

Introduction to MATLAB

- getting started: basics
- arrays, vectors, matrices
- plotting
- M-files
- control flow

Basic commands

MATLAB is a computer program for numerical computations and programming

- when MATLAB is ready to accept instructions, a command prompt (`>>`) is displayed in the command window
- scalar addition, subtraction, multiplication, division, and exponentiation can be computed using the symbols `+`, `-`, `*`, `/` and `^`, for example:

```
>> 2+2*3+4^2  
ans =  
24
```

- MATLAB automatically assigns the answer to a variable, `ans`; example:

```
>> ans/2  
ans =  
12
```

- assignment of values to variables can be done using equal sign; example:

```
>> a=-3.15  
a =  
-3.1500
```

creates a variable named “a” with value equal to -3.15 and displays result

Basic commands

- the priority order can be overridden with parentheses
- for example, because exponentiation has higher priority than negation:

```
>> y = -4^2  
y =  
-16
```

thus, 4 is first squared and then negated

- parentheses can be used to override the priorities as in

```
>> y = (-4)^2  
y =  
16
```

- within each precedence level, operators have equal precedence and are evaluated from left to right; as an example,

```
>> 4^2^3  
>> 4^(2^3)  
>> (4^2)^3
```

- in the first case $4^2 = 16$ is evaluated first, which is then cubed to give 4096
- second case $2^3 = 8$ is evaluated first and then $4^8 = 65,536$
- third case is the same as the first, but uses parentheses to be clearer

Basic commands

- adding a semicolon (;) at end of command suppresses displaying result
- text after (%) on same line are treated as comments and ignored

```
>> a=4; % create variable 'a' equal 4 without displaying result
```

- you can type several commands on same line by separating them with commas or semicolons; if you separate them with commas, they will be displayed

```
>> a = 4, A = 6; x = 1;  
a = 4
```

- MATLAB is case-sensitive manner; variable a is not the same as A
- an integer after 1e is used for powers of ten, e.g., 10^2 can be found using

```
1e2 % same as 10^2  
ans =  
100
```

- MATLAB predefines the variables: π ; $\text{Inf} = \infty$; NaN means not a number
- MATLAB displays four decimal points; for additional precision, use `format long`; we can switch back using `format short`
- `format rational` switch to rational format of numbers

Basic commands

- `clear` command deletes all objects (variables) from the workspace
- `clear` followed by the names of the variables removes specific variables; *e.g.*,
`>> clear a %removes the variable 'a' from the workspace`
- `clc` command clears the command window
- in the command window, pressing the up or down arrow key scrolls through previous commands and redisplay them at the command prompt
 - typing the first few characters and then pressing the arrow keys scrolls through the previous commands that start with the same characters
- long lines can be continued by placing an ellipsis (three consecutive periods):
`>> a=1,b=2; ...
c=3;`

`a =
1`

Built-in functions

function	command
\sqrt{x}	<code>sqrt(x)</code>
$x^{1/N}$	<code>nthroot(x,N)</code>
e^x	<code>exp(x)</code>
$\sin(x)$	<code>sin(x)</code>
$\cos(x)$	<code>cos(x)</code>
$\tan(x)$	<code>tan(x)</code>
$\tan^{-1}(x)$	<code>atan(x)</code>
$\tanh(x)$	<code>tanh(x)</code>
$\log_{10} x$	<code>log10(x)</code>
$\ln x$	<code>log(x)</code>
$\text{sign}(x)$	<code>sign(x)</code>

(for list of functions type `help elfun`)

Complex numbers

- unit imaginary number $j = i = \sqrt{-1}$ is preassigned to the variable `i` or `j`
- for example, we can create a complex number

```
>> x=pi+2i  
x =  
3.1416 + 2i
```

Complex numbers built-in functions

command	meaning
<code>real(x)</code>	real part of <code>x</code>
<code>imag(x)</code>	imaginary part of <code>x</code>
<code>abs(x)</code>	absolute value of <code>x</code>
<code>angle(x)</code>	phase of <code>x</code> in rad/s
<code>conj(x)</code> (or <code>x'</code>)	complex conjugate of <code>x</code>
<code>isreal(x)</code>	logical 1 for real <code>x</code> ; 0 otherwise

Rounding and remainder

command	meaning
<code>round(x)</code>	rounds to nearest integer
<code>fix(x)</code>	rounds to nearest integer towards zero
<code>floor(x)</code>	rounds down (towards negative infinity)
<code>ceil(x)</code>	rounds up (towards positive infinity)
<code>rem(x,y)</code>	remainder after division
<code>mod(x,y)</code>	modulus (same as $x - \text{floor}(x/y)*y$)

Example

```
>> x = 2.3 - 4.7*i;  
>> round(x);    % results in (2 - 5i)  
>> fix(x);      % results in (2 - 4i)  
>> floor(x);    % results in (2 - 5i)  
>> ceil(x);     % results in (3 - 4i)
```


Relational operations

a relational operator compares two items and indicates whether a condition is true

relational operator	meaning
<	less than
>	greater than
<=	less than or equal to
>=	greater than or equal to
==	equal to
~=	not equal to

- if true, a logical true (1) is returned; else, a logical false (0) is returned
- for example

```
>> 1>2  
ans =  
logical  
0
```

Logical operations

logical operator	meaning	<i>A</i>	<i>B</i>	<i>A</i> And <i>B</i>	<i>A</i> OR <i>B</i>
& or &&	logical AND	0	0	0	0
or	logical OR	0	1	0	1
~	logical negation	1	0	0	1
		1	1	1	1

- relational operators can be combined using logical operators
- for example, we can test the condition $0 < t < 1$ using
`>>(t>0)&(t<1)`
or
`>>~((t<=0)|(t>=1))`
- & and | always evaluate both sides
- short-circuit behavior:
 - && stops if the first condition is `false` and returns `false`
 - || stops if the first condition is `true` and returns `true`
 - useful for avoiding errors (e.g., division by zero) or extra computations

Logical operator priority

- MATLAB evaluates logical operations according to a fixed priority order
- the priority from highest to lowest is $\sim > \& > |$
- operators with the same priority are evaluated from left to right
- parentheses can always be used to change or override the natural priority

Example

$-1 * 2 > 0 \& 2 == 2 \& 1 > 7 | \sim(-1 > 2)$

the first thing that MATLAB does is to evaluate any mathematical expressions; in this example, there is only one: $-1 * 2$

$-2 > 0 \& 2 == 2 \& 1 > 7 | \sim(-1 > 2)$

next, evaluate all the relational expressions:

```
-2 > 0 & 2 == 2 & 1 > 7 | ~(-1 > 2)  
F & T & F | ~F
```

at this point, MATLAB evaluates logical operators in priority order
since ~ has the highest priority, the negation ~F is evaluated first:

```
F & T & F | T
```

next, the & operator is evaluated from left to right:

```
F & T    ->    F  
F & F | T
```

the & again has higher priority than | :

```
F | T
```

finally, the | is evaluated as true and returns logical 1

Anonymous function

an *anonymous function* provides a symbolic representation of a function defined in terms of MATLAB operators, functions, or other anonymous functions

`fhandle = @(arglist) expression`

- `fhandle`: function handle used to call the function
- `arglist`: comma-separated list of input arguments
- `expression`: any single valid MATLAB expression

Example 1: we can define $f(t) = e^{-t} \cos(2\pi t)$ as

```
>> f = @(t) exp(-t)*cos(2*pi*t);
```

$f(t)$ can be evaluated simply by passing the input values of interest

```
>> t = 0; f(t)
ans = 1
```

Example 2

```
>> f1 = @(x,y) x^2 + y^2;
>> f1(3,4)
ans =
25
```

Example: piecewise functions

- the unit step function

$$u(t) = \begin{cases} 1 & t \geq 0 \\ 0 & t < 0 \end{cases}$$

can be created using the command

```
>> u = @(t) 1.0*(t>=0);
```

- the function

$$f(t) = \begin{cases} 1 & 0 \leq t \leq 2 \\ -t & -1 \leq t < 0 \end{cases}$$

can be created using the command

```
>> f = @(t) 1.0*((t>=0)&(t <=2))-t*((t<0)&(t>=-1));
```

Strings

- strings can be represented by using single quotation marks; for example

```
>> f = 'Miles ';  
>> s = 'Davis';
```

- we can concatenate (paste together) strings as in

```
>> x = [f s]  
x =  
'Miles Davis'
```

- some useful commands

command	meaning
<code>str2num(s)</code>	converts string <code>s</code> to a number
<code>num2str(n)</code>	converts number <code>n</code> to a string
<code>b=strncmp(s1,s2)</code>	compares two strings, <code>s1</code> and <code>s2</code> ; if equal returns true (<code>b = 1</code>); if not equal, returns false (<code>b = 0</code>)
<code>i=strfind(s1,s2)</code>	returns the starting indices of any occurrences of the string <code>s2</code> in the string <code>s1</code>

The input function

- input function allows you to prompt the user for values directly from the command window

- its syntax is

```
n = input('promptstring')
```

- the function displays the promptstring, waits for keyboard input, and then returns the value from the keyboard

- for example,

```
m = input('Mass (kg): ')
```

when this line is executed, the user is prompted with the message

Mass (kg):

if the user enters a value, it would then be assigned to the variable `m`

- to input string, an 's' is appended to the function's argument list; for example,

```
name = input('Enter your name: ','s')
```


The disp function

- the disp function displays a value or message to the command window
- syntax

`disp(value)`

- the argument can be a number variable or text string
- disp does not print the variable name only the value

Example

```
>> x = 5;  
>> y = x^2;  
>> disp('the value of y is:'), disp(y)
```

output

```
the value of y is:  
25
```

The fprintf function

- fprintf provides detailed control over how information is displayed
- general syntax

```
fprintf('format', x, ...)
```

- the format string specifies how each variable is printed (integer, decimal, scientific...etc)
- MATLAB scans the string from left to right printing characters until it encounters a percent sign % which indicates a format code
- after printing the numeric value MATLAB continues printing normal text until it encounters a backslash \ which introduces a control code such as \n (newline)

Example

```
>> velocity = 50.6175;  
>> fprintf('The velocity is %8.4f m/s\n', velocity)
```

output

```
The velocity is 50.6175 m/s  
>>
```

Common fprintf format and control codes

format codes	
%d	integer format
%e	scientific format with lowercase e
%E	scientific format with uppercase E
%f	decimal format
%g	compact form of %e or %f

control codes	
\n	start new line
\t	horizontal tab
\v	vertical tab

Example

```
>> fprintf('%5d %10.3f \v %8.5e\n',100,2*pi,pi);  
100      6.283 3.14159e+00
```

The save and load commands

- the save command stores variables in a mat-file
- syntax

```
save filename var1 var2 ... varn
```

- this creates a file `filename.mat` containing the listed variables
- if no variables are specified the entire workspace is saved
- the load command retrieves variables from a mat-file

```
load filename var1 var2 ... varn
```

- only listed variables are loaded; if none are listed all variables in file are loaded

MATLAB toolboxes

- MATLAB provides a wide range of *toolboxes* that extend the core environment
- each toolbox contains specialized functions designed for solving problems in a specific domain

Some useful toolboxes

- Optimization Toolbox
- Symbolic Math Toolbox
- Statistics and Machine Learning Toolbox
- Deep Learning Toolbox
- Curve Fitting Toolbox
- Control System Toolbox
- Signal Processing Toolbox
- many others – see <https://www.mathworks.com/products.html>

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Vectors

vector arrays x with elements x_1, \dots, x_n are created using square brackets

- row vector $x = [1 \ 2 \ 3]$ is created via spaces (or commas) between elements:

```
>> x = [1 2 3]
x = 1 2 3
```

- for column vector $y = \begin{bmatrix} -1+j2 \\ 3.2 \\ 5 \end{bmatrix}$, use semicolon between elements

```
>> y=[-1+2i;3.2;5]
y =
-1.0000 + 2.0000i
 3.2000 + 0.0000i
 5.0000 + 0.0000i
```

– Enter key (carriage return) can also be used to separate elements

- (conjugate) transpose of a vector can be found using apostrophe

```
>> y'
ans =
-1.0000 - 2.0000i    3.2000 + 0.0000i    5.0000 + 0.0000i
```

Vector indexing

- the l th element of x can be extracted using $x(l)$, for example,

```
x=[1 -1 2 4.5];  
x(3)  
ans =  
2
```

- we can use $x(1:k)$ to extract a slice of a vector for element 1 to element k
- for example,

```
x(2:3)  
ans =  
-1    2
```

- end command automatically references the final index of an array; for example,

```
>> x(end-9:end) % extract last 10 values of vector x
```
- we can concatenate vectors to create a larger vector; for example,

```
>> a=[1;2];b=[1;1];c=[-1;-1]  
>> d=[a;b;c]; % create concatenated vector
```


Vector operations

- vector addition and subtraction are carried out using the commands `+`, `-`
- for example,

```
>> x=[1 2 3]+[4 5 6]
x =
5      7      9
```

- multiplying scalar by a vector is done using `*` command, *e.g.*,

```
>>-3*[1 2 3]
ans =
-3     -6     -9
```

- element-by-element operations are computed using `.*`, `./`, `.^`; example:

```
>> u=[1 2 3]; v=[-1 -2 -3];
>> w=u.*v
w =  -1     -4     -9
>> w.^2
ans =
1     16     81
```

Useful vector commands

command

`a:b:c`

`linspace(x1,x2,n)`

`logspace(x1,x2,n)`

`sum(x)`

`mean(x)`

`prod(x)`

`max(x)/min(x)`

`sort(x)`

`ones(1,n)` or `ones(n,1)`

`zeros(1,n)` or `zeros(n,1)`

`length(x)`

`x'y` or `dot(x,y)`

`norm(x)`

`flipud(x)`

`fliplr(x)`

meaning

row vector with elements between a , c ; increments b
(command `a:c` assumes increment of 1)

row n -vector from x_1 to x_2 ; spacing $(x_2-x_1)/(n-1)$

row n -vector from 10^{x_1} to 10^{x_2} logarithmic spacing

sums the elements of x

average of the elements of x

return products of elements of x

max/min value in x

sorts elements in ascending order

row or column n -vector of all ones

row or column n -vector of all zeros

the length (size, dimension) of the vector x

inner (dot) product between vectors x and y

the 2-norm of vector x

reverses the order of elements in a column vector x

reverses the order of elements in a row vector x

Example

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 4 \\ -2 \\ 3 - j2 \end{bmatrix}, \quad y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} -3 \\ 5 + j7 \\ 6 \\ 2 \end{bmatrix}$$

use MATLAB to compute

(a) $x + y$

(b) inner product: $\langle x, y \rangle = x^* y = \sum_{k=1}^4 x_k^* y_k$

(c) mean or average: $\text{avg}(x) = (1/4) \sum_{k=1}^4 x_k$

(d) average energy: $E_x = (1/4) \sum_{k=1}^4 |x_k|^2$

(e) variance: $\text{var}(x) = (1/4) \sum_{k=1}^4 |x_k - \text{avg}(x)|^2$

Solution:

- (a) `>> x = [1;4;-2;3-2*i];`
`>> y = [-3;5+7*i;6;2];`
`>> sum_xy = x + y;`
- (b) `>> dot_xy = dot(x,y);`
`>> dot_xy = x'*y; % alternative computation`
- (c) `>> mean_x = sum(x)/length(y);`
`>> mean_x = mean(x); % alternative computation`
- (d) `>> avg_x = sum(x.*conj(x))/length(x);`
`>> avg_x = sum(x'*x)/length(x); % alternative computation`
`>> avg_x = norm(x)^2/length(x); % alternative computation`
`>> avg_x = mean(abs(x).^2); % alternative computation`
- (e) `>> z=x-mean(x);`
`>> var_x = sum(z.*conj(z))/length(x);`
`>> var_x = sum(z'*z)/length(x); % alternative computation`
`>> var_x = mean(|z|. ^2); % alternative computation`

Functions of vectors

- common built in functions operates elementwise on vectors
- example: to compute \sqrt{x} for all values $(1, 2, \dots, 100)$, we can use

```
>> x = 1:100; y=sqrt(x);
```
- vectors can be used to represent points of a function f over some interval
- for example, we can represent $f = \sin(2\pi 10t + \pi/6)$ over $0 \leq t \leq 2$ using

```
>> t = linspace(0,2,500); %500 points between 0 and 2  
>> f = sin(2*pi*10*t+pi/6) %500 functions evaluation at t
```
- indexing in MATLAB starts from 1
- for example, the value of $f(t)$ at $t = 0$ is the first element of the vector $f(1)$
- anonymous functions can be used with vector argument, *e.g.*,

```
>> f = @(x) x(1)^2+x(2)^2  
>> x=[2;3]  
>> f(x)  
ans =  
13
```

Matrices

matrices can be created similar to vectors using square brackets and semicolon

- row elements are separated by spaces
- a semicolon is used to move to separate rows
 - or the Enter key (carriage return) can be used to separate the rows

- for example, we can create the 3×4 matrix $A = \begin{bmatrix} 2 & 3 \\ 4 & 5 \\ 0 & 6 \end{bmatrix}$ by the command

```
>> A = [2 3;4 5;0 6]
A = 2 3
    4 5
    0 6
```

- (conjugate) transpose of a matrix can be found using apostrophe

```
>> A'
ans =
    2    4    0
    3    5    6
```

Matrix indexing

- element (k, l) of matrix A can be extracted using $A(k, l)$
- subblocks of A can be extracted using indexing; for example

```
>> A = [1 2 3; 0 4 5; 0 0 6];  
>> A(1:2, 2:3)  
ans = 2 3  
      4 5
```

- colon in place of a specific subscript represents the entire row or column
for example, $A(2, :)$ extracts the second row

```
>> A(2, :)  
ans = 0 4 5
```

- we can concatenate arrays to create larger arrays; for example

```
>> a = [1; 0; 0]; B = [2 3; 4 5; 0 6]  
>> C = [a B]  
C = 1 2 3  
    0 4 5  
    0 0 6
```

Matrix operations

- matrix addition and subtraction are carried out using the commands `+`, `-`
- matrix-vector and matrix-matrix multiplication is done using `*`, *e.g.*,

```
>> A=[1 2;3 4];  
>> b=[1;2];  
>> A*b  
ans =  
5  
11
```

- matrix power can be found using `^` (*e.g.*, `A^3`)
- *element-by-element operations* are computed using `.*`, `./`, `.^`
- passing a matrix into a function computes the function elementwise

Linear equation: we can solve $Ax=b$, if a solution exists, using

- backlash operator (left division): $x=A \backslash b$ (A can be square singular, tall, or wide)
- or `inv(A)*b` if A is nonsingular, which is less efficient than $x=A \backslash b$

Useful matrix commands

command	meaning
<code>size(A)</code>	the size of the array A
<code>length(A)</code>	the length of the largest array dimension in A
<code>numel(A)</code>	number of elements in A (same as <code>prod(size(A))</code>)
<code>sum(A)</code>	a row vector containing the sum of each column
<code>sum(A,2)</code>	a column vector containing the sum of each row
<code>sum(A,"all")</code>	the sum of all elements of A
<code>prod(A)</code>	a row vector containing the sum of each column
<code>max(A)/min(A)</code>	max/min value in A
<code>eye(m)</code>	$m \times m$ identity matrix
<code>ones(m,n)/zeros(m,n)</code>	$m \times n$ matrix of all ones/zeros
<code>diag(x)</code>	creates diagonal matrix with diagonal elements x
<code>flipud(A)</code>	reverses the order of rows of A
<code>fliplr(A)</code>	reverses the order of columns of A
<code>rand(dims...)</code>	array with random, iid, uniformly distributed over $[0, 1)$
<code>randn(dims...)</code>	array with random, iid, standard normally distributed
<code>randi(imax,dims...)</code>	returns random array of integers drawn from the discrete uniform distribution on the interval $[1, imax]$

Useful matrix commands

command

`det(A)`

`inv(A)`

`rank(A)`

`norm(A)`

`norm(A,"fro")`

`sqrtm(A)`

`[Q,R,P] = qr(A)`

`[L,U,P] = lu(A)`

`R = chol(A)`

`eig(A)`

`[V,D] = eig(A)`

`[U,S,V] = svd(A)`

meaning

determinant of a square matrix A

inverse of a square matrix A

computes rank of A

return the 2-norm of A

the Frobenius norm of A

square root of matrix $A^{1/2}A^{1/2} = A$

returns QR decomposition $A*P = Q*R$

returns LU factorization $A = P'*L*U$

Choleskey factorization of positive definite matrix $A = R'*R$

computes eigenvalues and eigenvectors of A

returns diagonal matrix D of eigenvalues and matrix V whose columns are the corresponding eigenvectors, $A*V = V*D$

singular value decomposition $A = U*S*V'$

The repmat command

`repmat(A,m,n)` replicate objects; it returns an array containing copies of A in the row and column dimensions

for example

```
>> A = diag([1 ;2])
```

```
A =
```

```
1    0
0    2
```

```
>> repmat(A,3,2)
```

```
ans =
```

```
1    0    1    0
0    2    0    2
1    0    1    0
0    2    0    2
1    0    1    0
0    2    0    2
```

creates a 3×2 block matrix with blocks A

The reshape command

- `B=reshape(A,sz)` reshapes A using the size vector, sz
- for example, `reshape(A,[2,3])` reshapes A into a 2-by-3 matrix
- sz must contain at least 2 elements, and `prod(sz)` must be same as `numel(A)`

Example

```
A = 1:10;  
B = reshape(A,[5,2])  
B =  
1     6  
2     7  
3     8  
4     9  
5    10
```

The find function

the find allows us to find indices satisfying certain conditions

Examples

- find indices of vector x bigger than 1

```
>> x=[1;-1;3;4]
>> find(x>1)
ans =
3
4
```

- find row and column indices of matrix X with entries $1 < X_{ij} < 5$

```
>> X=magic(3)
X =
8     1     6
3     5     7
4     9     2
```

```
>> [row,col] = find(X>1 & X<5)
row =
2
3
3
col =
1
1
3
```

Multidimensional array

- you can create a multidimensional array by creating matrix, then extend it
- for example, first define a 3-by-3 matrix as the first page in a 3-D array:

```
A = [1 2 3; 4 5 6; 7 8 9]
```

```
A =
```

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

- now add a second page; to do this, assign another 3-by-3 matrix to the index value 2 in the third dimension:

```
A(:,:,2) = [10 11 12; 13 14 15; 16 17 18]
```

```
A =
```

```
A(:,:,1) =
```

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

```
A(:,:,2) =
```

```
10    11    12
13    14    15
16    17    18
```

Elementwise logical operations

- use `&` and `|` when performing *elementwise* logical comparisons on arrays:

```
>> x = -3:3;
>> mask = (x>0) & (x<3);    % element-wise AND
mask =
1×7 logical array
0    0    0    0    1    1    0
```

- use `&&` and `||` when combining *scalar logical expressions*:

```
>> t = 2;
>> condition = (t>0) && (t<5);    % scalar short-circuit AND
condition =
1
```

- `&` and `|` work on arrays (element-by-element)
- `&&` and `||` only work for single (scalar) logical values

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- M-files
- control flow

Plotting commands

command	meaning
<code>plot(x,y)</code>	plots the vector x versus the vector y
<code>semilogx(x,y)</code>	x-axis is log10; the y-axis is linear
<code>semilogy(x,y)</code>	x-axis is linear; the y-axis is log10
<code>loglog(x,y)</code>	creates a plot with log10 scales on both axes

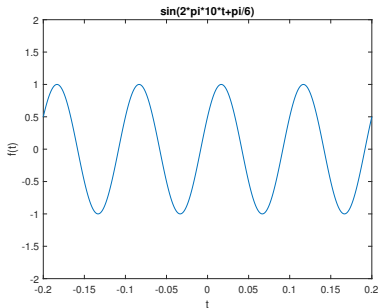
- there are also several other graphical functions in MATLAB including

`stem, bar, hist, polar, stairs, plot3...`

- `clf` command clears the current figure window
- `axis equal` command ensures that the scale used for the horizontal axis is equal to the scale used for the vertical axis
- we can add labels, change axis range, plot color,...etc

Example: plot command

```
>> t = linspace(-0.2,0.2,500);  
>> f = sin(2*pi*10*t+pi/6);  
>> plot(t,f);  
>> axis([-0.2 0.2 -2 2]) % plot range  
>> xlabel('t'); ylabel('f(t)'); % label the x and y axis  
>> title('sin(2*pi*10*t+pi/6)'); %label the title
```



Specifiers for colors, symbols, and line types

Colors		Symbols		Line types	
Blue	b	Point	.	Solid	-
Green	g	Circle	o	Dotted	:
Red	r	X-mark	x	Dashdot	-.
Cyan	c	Plus	+	Dashed	--
Magenta	m	Star	*		
Yellow	y	Square	s		
Black	k	Diamond	d		
White	w	Triangle (down)	v		
		Triangle (up)	^		
		Triangle (left)	<		
		Triangle (right)	>		
		Pentagram	p		
		Hexagram	h		

for example

```
>> plot(t, f, 's--g')% green square markers connected by dashed lines
```

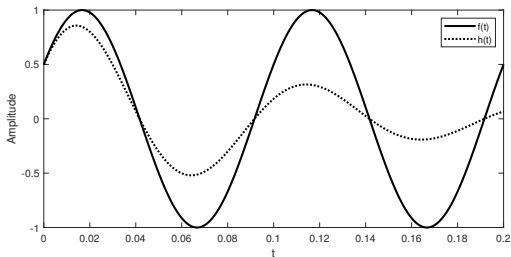
Multiple curves

MATLAB allows you to display more than one data set on same plot; e.g.,

```
>> plot(x, y1, x, y2)
```

Example

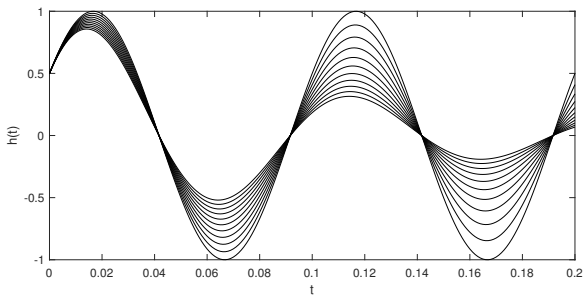
```
>> t = linspace(0,0.2,500);  
>> f = sin(2*pi*10*t+pi/6);  
>> g = exp(-10*t);  
>> h = f.*g;  
>> plot(t,f,'-k',t,h,':k','linewidth',2);  
>> xlabel('t'); ylabel('Amplitude');  
>> legend('f(t)', 'h(t)');
```



Family of curves

matrices can be used to create a family of curves

```
>> alpha = (0:10);  
>> t = (0:0.001:0.2)'; %defined as column vector  
>> T = repmat(t,1,11); %matrix T, columns t repeated 11 times  
>> H = exp(-T*diag(alpha)).*sin(2*pi*10*T+pi/6);  
>> plot(t,H,'k'); xlabel('t'); ylabel('h(t)');
```

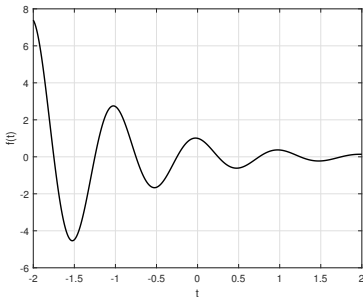


$$h_{\alpha}(t) = e^{-\alpha t} \sin(2\pi 10t + \pi/6) \text{ for } \alpha = [0, 1, \dots, 10]$$

Plotting using anonymous functions

we can use anonymous functions for plotting

```
>> f = @(t) exp(-t).*cos(2*pi*t);  
>> t = (-2:0.01:2);  
>> plot(t,f(t),'k','linewidth',1.4);  
>> xlabel('t'); ylabel('f(t)');  
>> grid; % adds grid lines
```



The hold on and subplot commands

- by default, previous plots are erased when new plot command is implemented
- hold on command holds the current plot and all axis properties so that additional graphing commands can be added to the existing plot
- for example, the following commands would result in both lines and symbols being displayed:

```
>> plot(t, f1)
>> hold on % keep plot
>> plot(t, f2, ':') %plot f2 on same figure
>> hold off
```

- subplot allows you to split the graph window into subwindows; it has syntax
subplot(m, n, p)

this command breaks the graph window into an m -by- n matrix of small axes, and selects the p -th axes for the current plot

- MATLAB numbers subplot positions by row
- first subplot is the first column of the first row, the second subplot is the second column of the first row, and so on

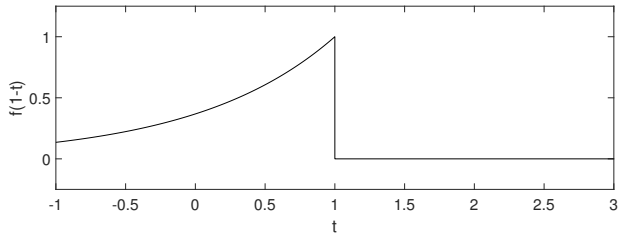
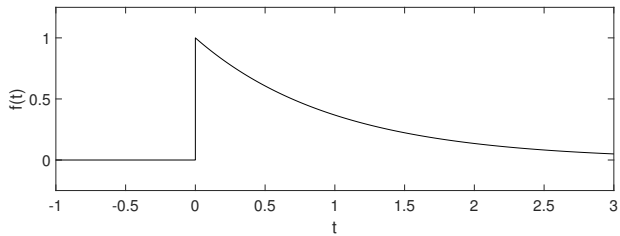
Example

plot $f(t) = e^{-t}u(t)$ and $f(1-t)$ over $-1 \leq t \leq 3$:

```
>> u = @(t) 1.0*(t>0);  
>> f = @(t) exp(-t).*u(t);  
>> t = -1:0.0001:3;  
>> subplot(2,1,1) % create multiple graphs in one figure  
>> plot(t,f(t),'k')  
>> axis([-1 3 -0.25 1.25]);  
>> xlabel('t'); ylabel('f(t)');
```

we can also evaluate a function by passing it an expression; this makes it very convenient to evaluate expressions such as $f(1-t)$:

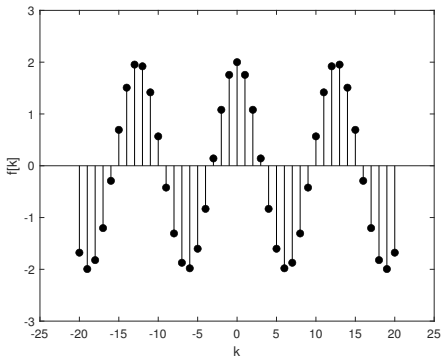
```
>> subplot(2,1,2)  
>> plot(t,f(1-t),'k')  
>> axis([-1 3 -0.25 1.25]);  
>> xlabel('t'); ylabel('f(1-t)');
```

the stem command

the stem command can be used to plot $f[k]$ against discrete k

```
>> k = -20:20;  
>> f = 2*cos(0.5*k);  
>> stem(k,f,k,'filled'); %'k' for black and filled circle  
>> xlabel('k'); ylabel('f[k]');  
>> axis([-25 25 -3 3])
```



Outline

- getting started: basics
- arrays, vectors, matrices
- plotting
- **M-files**
- control flow

M-files

Script files

- *script M-files* file is a series of commands saved on a file that can be run at once
- script can be executed by typing the file name in the command window or by pressing the Run button

Function files

- *function M-files* can accept input arguments as well as return outputs
- syntax:

```
function outvar = funcname(arglist)
% helpcomments
statements
outvar = value;
end % required when function is written within code
```

- an M-file is executed by simply typing the filename (without the .m extension)

Example

a bungee jumper velocity with mass m and drag coefficient c_d can be described as:

$$v(t) = \sqrt{\frac{gm}{c_d}} \tanh\left(\sqrt{\frac{gc_d}{m}} t\right)$$

where $\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}}$ is the hyperbolic tangent and g gravity acceleration

M-file content

```
function v = freefall(t, m, cd)
% freefall: bungee velocity with second-order drag
% v=freefall(t,m,cd) computes the free-fall velocity
% of an object with second-order drag
% input:
% t = time (s)
% m = mass (kg)
% cd = second-order drag coefficient (kg/m)
% output:
% v = downward velocity (m/s)
g = 9.81; % acceleration of gravity
v = sqrt(g * m / cd)*tanh(sqrt(g * cd / m) * t);
```

Example

Execute function M-file

to invoke the function, return to the command window and type in

```
>> freefall(12,68.1,0.25)
```

the result will be displayed as

```
ans =  
50.6175
```

- can be invoked repeatedly for different argument values
- note that, at the end of the previous example, if we had typed

```
>> g
```

the following message would have been displayed:

```
??? Undefined function or variable 'g'.
```

- variables within function are *local* and are erased after function is executed

Example

- function M-files can return more than one result
- in such cases, the variables containing the results are comma-delimited and enclosed in brackets

Example: `stats.m`, computes mean and standard deviation of a vector:

```
function [mean, stdev] = stats(x)
n = length(x);
mean = sum(x)/n;
stdev = sqrt(sum((x-mean).^2/(n - 1)));
```

here is an example of how it can be applied:

```
>> y = [8 5 10 12 6 7.5 4];
>> [m,s] = stats(y)
m =
7.5000
s =
2.8137
```

Variable scope

- variable's scope is limited either to the MATLAB workspace or within a function
- this principle prevents errors when a programmer unintentionally gives the same name to variables in different contexts
- variables defined through command line are within the MATLAB workspace
- workspace variables are not directly accessible to functions but rather are passed to functions via their arguments

Example

```
function c = adder(a,b)
x = 88
a
c = a + b
```


if we type

```
>> x = 1; y = 4; c = 8;  
>> d = adder(x,y)  
x =  
88  
a =  
1  
c =  
5  
d =  
5
```

but, if you then type

```
>> c, x, a  
c =  
8  
x =  
1  
Undefined function or variable 'a'.  
Error in ScopeScript (line 6)  
c, x, a
```

Global variables

global variables can be defined as in `global X Y Z` and can be accessed in several contexts without passing it as an argument

- if several functions (or workspace), all declare a particular name as global
- then they all share a single value of that variable
- any change to that variable, in any function, is then made to all the other functions that declare it global

Example

```
function C=add(B)
global A
C=A+B;
end
>> global A
>> A=2.4;
>> B=1.2;
>> C=add(B)
C =
3.6000
```

Subfunctions

- functions can call other functions
- such functions can exist as separate M-files or contained in a single M-file

Example: consider writing the function in example 50 in an M-file is given as

```
function v = freefallsubfunc(t, m, cd)
v = vel(t, m, cd);
end
function v = vel(t, m, cd)
g = 9.81;
v = sqrt(g * m / cd)*tanh(sqrt(g * cd / m) * t);
end
```

then

```
>> freefallsubfunc(12,68.1,0.25)
ans =
50.6175
```

however, if we attempt to run the subfunction vel, an error message occurs:

```
>> vel(12,68.1,.25)
??? Undefined function or method 'vel' for input arguments of type 'double'.
```

Passing functions to M-files

anonymous functions can be passed into function M-files

example:

```
function favg = funcavg(f,a,b,n)
% funcavg: average function height
% favg = funcavg(f,a,b,n): computes average value
% of function over a range
% input:
% f = function to be evaluated
% a = lower bound of range
% b = upper bound of range
% n = number of intervals
% output:
% favg = average value of function
x = linspace(a,b,n);
y = f(x);
favg = mean(y);

>> vel = @(t) sqrt(9.81*68.1/0.25)*tanh(sqrt(9.81*0.25/68.1)*t);
>> funcavg(vel,0,12,60)
ans =
36.0127
```

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If statements

if statements execute commands when a certain condition is met

if structure

```
if condition
statements
end
```

if...else structure

```
if condition
statements1
else
statements2
end
```

if...elseif structure

```
if condition1
statements1
elseif condition2
statements2
elseif condition3
statements3
.
.
.
end
```

Example: set $x = 5$ if $a > 0$ and $x = 100$ otherwise

```
>> a = 15;
>> if a > 0,
x = 5;
else
x = 100
end
```

Example

construct sign function:

```
function sgn = mysign(x)
% mysign(x) returns 1 if x is greater than zero.
% -1 if x is less than zero.
% 0 if x is equal to zero.
if x > 0
    sgn = 1;
elseif x < 0
    sgn = -1;
else
    sgn = 0;
end
```

```
>> mysign(0)
ans =
0
```

this does the same as built-in function `sign` in MATLAB

The switch structure

General syntax

```
switch testexpression
case value1
statements1
case value2
statements2
.
.
.
otherwise
statementsotherwise
end
```

Example

```
grade = 'B';
switch grade
case 'A'
disp('Excellent')
case 'B'
disp('Good')
case 'C'
disp('Mediocre')
case 'D'
disp('Whoops')
case 'F'
disp('Fail')
otherwise
disp('Huh!')
end
```


Variable argument lists and `nargin`

- MATLAB functions can receive a variable number of input arguments
- the function `nargin` returns how many arguments the user supplied
- typical pattern (useful for setting default values when inputs are omitted)

```
function y = myfun(a,b,c)
if nargin < 3
c = 10;      % default value
end
if nargin < 2
b = 5;      % default value
end
if nargin == 0
a = 2;      % default value
end
y = a + b + c;
end
```

- this allows flexible function calls: `myfun(2)`, `myfun(2,7)`, or `myfun(2,7,9)`
 - in the command window, `nargin` behaves a little differently
 - it must include a string argument specifying function and it returns no. of arguments
 - for example, `>> nargin('myfun')` return `ans = 3`

For loop

- *for* statements loop a specific number of times, and keep track of iteration index

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

- **example:** determine the product of all prime numbers between 1 and 20

```
>> result = 1;  
>> for n = 1:20 % iterate over 'n' from 1 to 20  
if isprime(n) % built-in function  
result = result*n;  
end  
end
```

Example

can implement for loop over columns of array:

```
>> A=[1 2;3 4]
```

```
A =
```

```
1     2
3     4
```

```
>> for r=A
```

```
    r
```

```
    end
```

```
r =
```

```
1
3
```

```
r =
```

```
2
4
```

Preallocation of memory

- MATLAB automatically resizes arrays when new elements are added
- resizing inside loops is slow and inefficient
- example of inefficient code that grows y one element at a time

```
t = 0:.01:5;
for i = 1:length(t)
    if t(i) > 1
        y(i) = 1/t(i);
    else
        y(i) = 1;
    end
end
```

- better approach: preallocate memory before the loop

```
t = 0:.01:5;
y = ones(size(t));           % preallocate
for i = 1:length(t)
    if t(i) > 1
        y(i) = 1/t(i);
    end
end
```

While loop

while statements loop as long as a condition remains true

```
while expression
statements
end
```

example: find the first integer n for which factorial(n) is a 100-digit number

```
n = 1;
nFact = 1;
while nFact < 1e100
n = n + 1;
nFact = nFact * n;
end
```

The while...break structure

- sometimes it is useful to terminate a loop in middle based on true condition
- MATLAB does not have a built-in mid-loop test structure, but the behavior can be mimicked using `while(1)` with `break`

```
while (1)
statements
if condition, break, end
statements
end
```

- `break` immediately terminates the loop when the condition becomes true
- placing `break` in the middle creates a midtest loop
- pretest version example

```
while (1)
if x < 0, break, end
x = x - 5;
end
```

- here 5 is subtracted from `x` each iteration so the loop eventually terminates
- loops must have a termination mechanism, otherwise an infinite loop results

The continue commands

continue commands jumps to the loop's end statement, but then starts the next iteration of the loop

Example: using continue to display multiples of 17

```
for i = 1:100
if mod(i,17) ~= 0
continue
end
disp([num2str(i) ' is evenly divisible by 17'])
end
```

- `mod(x,n)` returns the remainder when `x` is divided by `n`
- if the remainder is not zero, `continue` skips to the next iteration
- if the remainder is zero, the number is displayed
- output is

```
17 is evenly divisible by 17
34 is evenly divisible by 17
51 is evenly divisible by 17
68 is evenly divisible by 17
85 is evenly divisible by 17
```

The pause command

- the pause command temporarily halts program execution
- execution resumes when the user presses any key
- useful when displaying a sequence of plots that user should view one at a time

Example: viewing a sequence of plots

```
for n = 3:10  
    mesh(magic(n))  
    pause  
end
```

- each mesh plot is displayed
- pause stops the program and waits for a key press
- after the user presses a key, the loop continues to the next plot

Other useful MATLAB functions

- beep causes the computer to emit a sound
- tic and toc measure elapsed time
- tic stores the current time; toc displays the time since the most recent tic

Example: testing pause(n) with sound and timing

```
tic  
beep  
pause(5)  
beep  
toc
```

- 1st beep sounds; pauses for 5 seconds; 2nd beep sounds after the pause
- toc prints elapsed time, for example:

Elapsed time is 5.006306 seconds

- using pause(inf) creates an infinite pause
- return to the command prompt with Ctrl + C or Ctrl + Break