

# Introduction to MATLAB

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Faculty of mathematics  
and physics

# Section 1

## Introduction



MATLAB is a high-level programming language for numerical computation.

- Can be used in an *interactive* calculator-style mode
- Can also be used to write complex scripts/programs for numerical computation

These slides present a *very brief* overview of MATLAB. You will potentially need to study more yourself using books/online resources.

The documentation within MATLAB is also a good place to look (especially to find built-in MATLAB functions).



Stormy Attaway.

*Matlab: A Practical Introduction to Programming and Problem Solving.*

Butterworth-Heinemann, Boston, third edition, 2013.

URL

<http://www.sciencedirect.com/science/book/9780124058767>.



Timothy A. Davis.

*MATLAB Primer.*

CRC Press, Boca Raton, eighth edition, 2010.



Brian R. Hunt, Ronald L. Lipsman, and Jonathan M. Rosenberg.

*A Guide to MATLAB for Beginners and Experienced Users.*

Cambridge University Press, Cambridge, third edition, 2014.

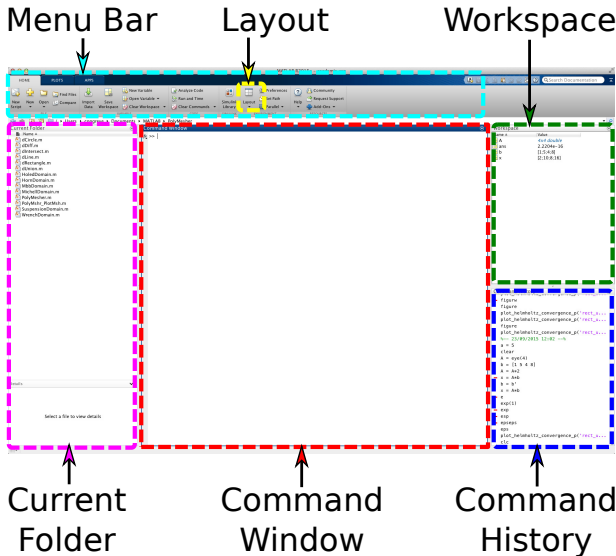


MathWorks.

MATLAB Central, 2019.

URL <https://www.mathworks.com/matlabcentral/>.  
[Online].

# Overview of the UI





*Command Window* consists of a prompt (`>>`) at which MATLAB commands can be entered. Results are also displayed in the *Command Window*.



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MATLAB keeps a history of all commands (see the *Command History* panel). Use  and  arrow keys on the keyboard to scroll through history.



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To exit MATLAB type `exit` at the prompt.



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```

A special `..` directory can be used to change to the *parent directory*. If any folder contains a space you should surround the path with single quotation marks:

```
>> cd '..\Folder With Space\Folder'
```



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You can also change the current directory by using

```
>> cd path
```

A special `..` directory can be used to change to the *parent directory*. If any folder contains a space you should surround the path with single quotation marks:

```
>> cd '.. /Folder With Space /Folder'
```

You can see a list of all files in the current directory with the `ls` command,



MATLAB has built-in documentation, which can be viewed in two different ways.

1. A graphical help window which can be launched via the UI, or by entering the command `doc`. The `doc` command can be followed by a name (MATLAB function) to display help for that function.





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1. A graphical help window which can be launched via the UI, or by entering the command `doc`. The `doc` command can be followed by a name (MATLAB function) to display help for that function.
2. A text-based help displayed directly in the *Command Window*. Enter the `help` command to view. Again you may add a name of a function/command to display the help for that command.



## help Example

```
>> help sin
sin      Sine of argument in radians.
sin(X)  is the sine of the elements of X.

See also asin, sind.

Other functions named sin

Reference page in Help browser
doc sin
```

## Section 2

# Basic Mathematics



MATLAB supports several basic scalar mathematical operators:

- + for addition,
- - for subtraction,
- \* for multiplication,
- / for division,
- ^ for raising to a power, and
- \ for left division (divides the second term by the first).



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- + for addition,
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Using these basic commands you can use MATLAB as a calculator; i.e., entering

## Basic Calculations

```
>> 5^2+9.5-11*2  
ans =  
    12.5000
```

displays the result of  $5^2 + 9.5 - 11 \times 2$



MATLAB follows the basic mathematical rules for precedence;  $\wedge$ , then  $*$  and  $/$ , and then  $+$  and  $-$ . Operators of same precedence evaluated left-to-right. Brackets  $( )$  can be used to specify order of evaluation.

## Evaluating $(2^2)^3$ and $2^{2^3}$

```
>> 2^2^3  
ans =  
    64
```

```
>> 2^(2^3)  
ans =  
   256
```

Multiplication symbol must be used wherever multiplication is required.

## Demonstration of Requirement for Multiplication Symbol

```
>> 2(4+5)
```

```
  2(4+5)
```

```
  |
```

```
Error: Unbalanced or unexpected parenthesis or bracket.
```

```
>> 2*(4 + 5)
```

```
ans =
```

```
  18
```



MATLAB all numbers generated are of *double* type (by default). This means it represents floating-point numbers, but we have to allow for rounding errors in computations.





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MATLAB allows numbers in an exponential (base 10) form:

- $1.5\text{e-}10 \equiv 1.5 \times 10^{-10}$ , and
- $7.95\text{e}5 \equiv 7.95 \times 10^5$ .



By default MATLAB displays numbers in *short* form (four decimal places).

## Short Format for Real Numbers

```
>> 190.2  
ans = 190.2000  
>> 1909.205  
ans = 1.9092e+03
```

By default MATLAB displays numbers in *short* form (four decimal places).

## Short Format for Real Numbers

```
>> 190.2  
ans = 190.2000  
>> 1909.205  
ans = 1.9092e+03
```

Enter `format long` to display in *long* form (15 decimal places) and `format short` for short form. See `help format` for complete list of formats.

## Short Format for Real Numbers

```
>> format long  
>> 19.2  
ans = 19.199999999999999  
>> 1909.205  
ans = 1.9092050000000000e+03
```



MATLAB has several built-in constants/special.

- `pi` returns the constant value for  $\pi$ ,
- `eps` returns difference between 1 and next largest double number,
- `inf` or `Inf` represent  $\infty$ ,
- `-inf` or `-Inf` represent  $-\infty$ , and
- `nan` or `NaN` represents a special *Not a Number* value.



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## MATLAB Constants/Special Values

```
>> 0/0
ans =     NaN
>> 1/0
ans =     Inf
>> -1/0
ans =   -Inf
>> pi
ans =     3.141592653589793
>> eps
```



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When assigning a variable, the value stored is output in the *Command Window*; this can be suppressed by suffixing with a semicolon (;).



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## Definition and Usage of Variables

```
>> x = 2^2
```

```
x =  
    4
```

```
>> 5*x+9
```

```
ans =  
    29
```

```
>> y = 9;
```

```
>> y  
y =  
    9
```



Several rules exist for variable names:

- Start with a letter,
- Contain letters, numbers or the underscore `_` only,
- They are *case sensitive* (`A`  $\neq$  `a`), and
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By *letters* we mean the 26 *English* letters (i.e., NO `č`, `ř`, `é`, etc).



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When working in the *Command Window* all variables are saved in the *Workspace*. Use the *Workspace* panel, or enter `who` or `whos` command, to see a list of variables.

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When working in the *Command Window* all variables are saved in the *Workspace*. Use the *Workspace* panel, or enter `who` or `whos` command, to see a list of variables.

Clear all variables from the current workspace with the `clear` command; alternatively, clear a single variable or list of variables by enter the names of the variables after the `clear` command.

## Clearing Only Some Variables

```
>> clear x y
```



MATLAB also supports complex numbers. To specify an imaginary number you use `i` or `j` directly or as a suffix to a number.



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## Definition of Complex Number

```
>> z = 5+4i  
z =  
    5.0000 + 4.0000i
```



MATLAB has a large collection of built-in functions for mathematical operations.

Functions are called by giving the name of the function followed by the arguments within brackets after the name.

## Calling a Function

```
>> sin(pi/2)
ans =
    1
```

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## Calling a Function

```
>> sin(pi/2)
ans =
    1
```

Some functions can take more than one argument; in this case, we enter the arguments separated by a comma.

## Calling a Function with Multiple Arguments

```
>> min(pi, 3)
ans =
```



Below is a non-exhaustive list of basic mathematical functions.

`sin, cos, tan, cot, sec, csc`

`asin, acos, atan, acot, sec, csc`

`sinh, cosh, tanh, coth, sech, csch`

`asinh, acosh, atanh, acoth, asech, acsch`

`abs`

`exp`

`log, log10, log2`

`fix, floor, ceil, round`

`sqrt, nthroot`

`angle`

`conj`

`real, imag`

Trigonometric functions

Inverse trigonometric functions

Hyperbolic functions

Inverse hyperbolic functions

Absolute value  $|x|$

Exponential function  $e^x$

Logarithmic function ( $e$ ,  $10$  &  $2$ )

Round: zero, down, up, nearest.

Square and  $n$ th root.

Phase angle (complex number)

Complex conjugate

Real/imaginary parts

Enter `help elfun` for a more complete list.

## Section 3

# Vectors & Matrices

The basic method to create a vector/matrix is to use square brackets `[]` containing a list of numbers to place in the matrix.

Each row of a matrix is a list of numbers separated by either a space and/or a comma, and each row is separated by a semi-colon `;`.

## Generating Matrices/Vectors Directly

```
>> A = [1 9 7; -3 8 0; 2 -7 -9]
```

```
A =
```

```
     1     9     7
    -3     8     0
     2    -7    -9
```

```
>> x = [5 -8 0 9]
```

```
x =     5     -8     0     9
```

```
>> y = [-2; 3; 6]
```

```
y =
```

```
    -2
     3
     6
```



The previous notation is really a concatenation of matrices/vectors. The space/comma concatenates columns and the semi-colon concentrates rows.

The previous notation is really a concatenation of matrices/vectors. The space/comma concatenates columns and the semi-colon concentrates rows. We can concatenate matrices into larger matrices using this notation, providing the sizes are compatible.

## Matrix/Vector Concatenation

```
>> B = [A y; x]
```

```
B =
```

1	9	7	-2
-3	8	0	3
2	-7	-9	6
5	-8	0	9

*start:step:end* or *start:end* syntax defines sequences (row vector), where

- *start* is the first number in the sequence,
- *step* is the difference between elements (defaults to 1), and
- *end* is the last number that can be contained in the sequence.

## Generating Sequence Vector

```
>> 1:4
```

```
ans =
```

```
1 2 3 4
```

```
>> 1:0.5:3
```

```
ans =
```

```
1.0000 1.5000 2.0000 2.5000 3.0000
```

```
>> 1:2:6
```

```
ans =
```

```
1 3 5
```

```
>> 7:-1:1
```

```
ans =
```

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



The *end* value is not always included in the sequence. A sequence of equally distributed values (including start and end) can be generated with the `linspace(start, end, no_points)` function.

## Example Usage of linspace

```
>> linspace(1,2,6)
ans =
    1.0000    1.2000    1.4000    1.6000    1.8000    2.0000

>> linspace(1,0,6)
ans =
    1.0000    0.8000    0.6000    0.4000    0.2000    0
```



Below is a list of basic matrix construction routines.

- `eye` Identity matrix (1 on diagonal, 0 elsewhere)
- `zeros` Matrix filled with 0
- `ones` Matrix filled with 1
- `rand` Uniformly distributed numbers between 0 and 1
- `randn` Normally distributed numbers between 0 and 1

These functions take three different formats:

- Single scalar ( $N$ ) — Generates a  $N \times N$  matrix
- Two scalars ( $N$  and  $M$ ) — Generates a  $N \times M$  matrix
- Vector of two values ( $[N M]$ ) — Generates a  $N \times M$  matrix



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- Vector of two values ( $[N M]$ ) — Generates a  $N \times M$  matrix

## Matrix Construction Functions

```
>> ones(2,3)
ans =
     1     1     1
     1     1     1
```



The `diag` function takes a vector and places entries on the leading diagonal of a matrix. A second optional integer allows a different diagonal to be set.

## Creating a Diagonal Matrix

```
>> diag([1 2])
```

```
ans =  
    1     0  
    0     2
```

```
>> diag([1 2],1)
```

```
ans =  
    0     1     0  
    0     0     2  
    0     0     0
```

```
>> diag([1 2],-1)
```

```
ans =  
    0     0     0  
    1     0     0  
    0     2     0
```

The `reshape` function allows a matrix to be reshaped. This function takes a matrix as the first argument followed by a matrix size. An empty vector `[]` allows MATLAB to automatically calculate the size of that dimension.

## Reshaping a Matrix

```
>> A = rand(4,2);  
>> reshape(A,[2 4])  
ans =  
    0.7363    0.6834    0.4423    0.3309  
    0.3947    0.7040    0.0196    0.4243  
  
>> reshape(A,2,[])  
ans =  
    0.7363    0.6834    0.4423    0.3309  
    0.3947    0.7040    0.0196    0.4243
```

The number of elements in the reshaped matrix must be the same as in the original matrix.

An vector/matrix is accessed with element index in brackets (starting at 1). Matrices should use two indices (row and column).

A special value of `end` can be used to index the last value.

## Basic Matrix/Vector Indexing

```
>> A = rand(2)
```

```
A =
```

```
    0.8147    0.6324
```

```
    0.9058    0.0975
```

```
>> A(1,2)
```

```
ans =
```

```
    0.6324
```

```
>> x = 1:5;
```

```
>> x(3)
```

```
ans =
```

```
    3
```

```
>> x(end)
```

```
ans =
```

An index can also be a vector of indices or a single `:` for *all* values (useful for extracting a complete row or column).

## Vector Indices for Matrix/Vector Indexing

```
>> x([1 3])
ans =
     1     3
>> x(end:-1:2)
ans =
     5     4     3     2
>> A(2,:)
ans =
    0.9058    0.0975
>> A(:,2)
ans =
    0.6324
    0.0975
```

You can change matrix entries by indexing and then assigning with `=`. You can delete values by assigning to them the empty matrix `[]`.

## Vector Indices for Matrix/Vector Indexing

```
>> A(2,2) = 1
A =
    0.8147    0.6324
    0.9058    1.0000
>> A(end, :3) = 0.5
A =
    0.8147    0.6324
    0.5000    0.5000
>> A(end, 1:2) = [0.25 0.7]
A =
    0.8147    0.6324
    0.2500    0.7000
>> x(2:3) = []
x =
```

The `size` returns a vector containing the dimension of a matrix.

The `length` function returns the size of the largest dimension.

## Obtaining Matrix/Vector Size

```
>> size(A)
ans =
     2     2
>> size(x)
ans =
     1     3
>> length(A)
ans =
     2
>> length(x)
ans =
     3
```

As `size` returns a two-value vector you can use the result as an argument

The basic mathematics function can be used for matrix operations.

- + for element-wise addition (can be applied to two matrices or a matrix and scalar),
- - for element-wise subtraction (can be applied to two matrices or a matrix and scalar),
- \* for matrix-scalar multiplication or matrix-matrix multiplication,
- / for division of each matrix element by a scalar,
- ^ for raising a matrix to a scalar power, and
- \ for left division of each matrix element by a scalar.

## Matrix Multiplication

```
>> A = [2 0.5 1.5 4; 0 6 3 1];  
>> x = [1;2;3;4];  
>> A*x  
ans =  
    23.5000  
    25.0000
```





MATLAB also supports element-wise arithmetic operators. These apply the matching scalar operation to the elements with the same index when applied to matrices of the same size.

- `.*` for element-wise multiplication,
- `./` for element-wise division,
- `.^` for element-wise raising to a power, and
- `.\` for element-wise left division.

When applied to a matrix and scalar the scalar is treated as a matrix of the same size filled with the scalar.

## Element-wise Multiplication

```
>> A = [2 0.5 1.5 4; 0 6 3 1];  
>> B = [3 1 4 6; 2 0 9 0];  
>> A.*B  
ans =  
    6.0000    0.5000    6.0000   24.0000  
         0         0   27.0000         0
```



MATLAB has two matrix suffix operators (and matching functions) to take the transpose.

- `'` (or `ctranspose`) transposes and takes the complex conjugate, and
- `.'` (or `transpose`) just transposes

## Transpose

```
>> Z = [2+1i 1-8i; 0.5-0.5i 9];
>> Z'
ans =
    2.0000 - 1.0000i    0.5000 + 0.5000i
    1.0000 + 8.0000i    9.0000 + 0.0000i
>> Z.'
ans =
    2.0000 + 1.0000i    0.5000 - 0.5000i
    1.0000 - 8.0000i    9.0000 + 0.0000i
```

MATLAB can solve linear systems by use of the left division ( $\backslash$ ) and division ( $/$ ) operators. Given two matrices  $A, B$  and a vector of unknowns  $x$ ; then,

- $x = A \backslash B$  gives the solution to the equation  $Ax = B$ , and
- $x = B/A$  gives the solution to the equation  $xA = B$ .

## Solving Linear Systems

```
>> A = [3 1 -1; 1 1 1; 0 1 -1];  
>> B = [0;0;1];  
>> A \ B  
ans =  
   -0.3333  
    0.6667  
   -0.3333  
>> B' / A  
ans =  
   -0.1667    0.5000   -0.3333
```

Below is a non-exhaustive list of functions for vectors.

<code>min, max</code>	Minimum/maximum value in the vector
<code>sum</code>	Sum of all values
<code>prod</code>	Product of all values
<code>mean, median</code>	Mean/median of the values
<code>std, var</code>	Standard deviation/variance of the values
<code>cumsum</code>	Cumulative sum of the values
<code>cumprod</code>	Cumulative product of the values
<code>sort</code>	Sorts the values in the vector

These can also be applied to matrices, in which case each column of the matrix is treated as a different vector by default, returning a row vector of the results.

Below is a non-exhaustive list of functions for matrices.

<code>inv</code>	Inverse a matrix (do not use for solving linear systems)
<code>det</code>	Calculate the determinant of a matrix
<code>trace</code>	Calculate the trace of a matrix
<code>norm</code>	Calculate a norm of the matrix (defaults to 2-norm)
<code>rank</code>	Calculate the rank of the matrix
<code>eig</code>	Calculate eigenvalues and eigenvectors of the matrix
<code>poly</code>	Calculate characteristic polynomial of the matrix
<code>cond</code>	Calculate the condition number of the matrix
<code>expm, logm</code>	Matrix exponential and logarithm
<code>sqrtm</code>	Square root of the matrix

The basic mathematics functions we saw earlier can also be applied to vectors/matrices (usually element-wise).

`eig` returns multiple values. To access all returns list variable names separated by commas (surrounded by square brackets `[]`) on the left of the assignment. To ignore a return use the tilde `~` instead of a function name.

## Multiple Returns

```
>> [V,D] = eig(A)
V =
   -0.9011    0.2579    0.2860
   -0.4226   -0.8773   -0.4480
   -0.0969   -0.4048    0.8471
D =
    3.3615         0         0
         0    1.1674         0
         0         0   -1.5289
>> [V,~] = eig(A)
V =
   -0.9011    0.2579    0.2860
   -0.4226   -0.8773   -0.4480
```

## Section 4

# Strings

MATLAB supports string/character values. A string is essentially a special vector of characters, entered using single quotation marks. You can access sub-strings and characters using standard indexing.

## String Example

```
>> str = 'This is a test string'  
str =  
This is a test string  
>> str(6)  
ans =  
i  
>> str(11:14)  
ans =  
test
```



You can concatenate strings by surrounding multiple values/literals with square brackets [].

## String Concatenation

```
>> newstr = ['Concatenate "' str '" in the middle']  
newstr =  
Concatenate "This is a test string" in the middle
```



MATLAB has a couple of functions for converting numbers to strings.

- `num2str` converts a number to a string (4 decimal places). An optional integer argument can specify the number of decimal places, and
- `sprintf` is a more complex number formatter (check documentation).

## Formatting Numbers

```
>> num2str(2.53380112)
ans =
2.5338
>> num2str(2.53380112,7)
ans =
2.533801
>> sprintf('%08d',4)
ans =
00000004
>> sprintf('Test %d %d %d; ', [3 1 -1; 1 1 1; 0 1 -1])
ans =
Test 3 1 0; Test 1 1 1; Test -1 1 -1;
```

MATLAB by default outputs results of its computation in its own format. Using strings it is possible to generate customised text output using the `disp` command, which outputs a string to the *Command Window*.

## Displaying Text

```
>> disp(['Fact.: ' sprintf('\n%4d: %8d', [x; cumprod(x)])])
```

Fact.:

1:	1
2:	2
3:	6
4:	24
5:	120
6:	720
7:	5040
8:	40320
9:	362880
10:	3628800

## Section 5

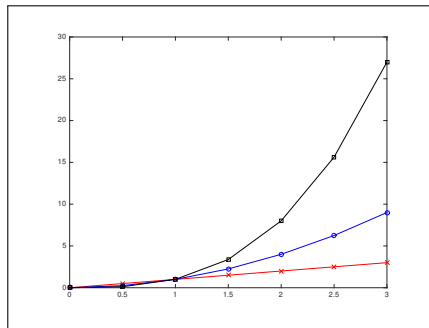
# Graphics

The `plot` function plots  $x$  and  $y$  data as a line plot. A third argument specifies a *line specification* string: colour, marker and line type.

	Colour		Marker		Line
b	Blue	.	Point	-	Solid
g	Green	o	Circle	:	Dotted
r	Red	x	Cross	-.	Dash-dot
c	Cyan	+	Plus	--	Dashed
m	Magenta	*	Star	(none)	No line
y	Yellow	s	Square		
k	Black	d	Diamond		
w	White	v	Triangle (down)		
		^	Triangle (up)		
		<	Triangle (left)		
		>	Triangle (right)		
		p	Pentagram		
		h	Hexagram		

## Basic Plotting

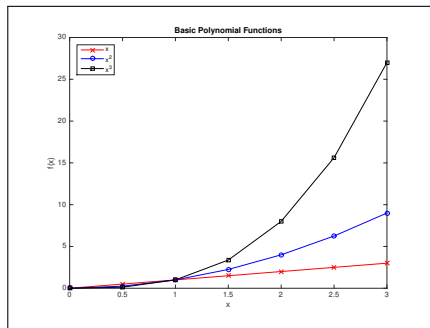
```
>> x = 0:0.5:3;  
>> plot(x,x, '-xr', x,x.^2, '-ob', x,x.^3, '-sk')
```



`plot` uses a linear x and y axis. `loglog`, `semilogx`, and `semilogy`, are identical but use (one or more) logarithmic axis.

## Annotating a Plot

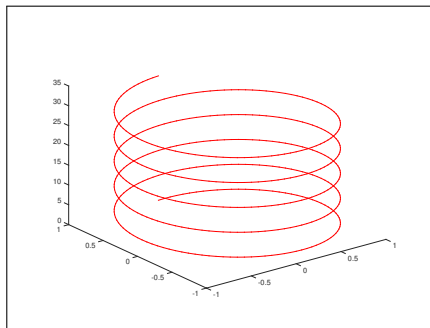
```
>> xlabel('x')  
>> ylabel('f(x)')  
>> title('Basic Polynomial Functions')  
>> legend('x', 'x^2', 'x^3', 'Location', 'NorthWest')
```



`plot3` is used for 3D line plots.

## 3D Line (Parametric) Plot

```
>> t = linspace(0,10*pi,501);  
>> plot3(sin(t),cos(t),t,'-r')
```



The annotations work as before (with an extra `zlabel` function).





`surf` is used to plot 3D data. This function takes three arguments, for the  $x$ ,  $y$  and  $z$  data.  $z$  must be a  $M \times N$  matrix; whereas,  $x$  and  $y$  can be a matrix or a vector.

- If  $x$  and  $y$  are matrices they must be the same size as the  $z$  matrix — matching elements from the vectors denotes a  $x$ ,  $y$  and  $z$  point to plot.
- If  $x$  is a vector of length  $N$  and  $y$  vector of length  $M$  each point plotted is  $(x(j), y(i), z(i, j))$ .

The `meshgrid` function takes a  $x$  and  $y$  vector and creates a full  $x$  and  $y$  matrix representing the tensor points.

## Mesh Grid

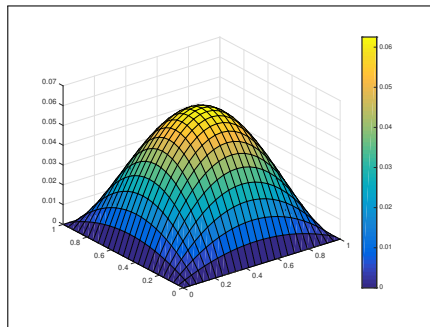
```
>> x = linspace(0,1,5);  
>> [X, Y] = meshgrid(x,x)
```

```
X =  
    0    0.2500    0.5000    0.7500    1.0000  
    0    0.2500    0.5000    0.7500    1.0000  
    0    0.2500    0.5000    0.7500    1.0000  
    0    0.2500    0.5000    0.7500    1.0000  
    0    0.2500    0.5000    0.7500    1.0000
```

```
Y =  
    0         0         0         0         0  
0.2500    0.2500    0.2500    0.2500    0.2500  
0.5000    0.5000    0.5000    0.5000    0.5000  
0.7500    0.7500    0.7500    0.7500    0.7500  
1.0000    1.0000    1.0000    1.0000    1.0000
```

## 3D Surface Plot


```
>> x = linspace(0,1,25);  
>> [X, Y] = meshgrid(x,x);  
>> surf(X, Y, X.*Y.*(1-X).*(1-Y))  
>> colorbar
```

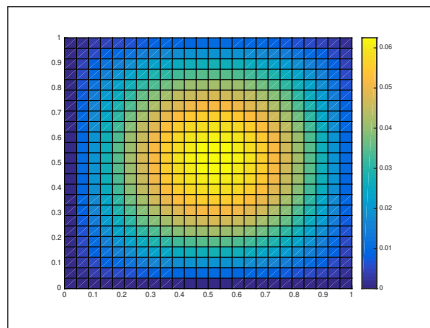




The `colorbar` function displayed a colour bar on the active plot. The colour scheme used can be changed by the `colormap` function. `help graph3d` for a list available colour maps.

The `colorbar` function displayed a colour bar on the active plot. The colour scheme used can be changed by the `colormap` function. `help graph3d` for a list available colour maps.

`Rotate 3D` tool-bar button () allows plot rotation by dragging within the plot area. The `view(2)` or `view(3)` function switches the current plot view to a 2D top-down view or the default 3D view, respectively.



Other 3D plot functions exist:

`mesh`

Plots mesh, rather than surface

`contour`

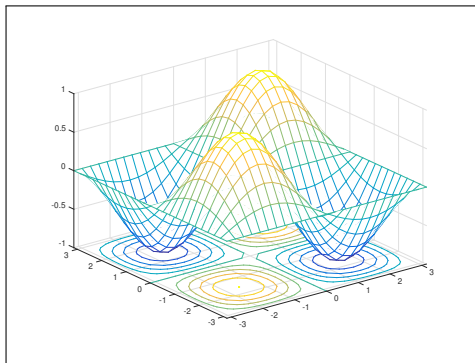
Plots a contour

`surf`, `meshc`

Plots surface/mesh with contour underneath

`trisurf`, `trimesh`

Takes 3 vectors and  $M \times 3$  vector of triangles (indices)



## Section 6

# Programming



MATLAB scripts are simple text files (with a `.m` extension) filled with MATLAB commands to execute.

Scripts are executed by typing the name of the file (without extension) at the prompt.

All variables and values in the script file are saved into the workspace.



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Scripts are executed by typing the name of the file (without extension) at the prompt.

All variables and values in the script file are saved into the workspace.

To start editing a script file within MATLAB either:

- Create a file with `Home` `>` `New Script` or `Home` `>` `New` `>` `Script` menu bar buttons, or
- Type `edit filename` at the prompt (where *filename* is the name of the file). If a file with the name already exists it will be opened for editing; otherwise, a prompt will ask if you want to create a script with that name.

The *Editor* window will appear with the file to edit.



MATLAB scripts may contain the following:

- Comments (lines not executed) in MATLAB start with a percentage sign %,
- Blank lines,
- MATLAB commands, and
- Block statements (`if`, `for`, `while`, `switch`, etc).

When run the script will output the result of any command not ending in a semi-colon ;.

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- Comments (lines not executed) in MATLAB start with a percentage sign %,
- Blank lines,
- MATLAB commands, and
- Block statements (`if`, `for`, `while`, `switch`, etc).

When run the script will output the result of any command not ending in a semi-colon ;.

With scripts it is desirable to keep lines short so they can be easily read. To split a line over multiple lines use the *line continuation ellipsis* ... (three periods) at the end of the line to continue.

## Sample Script

```
% This is a comment

% Set up variables
A = [3 1 -1; 1 1 1; 0 1 -1];
B = [0;0;1];

% Print out some matrix properties
disp('Properties of A:');
disp(['    Condition number:          ' num2str(cond(A))]);
disp(['    Determinant:                ' num2str(det(A))]);

% Following command is split over two lines
fprintf(['    Characteristic Polynomial: ' ...
        '%.1fx^3+.1fx^2+.1fx%+.1f\n\n'], charpoly(A));

% Solve Ax=b
disp('Solving Ax=b');
x = A\B

% Display the output
disp(['x = [' sprintf('%8.4f', x) ']]');
```

To execute the script, do one of the two following options:

- Ensure you are in the directory containing the file (`cd` as necessary) and enter the script name into the *Command Window*, or
- Click the `Run` button in the `Editor` tab of the *Editor* window with the script file open (if you are not in the correct folder MATLAB will present a warning dialog — select *Change Folder* from this dialog).

Either method will run the code and output the results.

## Sample Script Output

```
>> sample_script
Properties of A:
    Condition number:          3.2355
    Determinant:              -6
    Characteristic Polynomial: 1.0x^3-3.0x^2-3.0x+6.0

Solving Ax=b
x = [ -0.3333    0.6667   -0.3333]
```

MATLAB allows us to define our own functions.

These are defined in a script file similar to basic scripts, but with a specific format. Create a function by editing a script file as specified above and entering the necessary code, or to have MATLAB automatically generate a template use the **Home** **>** **New** **>** **Function** menu bar button.

## Function Structure

```
function [ output_args ] = functionname( input_args )  
%FUNCTIONNAME Summary of this function goes here  
% Detailed explanation goes here  
  
end
```

A function breaks down into the following components:

**function** **Keyword** Keyword to denote we are writing a function.

*output\_args* Comma-separated list of output argument names.

*functionname* The name of the function (used when calling the function).  
The file name of the file containing the function must be  
*functionname.m*.

*input\_args* Comma-separated list of input argument names.

**H1 Comment Line** The first comment line. Should contain the function name followed by a very short description.

**Further documentation comments** More comment lines immediately following the function definition. The text in these comment lines, along with the *H1 Comment Line*, will be displayed when **doc** *functionname* or **help** *functionname* are called.

**Main Body** All code between the function definition and the matching **end** keyword.

**end** **Keyword** The end of the function definition.



## Sample Function

```
function [ z, w ] = sample_function( x, y )  
%SAMPLE_FUNCTION Calculates the product and difference  
z = x*y;  
w = x-y;  
end
```



## Sample Function

```
function [ z, w ] = sample_function( x, y )
%SAMPLE_FUNCTION Calculates the product and difference
z = x*y;
w = x-y;
end
```

This function is called like any other MATLAB function.

## Calling Sample Function

```
>> x = sample_function(2,3)
x =
    6
>> [x,y] = sample_function(2,3)
x =
    6
y =
```

While this function works for scalars it will fail with vector/matrix inputs.

## Calling Sample Function with Vector Arguments

```
>> [x,y] = sample_function([1 5],[2 5])  
Error using *  
Inner matrix dimensions must agree.  
  
Error in sample_function (line 3)  
z = x*y;
```

While this function works for scalars it will fail with vector/matrix inputs.

## Calling Sample Function with Vector Arguments

```
>> [x,y] = sample_function([1 5],[2 5])  
Error using *  
Inner matrix dimensions must agree.  
  
Error in sample_function (line 3)  
z = x*y;
```

We can fix this by using the element-wise operators.

## Sample Function Changed for Vector/Matrix Arguments

```
function [ z, w ] = sample_function_vec( x, y )  
%SAMPLE_FUNCTION_VEC Calculates the product and difference  
z = x.*y;  
w = x-y;
```



Function files can contain more than one function.

Only the first “main” function defined in a file is *visible* outside the file. This allows you to write local functions used by the main function in the file but not usable by anyone else.

## Sub-functions

```
function [ z, w ] = sample_subfunction( x, y )
%SAMPLE_SUBFUNCTION Calculates the product and difference
z = multiply(x, y);
w = x-y;
end

function [z] = multiply(x,y)
%MULTIPLY Elementwise multiplication of the vectors
z = x.*y;
end
```



A special statement, `return`, can be used anywhere in a function.  
This statement exits the current function and executes no more commands from the function.



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*Unlike in some other programming languages `return` does not take any arguments (a return value), as return values are set by assignment.*



MATLAB has a built-in *logical* type, which can take a *true* or *false* value only (represented in MATLAB by 1 and 0, respectively). The following element-wise *comparison operators* return logical matrices:

$A < B$	Checks if $A < B$
$A > B$	Checks if $A > B$
$A \leq B$	Checks if $A \leq B$
$A \geq B$	Checks if $A \geq B$
$A == B$	Checks if $A = B$
$A \sim= B$	Checks if $A \neq B$

The first four work on the real part only; whereas,  $==$  and  $\sim=$  works on the real and imaginary parts.



Previously we mentioned that doubles suffer from rounding error.





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The issue is equality comparisons do not always return true when expected.



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## Rounding Error in Comparisons

```
>> (19.2-19) == 0.2
ans =
     0
>> 19.2-19-0.2
ans =
-7.216449660063518e-16
```



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```

When comparing floating point numbers instead calculate the absolute value of the difference and check if it less than some tolerance value. For example, rather than evaluate  $A==B$ , we instead use,  $\text{abs}(A-B) < 1e-8$ .

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ans =
-7.216449660063518e-16
```

When comparing floating point numbers instead calculate the absolute value of the difference and check if it less than some tolerance value. For example, rather than evaluate  $A=B$ , we instead use,  $\text{abs}(A-B) < 1e-8$ . The comparison operators work on numbers. The `strcmp` and `strcmpi` perform *case sensitive* and *case insensitive*, respectively, comparisons on two strings.

The following element-wise *logical operators* and functions work on logical matrices.

Operator	Function	Description
$\sim A$	<code>not(A)</code>	Logical NOT (0 becomes 1, 1 becomes 0)
$A \& B$	<code>and(A,B)</code>	Logical AND (1 if both $A$ and $B$ are 1)
$A   B$	<code>or(A,B)</code>	Logical OR (1 if either $A$ or $B$ are 1)
	<code>xor(A,B)</code>	Logical XOR (1 if <i>only one</i> of $A$ and $B$ are 1)

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The **all** function logically ANDs vector elements and **any** logically ORs vector elements.

Applied to a matrix the logical AND or OR is applied to each column (returning a row vector).

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The **all** function logically ANDs vector elements and **any** logically ORs vector elements.

Applied to a matrix the logical AND or OR is applied to each column (returning a row vector).

Short-circuit logical AND `&&` and short-circuit logical OR `||` can be applied to scalar logical arguments.

These functions are called short-circuit because they only evaluate the second argument if necessary.



A logical matrix can be used to index a matrix.

## Logical Indexing

```
>> x = rand(1,4)
x =
    0.7803    0.0965    0.3897    0.1320
>> x(x < 0.5) = 0
x =
    0.7803         0         0         0
```



A logical matrix can be used to index a matrix.

## Logical Indexing

```
>> x = rand(1,4)
x =
    0.7803    0.0965    0.3897    0.1320
>> x(x < 0.5) = 0
x =
    0.7803         0         0         0
```

The `find` function returns indices of all non-zero entries in a matrix.

## Find Indices of all Values $< 0.02$ in matrix

```
>> [i,j] = find(x < 0.02)
i =
     1
j =
     1
```



*Loops* are a programming structure that allows us to execute a number of statements several times.

MATLAB has both `for` and `while` loop types.

*Loops* are a programming structure that allows us to execute a number of statements several times.

MATLAB has both `for` and `while` loop types.

*Important: Although we can use loops to iterate through the elements in a vector/matrix and handle them one at a time this should be avoided wherever possible (by using element-wise and matrix operations) for performance (speed) reasons.*



A **for** loop executes a set of statements a set number of times. Each time it executes the *index* variable takes the next value/column from an vector/matrix.

## General for Loop Structure

```
for index = values  
    statements  
end
```



A **for** loop executes a set of statements a set number of times. Each time it executes the *index* variable takes the next value/column from an vector/matrix.

## General for Loop Structure

```
for index = values  
    statements  
end
```

Here,

- *index* is a variable name to use as the index variable,
- *values* is the vector/matrix of values to take, and
- *statements* is the list of statements to execute each loop.



## Factorial Calculation with for Loop

```
disp('The first 10 factorials');  
v = 1;  
for i = 1:10  
    v = v*i;  
    fprintf('%3d : %8d\n', i, v);  
end
```



## Factorial Calculation with for Loop

```
disp('The first 10 factorials');  
v = 1;  
for i = 1:10  
    v = v*i;  
    fprintf('%3d : %8d\n', i, v);  
end
```

Within a `for` loop, two special statements can be used.

- `break` exits the loop completely (no more values from *values* list are evaluated), and
- `continue` stops executing the *statements* for the current value and moves to the next value from *values* (if one exists).



The `while` loop continues to execute the statements it contains while some condition holds true.

## while Loop Structure

```
while expression  
    statements  
end
```



The **while** loop continues to execute the statements it contains while some condition holds true.

## while Loop Structure

```
while expression  
    statements  
end
```

- The *expression*, which should return a logical matrix, is evaluated.
- If all values in the matrix are non-zero (true) then the *statements* are executed.
- The *expression* is then evaluated again and *statements* executed if all entries of the matrix are non-zero.
- This continues until one entry of *expression* evaluates to 0 (false).



## while Loop Example

```
v = 100;  
while v > 0.5  
    disp(num2str(v,8));  
    v = v/2;  
end
```



## while Loop Example

```
v = 100;  
while v > 0.5  
    disp(num2str(v,8));  
    v = v/2;  
end
```

If the *expression* never evaluates to false then the code will be stuck in an *infinite loop*.

You can force a running script to terminate by using the Ctrl + C keyboard shortcut.

## while Loop Example

```
v = 100;  
while v > 0.5  
    disp(num2str(v,8));  
    v = v/2;  
end
```

If the *expression* never evaluates to false then the code will be stuck in an *infinite loop*.

You can force a running script to terminate by using the Ctrl + C keyboard shortcut.

A **while** loop can contain **break** and **continue** statements.

An **if** statement executes commands dependent on if a condition is true.

## if-elseif-else Structure

```
if expression  
    if_statements  
elseif expression  
    elseif_statements  
else  
    else_statements  
end
```

An **if** statement executes commands dependent on if a condition is true.

## if-elseif-else Structure

```
if expression  
    if_statements  
elseif expression  
    elseif_statements  
else  
    else_statements  
end
```

The **elseif** (with following statements) and the **else** (with following statements) are both optional. Multiple **elseif** statements are also allowed.

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## if-elseif-else Structure

```
if expression  
    if_statements  
elseif expression  
    elseif_statements  
else  
    else_statements  
end
```

The **elseif** (with following statements) and the **else** (with following statements) are both optional. Multiple **elseif** statements are also allowed.

- The **if** *expression* is evaluated. If *true*, *if\_statements* are executed;
- if *false* then the *expression* for the first **elseif** statement is evaluated and *elseif\_statements* executed if this is true.
- Each **elseif** *expression* is evaluated, in order, until one is true.
- If no *expression* evaluates to true then *else\_statements* are executed.



## if Example

```
function plotdata(x, y, xtype, ytype)
% plotdata Plots the data on linear or log plots
%     xtype and ytype are strings specify the type of
%     scale for that axis - either 'log' or 'linear'.

if (strcmpi(xtype, 'log') && strcmpi(ytype, 'log'))
    loglog(x, y);
elseif strcmpi(xtype, 'log')
    semilogx(x, y);
elseif strcmpi(ytype, 'log')
    semilogy(x, y);
else
    plot(x, y);
end

end
```



A **switch** selects statements to execute based on number/string value.

## switch Structure

```
switch expression
    case case_expression
        statements
    otherwise
        otherwise_statements
end
```

The **otherwise** is optional and you can have multiple **case** statements. *case\_expression* can be single value, or multiple values (comma-separated and surrounded by braces `{}`).

- **switch** evaluates the *expression* and compares the result against all *case\_expression*s.
- The statements of first matching *case\_expression* are executed.
- If no match occurs then the *otherwise\_statements* are evaluated.



## switch Example

```
function [city] = capital(country)

switch country
    case 'Austria'
        city = 'Vienna';
    case 'Germany'
        city = 'Berlin';
    case {'United Kingdom', 'Great Britain'}
        city = 'London';
    otherwise
        city = '<Unknown>';
end

end
```



It is possible to store a reference to a function within a variable.  
You call that function via the variable by just using the variable like a function.



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To take function handle just use the function name prefixed by a @ symbol.

## Taking & Using a Function Handle

```
>> sinhandle = @sin;  
>> sinhandle(pi/2)  
ans =  
    1
```

This allows generic functions to be written that operate on a function, without having to know what function it operates on.

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To take function handle just use the function name prefixed by a `@` symbol.

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ans =  
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```

This allows generic functions to be written that operate on a function, without having to know what function it operates on.

The `ezplot` function takes a function handle of the function to plot.

## Calling ezplot with Function Handle

We can use function handles to functions we have written as well.

## Calling ezsurf with Handle to own Function

```
>> ezsurf(@sample_function)
Warning: Function failed to evaluate on array inputs;
vectorizing the function may speed up its evaluation and
avoid the need to loop over array elements.
> In ezplotfeval (line 56)
   In ezgraph3>ezeval (line 635)
...
>> ezsurf(@sample_function_vec)
```

Previously we mentioned that functions should be written as generic as possible, we have here another demonstration of why.



Using function handles we can also define *anonymous functions*.  
These are functions that are written inline in MATLAB (usually fairly simple one-line functions).

## Anonymous Function Syntax

```
@(input_args) functioncode
```



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These are functions that are written inline in MATLAB (usually fairly simple one-line functions).

## Anonymous Function Syntax

```
@(input_args) functioncode
```

You can use this anonymous function like a normal function handle (passing to a function or assigning to a variable).  
For example, we can write the `meshc` example as follows.

## 3D Mesh/Contour plot Using Anonymous Function

```
>> ezmeshc(@(x, y) sin(x).*sin(y), [-pi pi])
```

## Section 7

# Structures



A MATLAB structure is essentially a group of variables stored together in a single object

The various variables (fields) in a structure can be different types.



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A structure type can be generated in two different ways:

- With the `struct` function, or
- by direct assignment of fields.

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A structure type can be generated in two different ways:

- With the `struct` function, or
- by direct assignment of fields.

The `struct` function takes a variable number of values, where each pair is a *key-value* pair.

## Generating Structure using struct Function

```
>> course = struct('Name','Numerical Solution of ODEs',...  
    'Year',2019,'Semester','Winter')  
course =  
    Name: 'Numerical Solution of ODEs'  
    Year: 2019  
    Semester: 'Winter'
```

You can access a field, for reading or assignment, by using the *dot* . notation. You use the variable name, followed by a period and then the name of the field.

## Generating & Reading Structure Directly

```
>> course.Name = 'Numerical Solution of ODEs';  
>> course.Year = 2019;  
>> course.Semester = 'Winter';  
>> course  
course =  
    Name: 'Numerical Solution of ODEs'  
    Year: 2019  
 Semester: 'Winter'  
  
>> course.Name  
ans =  
Numerical Solution of ODEs
```

Structure arrays are also possible. Structure arrays are accessed in the same way as vectors, and the array will grow to the correct size.

## Accessing Structure Array

```
>> course(3).Year = 2018;
```

```
>> course(2)
```

```
ans =
```

```
    Name: []
```

```
    Year: []
```

```
 Semester: []
```

```
>> course(3)
```

```
ans =
```

```
    Name: []
```

```
    Year: 2018
```

```
 Semester: []
```

## Section 8

# Error Handling





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Often the error message will include a line number inside a script/function file where the error occurred. Clicking on this line number takes us to the *Editor* with the relevant file open.

See if you can spot the error in the following before running.

## Function with Error

```
function [b] = invalid_func(n)
% invalid_func Function that we want to take a number
% and perform Ax for A=rand(n), x=1:n
A = rand(n);
x = 1:n;
b = A*x;
end
```



If we try to run this function we get an error.

## Running Function with Error

```
>> invalid_func(4)
Error using *
Inner matrix dimensions must agree.

Error in invalid_func (line 6)
b = A*x;
```



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MATLAB has told us the error (matrix multiplication with incorrect dimensions), the line the error occurred on, and has even printed the line causing the error as well.

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The problem is  $x$  is a *row vector* and it needs to be a *column vector*.



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To generate an error call the `error` function, passing an error message.

## Generating Errors

```
function [x] = basic_factorial(n)
% basic_factorial A very basic factorial implementation
x = 1;
if (n < 0)
    error('Factorial only defined for non-negative numbers');
elseif (round(n) ~= n)
    error('Factorial only defined for integer values');
elseif (n > 0)
    for i=1:n
        x = x*i;
    end
end
end
```



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A similar `warning` function also exists



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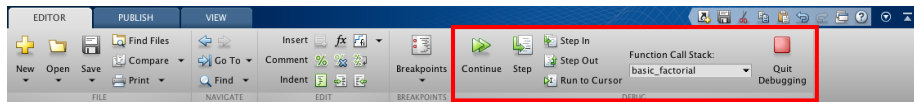
When a breakpoint is active a red circle appears in the left margin.

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While debugging you can inspect values by:

- Hovering over them with the mouse.
- By entering a variable name or expression at the `κ>>` prompt.
- Select some code, right-click and select `Evaluate Expression`.

Note that a breakpoint pauses the code *before* execution of a line (so any variables on that line will not exist yet).



In debug mode the `Editor` tab on the *Editor* window contains a set of tools for controlling the execution of the script.

**Continue** continues running the script until the next breakpoint.

**Step** executes the current line and then pause on the next line.

**Step In** does the same, but if the line contains a function call then instead it will pause at the first line *inside* that function.

**Step Out** will run the rest of the current function and will pause at the line of code after the function call.

**Quit Debugging** will terminate the currently executing script and exit the debugger.