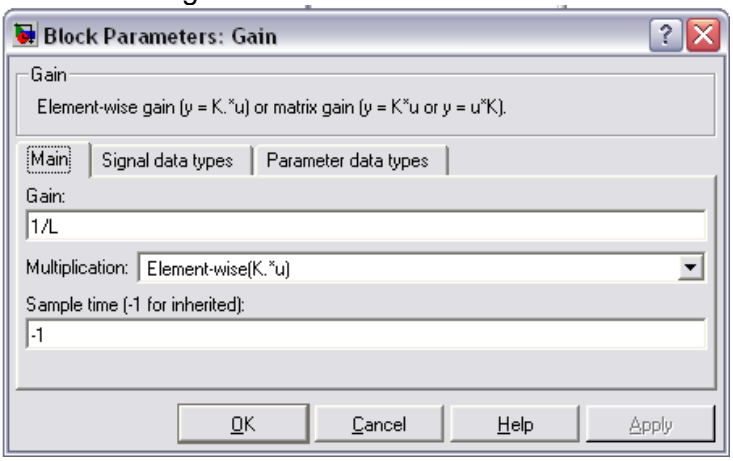
Just click and drag the block to the model:



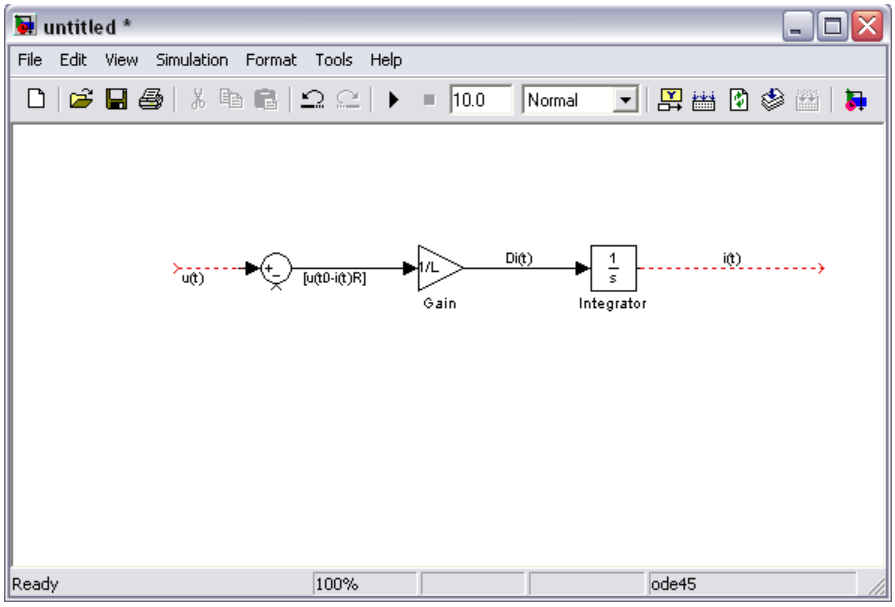
- Step 3: Beginning at the input of the integrator we construct what we need, hence here we must create the factor $\frac{1}{L}\left(u(t)-i(t)R\right)$ which is equal to *Di(t)*. First put a gain of $1/L$:

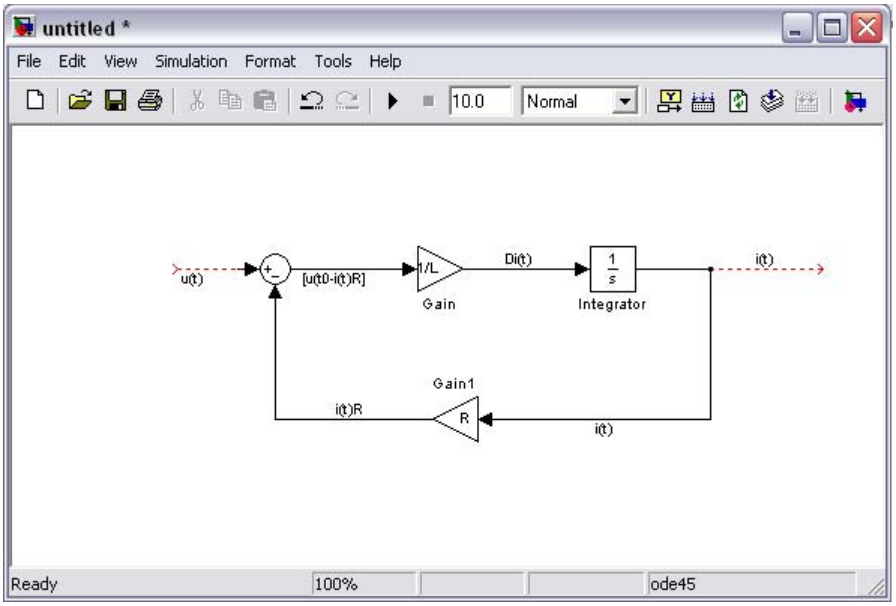


To set the value of the gain block double click on it and then change its value:

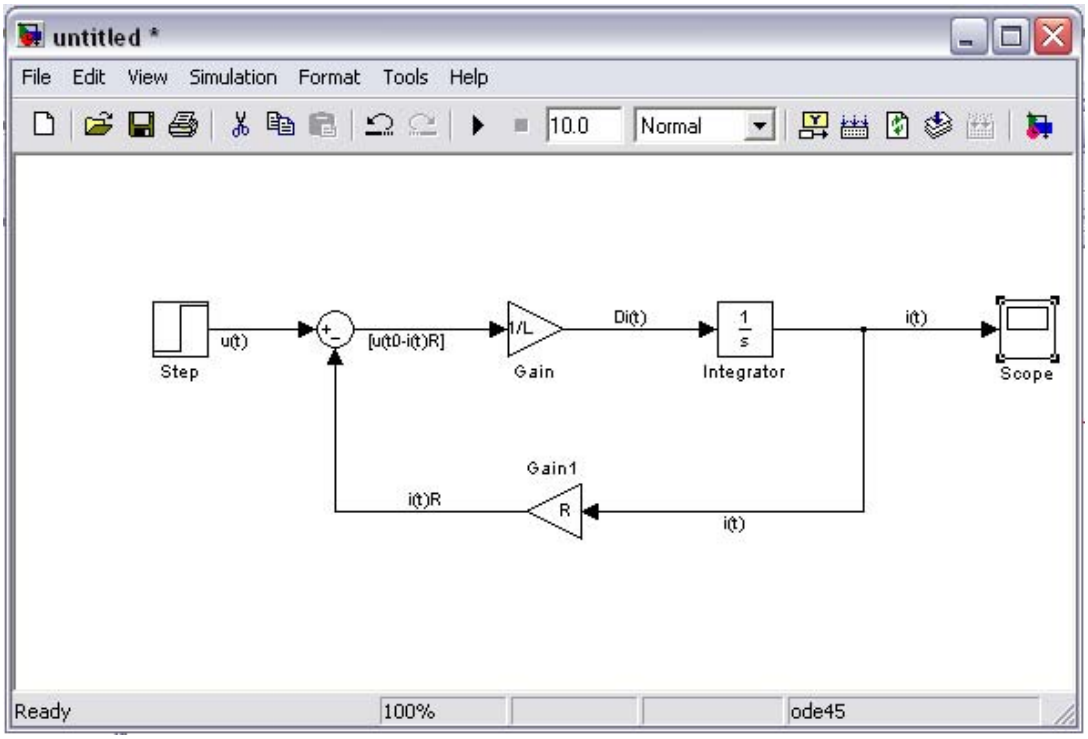


- Step 4: Now the term [*u(t)-I(t)R*] must be constructed, we will need a summation point and another gain:

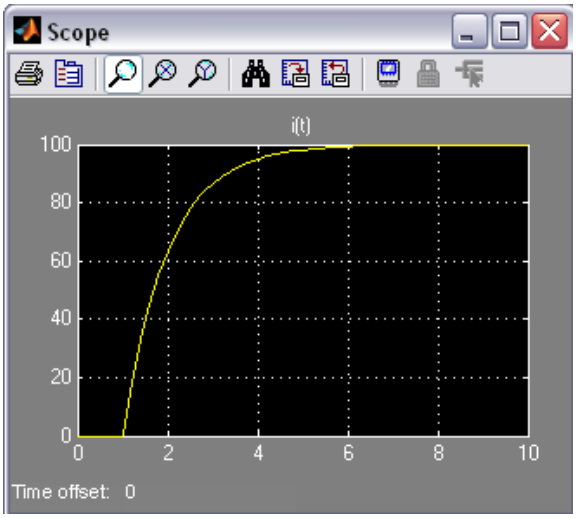




- Step 5: Now we must add an input signal to simulate the voltage change and something to see the response of the current. For the voltage change we chose to use a step input of amplitude 1 and for the output we can use a scope:

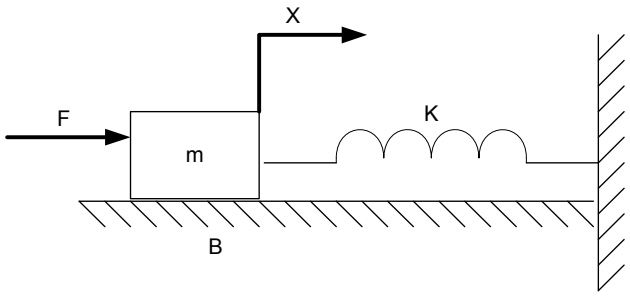


- Step 6: To run the simulation we must give values to *L*, *R*. In the workspace we type: *R*=0.01; *L*=0.01.
- Step 7: To see the solution we must run the simulation and then double click on the Scope:



Example B

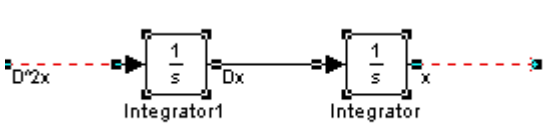
The second example is a classical mass-spring system:



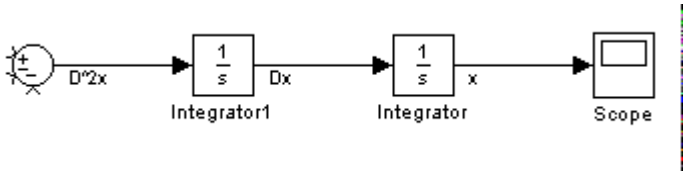
By applying Newton's second law: $\sum \bar{F} = m\bar{a}$, or: $F(t) - Kx(t) - Bu(t) = ma(t)$, where *F* is the external force applied on the mass (*m*), *K* is the spring constant, *a* is the acceleration of the mass, *u* is the speed of the mass, *x* is the distance that is covered and *B* is the friction factor. $F(t) - Kx(t) - B\frac{dx(t)}{dt} = m\frac{d^2x(t)}{dt}$. The question here is what is going to be the behaviour of the mass due to a sudden force change, assuming again zero initial conditions. To solve we will follow the previous steps:

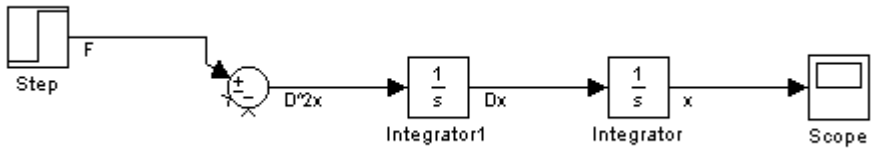
First isolate the highest derivative: $\frac{d^2x(t)}{dt} = \frac{1}{m}\left(F(t) - Kx(t) - B\frac{dx(t)}{dt}\right)$

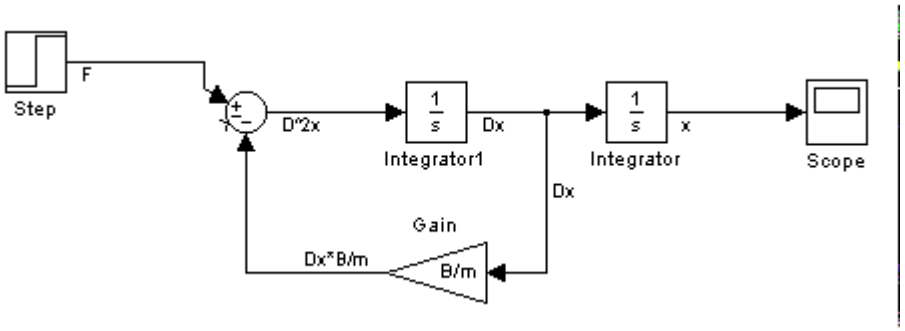
Secondly place as many integrators as the order of the DE:

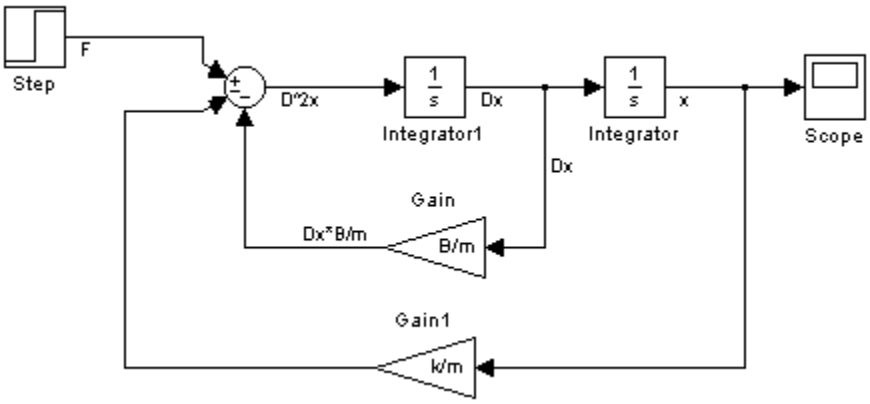


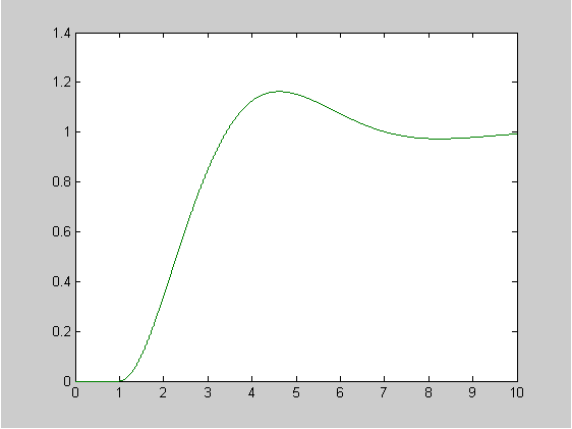
Beginning from the end construct everything that you need:









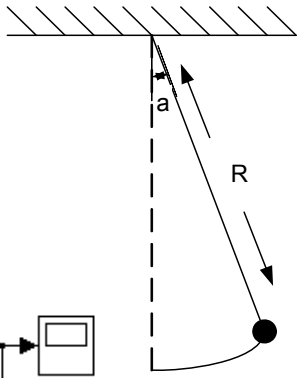


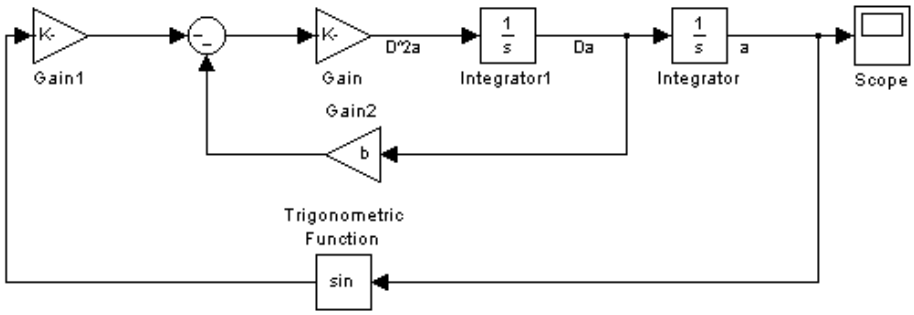
Example C

The pendulum shown has the following nonlinear DE:

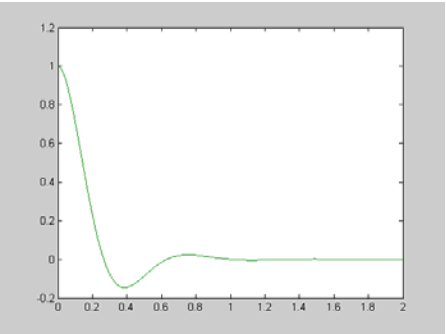
$$MR^2 \ddot{a} + b\dot{a} + MgR\sin(a) = 0$$

Its Simulink block is:





To find its response we must double click on the last integrator whose output is the angle *a* and set the initial conditions to 1.



8.2.4 Exercise

Solve the following nonlinear DE: $m\ddot{x} + 2c\left(x^2 - 1\right)\dot{x} - kx = 0$. Take: *m*=1, *c*=0.1 *k*=1.

This is the Van der Pol equation and can correspond to a mass spring system with a variable friction coefficient.