MATLAB Primer

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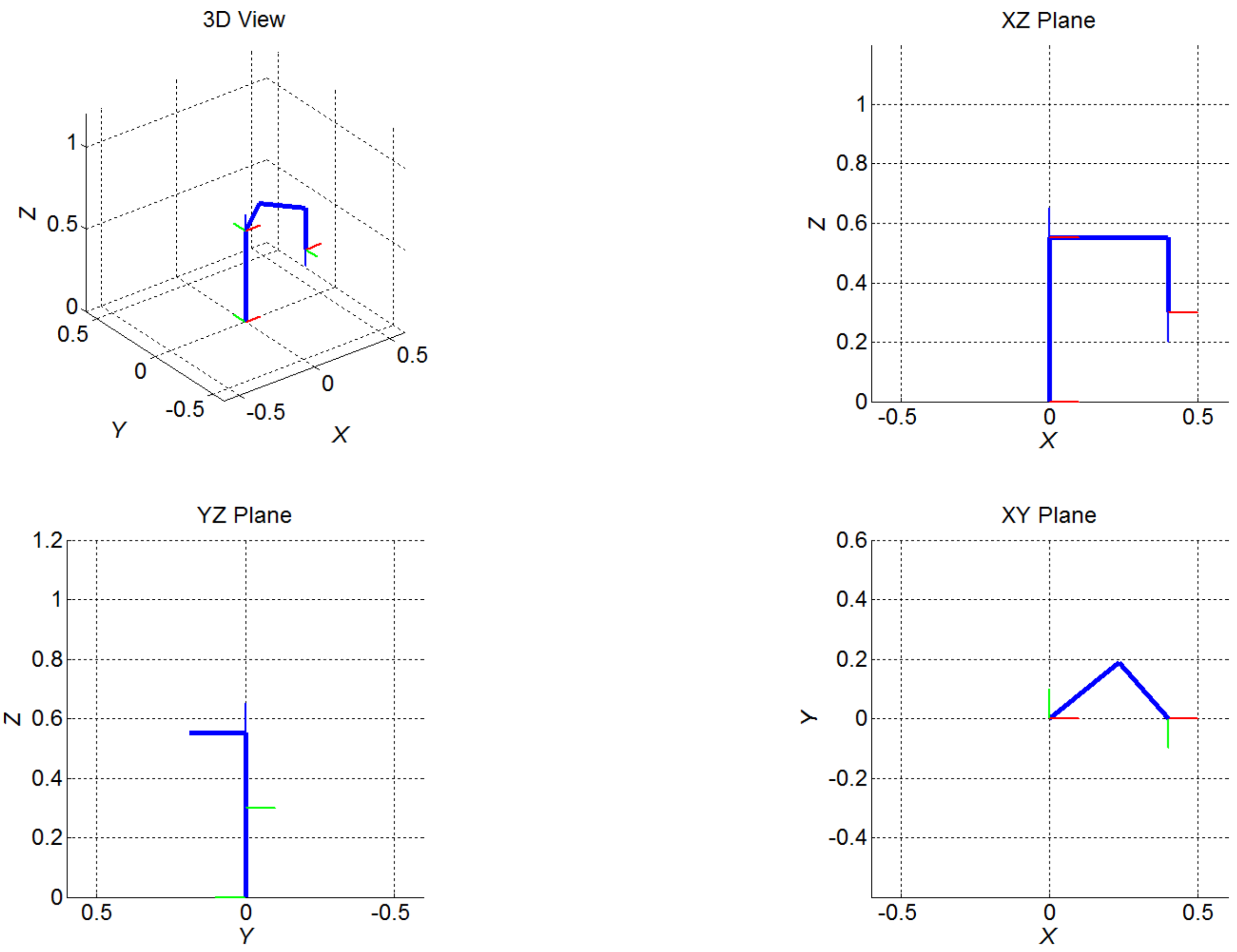

Adept 550 SCARA Robot MATLAB Simulation/Animation

This document is intended as a reference guide to help students learn MATLAB software for simulations and animations in kinematics, dynamics, controls, biomechanics, and robotics. The usefulness of this primer extends well beyond these fields.

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The purpose of this primer is to familiarize the student with MATLAB software in engineering design, analysis, and simulation. MATLAB is used extensively in all of my required and elective undergraduate and graduate engineering courses at Ohio University. My primary teaching and research interests are kinematics, dynamics, controls, haptics, biomechanics, and robotics, so I would not be surprised if this primer favors those areas. However, MATLAB is very general, with many toolboxes and specific functions for many engineering, technical, and scientific fields. This primer is intended to be a good introduction and reference for all students interested in applying the power of MATLAB to their engineering problems.

This primer presents the following MATLAB topics: introduction, basics, help, reserved names, basic operations and functions, precision, strings, arrays, plotting, nonlinear equations solvers, differential equations solvers, polynomials, vectors, matrices and linear algebra, workspace data archiving, programming, functions, the editor/debugger, m-files management, toolboxes, potential pitfalls, and sample m-files.

MATLAB stands for **MAT**rix **LAB**oratory. In this primer **`bold Courier New`** font indicates MATLAB function names, user inputs, variable names, and MATLAB outputs; this is given for emphasis only.

Since MATLAB is relatively expensive software and since Mathworks seems to be getting more and more like Microsoft as time goes by, one may want to check out FreeMat: freemat.sourceforge.net. Currently this FreeMat does not include a lot of the commands covered in this MATLAB Primer, especially the graphical and user-interface commands.

See Dr. Bob's Atlas of Structures, Mechanisms, and Robots for an extensive gallery of MATLAB Simulations/Animations developed by Dr. Bob at Ohio University to support specific courses:

www.ohio.edu/people/williar4/html/PDF/MechanismAtlas.pdf

1. Introduction

MATLAB is a general engineering analysis and simulation software. It was originally developed specifically for control systems simulation and design engineering, but it has grown over the years to cover many engineering and scientific fields. MATLAB is based on the C language, and its programming is vaguely C-like, but simpler. MATLAB is sold by Mathworks Inc. (www.mathworks.com).

Ohio University has a limited site license and all students are encouraged to buy the student version of MATLAB for installing on their personal computers (versions are available for the major computer platforms and operating systems). The student version is basically the same as the full professional version, with artificial limits on variables such as limiting maximum matrix size. Additionally, the student version includes all toolboxes, many of which must be purchased separately in the professional version.

When Dr. Bob worked at NASA Langley Research Center in the late 1980s and early 1990s we sponsored a fledgling company called Mathworks to develop a controls engineering software that grew into MATLAB. We were able to evaluate and use early beta versions, providing feedback for early MATLAB development. Dr. Bob was one of the first, if not the first, to bring MATLAB software to Ohio University for engineering education and research.

2. Basics

To start the MATLAB software in the Windows or Mac environment simply double-click on the MATLAB icon. Upon initiation of the MATLAB software my MATLAB window displays:

```
        To get started, select MATLAB Help or Demos from the Help
menu.

>>
```

The **>>** symbol is the MATLAB command prompt, where the user can type inputs to MATLAB. MATLAB provides several windows in the initial interface (Command Window, Command History, File Search Path) – I generally **X** out most of these with the mouse and just use the Command Window (and the MATLAB Editor/Debugger – described later).

MATLAB is case-sensitive, which means that variables **a** and **A** are different.

At the command prompt **>>** MATLAB can be used like a calculator. Press **<Enter>** to see a result or semi-colon (**;**) followed by **<Enter>** to suppress a result.

```
>> 2+3
ans =
     5

>> 2*3
ans =
     6

>> 2-3
ans =
    -1

>> 2/3
ans =
    0.6667

>> sqrt(9)
ans =
     3

>> 4^2
ans =
    16

>> a = 4; b = 6; a+b
ans =
    10
```

`%`	The `%` symbol at any point in the code indicates a comment; text beyond the `%` is ignored by MATLAB and is highlighted in `green`. This primer will henceforth use this notation for explanations.
`;`	% The semicolon is used at the end of a line suppresses display of the line's result to the MATLAB workspace. It is also used to separate rows in entering arrays, vectors, and matrices.
`clear`	% This command clears the MATLAB workspace, i.e., erases any previous user-defined variables.
`clc`	% Clear the MATLAB Command Window and move the cursor to the top.
`...`	% Continue statement to the next line.
`who`	% Displays a list of all user-created variable names.
`whos`	% Same as `who` but additionally gives the dimension of each variable.

MATLAB is interpretive like the Basic programming language, that is, it executes line by line without the need for a compiler. MATLAB commands and functions can be typed right into the MATLAB command window – this gets old fast, especially with complicated statements. Therefore, the recommended mode to execute MATLAB statements is to develop **`m-files`** containing your desired program to execute. Put your sequence of MATLAB statements in an ASCII file **`name.m`**, created with the beautiful MATLAB Editor/Debugger – this is color-coordinated, tab-friendly, with parentheses alignment help and debugging capabilities.

To run an existing m-file **`name.m`**, type the filename **`name`** in the MATLAB command window, making sure that the m-file exists in the MATLAB file search path. DO NOT type **`name.m`**, only **`name`**. As an alternative, click the save-and-run button in the MATLAB editor to run the m-file. Using this method, if the m-file is not within the MATLAB search path, it automatically offers to add your current folder location to the search path. To set the MATLAB working directory to one that you have used before, click the down-arrow up at the top of the MATLAB window – the text box displays the current working directory and the list shows recently-used directory choices. To browse for new folders not on this list and set one as the current working directory, use the **...** button directly to the right of the working directory down-arrow.

To halt an m-file prematurely (e.g. to stop execution of an unintended infinite loop), press **`ctrl-c`**.

If you use the **`;`** suppression discussed earlier, the variable name(s) still hold the resulting value(s) – just type the variable name at the command prompt after the program runs to see the value(s). If there is a syntax or programming logic error, it will give an error message at the bad line and then quit. Even though there is no compiler, MATLAB can recognize certain errors up-front and refuse to execute until those errors are corrected. For other errors, the program will execute until reaching the bad line. Error messages in MATLAB are generally very specific and helpful, sometimes including the precise m-file line and column number where the error occurs.

The up-arrow recalls previously-typed MATLAB commands at the MATLAB prompt, in reverse order (most recent first). The down-arrow similar scrolls forward through previously-typed MATLAB commands.

Almost all of my m-files start with the following line (multiple commands may appear on the same line, separated by space(s) and/or a semi-colon):

```
clear;  clc;
```

(Exception – if I want to use the results of one m-file in another m-file executed after the first, I omit **`clear`** so those results will not be erased..)

I have found that MATLAB is generally very reliable in terms of changes between software versions, i.e. old m-files can be run reliably using newer versions. If MATLAB plans to obsolete a function or command they prepare you for this with informational messages when using those commands. To determine the MATLAB software version number you are running type **`version`**:

```
>> version
ans =
7.3.0.267 (R2006b)
```

This primer was developed mainly using the **`R2006b`** version – it should be largely compatible with the future MATLAB versions.

3. Help

After initiating the MATLAB software, a good way to start learning is to click on **`MATLAB Help`** and/or **`Demos`**. Alternatively, one may type **`MATLAB Help`** and/or **`Demos`** at any time from the MATLAB prompt **`>>`**.

On-line MATLAB **`help`** is generally very useful. If you are really lost type **`help help`** to learn how to use the MATLAB help facility.

`help`	% Provides a list of topics for which you can get online help, sorted in logical groups. Click on any topics to see the applicable MATLAB functions.
`help` ***`fname`***	% Provides online help for MATLAB function ***`fname`*** (see **`help`** for function names).

The **`help`** ***`fname`*** command prints the header of the m-file **`help.m`**. That is, MATLAB includes comments at the top of each m-file to explain what each function or command does, how to use it, and the input/output requirements (usually there are several I/O options). MATLAB m-files are viewable by the user if you look in the MATLAB install folder. But you needn't look inside any m-files, the **`help`** command prints the header to the command window to explain the function.

Related functions of interest are generally suggested when using **`help`** ***`fname`***, at the end of the help text (**`See also . . .`**). This is a good way to find other related functions that you will want to learn and use. If you don't know the specific MATLAB function name but only the general topic, use:

`lookfor` ***`topic`***	% Provides a list of functions for which you can get online help, related to your search *`topic`*.

For instance, **`lookfor matrices`** responds with a host of available functions for matrices and linear algebra.

Here are some more help-related functions:

`info`	% Provides contact info for Mathworks Inc., who makes MATLAB.
`whatsnew`	% Highlights changes from the previous MATLAB versions.

4. Reserved names

The following variable names are reserved for specific standard reasons by MATLAB. All can be overwritten, i.e. re-defined using the **`=`** assignment, but this is to be avoided (except when using **`i`** and **`j`** for loop counters).

`pi`	% `3.1415926535897.... = 4*atan(1)`
`inf`	% infinity
`NaN`	% Not a Number, such as `0 / 0` or `inf-inf`
`i`	% `sqrt(-1)`
`j`	% `sqrt(-1)`
`eps`	% machine precision, **`2.2204e-016`** on my computer
`ans`	% answer: the result of a MATLAB operation when no name is assigned (**`ans`** is constantly overwritten with the latest non-named operation)
`flops`	% number of floating point operations (obsolete since MATLAB 6)

5. Basic Operations and Functions

This section covers some basic MATLAB operations and built-in functions.

`=`	% assignment of a calculation result to a variable name
`+`	% addition
`-`	% subtraction
`*`	% multiplication
`/`	% division
`\`	% left division
`^`	% exponentiation
`sin  cos  tan  cot  sec  csc`	% trigonometric functions
`asin acos atan acot asec acsc`	% inverse trigonometric functions
`atan2(num,den)`	% quadrant-specific inverse tangent
`sinh  cosh  tanh  coth  sech  csch`	% hyperbolic trig functions
`asinh acosh atanh acoth asech acsch`	% inverse hyperbolic trig functions
`sind  cosd  tand  cotd  secd  cscd`	% trigonometric functions in degrees
`asind acosd atand acotd asecd acscd`	% inverse trig functions in degrees
`exp`	% exponential function, base e
`log`	% natural logarithm
`log2`	% base 2 logarithm
`log10`	% base 10 logarithm
`sqrt`	% square root

`abs`	% absolute value
`sign`	% signum function (returns +1 for positive, 0 for zero, –1 for negative)
`rand`	% random number or array generator
`randn`	% random number or array generator with normal distribution
`factorial`	% factorial function

Most operations and functions in MATLAB are overloaded, i.e. they work appropriately differently when the same function (operator) is presented with different input data types; e.g. scalars, vectors, and matrices can all be added or subtracted. These data types can also be multiplied, but only if the indices line up correctly for matrix multiplication.

Order of Operations. MATLAB follows the standard precedence of mathematical operations you are already familiar with, i.e. from first to last priority:

1. parentheses
2. exponentials
3. multiplication and division
4. addition and subtraction

For equal precedence operations, the calculation proceeds left-to-right. Then function evaluations are last (nested from within first if there are functions of functions). That is, you can place any computations within a function call and MATLAB will evaluate the computations first and then call the function evaluation with the result. For example:

```
>> x = 1;  y = 2;  z = 3;
>> cos(x^2 + (2*y - z))

ans =

   -0.4161
```

Since **`x^2 + (2*y - z)`** first yields **`2`**.

6. Precision

All MATLAB numerical computations are performed in double precision by default, but the user can enter the following commands to control the numerical display format. As presented earlier, **`eps`** is the reserved MATLAB name for machine precision.

```
format short        % 4 decimals

format long         % 14 decimals

format short e      % scientific notation with 4 decimals

format long e       % scientific notation with 15 decimals

format rat          % ratio of integers approximation

format hex          % hexadecimal format
```

There are many other format options one can learn by entering **`help format`**.

Here are the MATLAB variable types (The FreeMat Primer, G. Schafer):

• int8	signed 8 bit integer, –128 to 127
• int16	signed 16 bit integer, –32,768 to 32,767
• int32	signed 32 bit integer, –2,147,483,648 to 2,147,483,647
• int64	signed 64 bit integer, -9,223,372,036,854,775,808 to 9,223,372,036,854,775,807
• uint8	unsigned 8 bit integer, 0 to 255
• uint16	unsigned 16 bit integer, 0 to 65,535
• uint32	unsigned 32 bit integer, 0 to 4,294,967,295
• uint64	unsigned 64 bit integer, 0 to 1.844674407370955e+019
• float	signed 32 bit floating point number, -3.4 x 1038 to 3.4 x 1038 (single precision)
• double	signed 64 bit floating point number, -1.79 x 10308 to 1.79 x 10308
• complex	signed 32 bit complex floating point number (real and imaginary parts are single)
• dcomplex	signed 64 bit complex floating point number (real and imaginary parts are double)
• string	letters, numbers, and/or special characters, up to 65535 characters long

7. Strings

Like most programming languages MATLAB can define and display text strings:

```
s = 'Place text here.'                  % create a MATLAB string
```

A string is a vector whose components are the numeric codes for the ASCII characters. The length and size functions (see the section on Arrays) also work for strings, giving the number of characters. An apostrophe within a string is indicated by two apostrophes.

```
disp(s)                                 % print the string  s  to the screen

disp('text')                            % print the string text to the screen

error('Error message here.')            % display an error message

warning('Warning message here.')        % display a warning message

strcmp                                  % compare strings – returns 1 for identical
                                        and 0 otherwise
```

For string formatting, MATLAB uses LaTex notation, as in the following examples:

Greek characters: **`\theta`** gives lower-case θ and **`\Theta`** gives upper-case Θ

You can use the entire Greek alphabet, both lowercase and capitals.

Font formatting: **`\it`** gives *italics*, **`\bf`** gives **bold type**, and **`\fontname`** changes the font type

`\fontsize` changes the font size

_**`{text}`** makes a subscript and **`^{text}`** makes a superscript

You can combine any of these formatting methods in any one text string. Use the curly brackets **`{ }`** to delineate formatting – they will not appear in the text.

A later section on Plotting includes more information on text strings to annotate plots.

8. Complex Numbers

MATLAB uses both **`i`** and **`j`** to represent the imaginary complex operator $\sqrt{-1}$. Caution: both **`i`** and **`j`** (as well as any other reserved names) can be re-defined, and these two often are, such as using **`i`** and **`j`** for loop iteration variables. To enter a complex number in MATLAB:

```
c = 8 + 3*i;          % enter a complex number

c = 8 + 3*j;          % enter a complex number

c = complex(8,3);     % enter the same complex number, alternative
```

Here are some useful MATLAB functions for complex numbers:

```
d = conj(c);          % define the complex conjugate of a complex number

real(c)               % returns the real part of a complex number

imag(c)               % returns the imaginary part of a complex number

abs(c)                % returns the magnitude of a complex number

angle(c)              % returns the direction of a complex number

isreal(c)             % returns 1 if the number is complex, 0 otherwise
```

9. Arrays

Arrays are **m x n** dimensional collections of numbers. MATLAB also allows 3D arrays. Scalars are 0-dimensional arrays, vectors are 1-dimensional arrays, matrices are 2-dimensional arrays, and a collection of matrices are 3-dimensional arrays. To establish an equally-spaced 1D array, use:

```
t = [t0:dt:tf];                    % equally-spaced time array
```

where **t0** is the initial time, **dt** is the time step, and **tf** is the final time. These numerical values should be set such that there is an integer number of time values *N*, i.e.:

$$N = \frac{t_f - t_0}{dt} + 1$$

For example, **t = [0:0.1:1];** yields the array **[0 0.1 0.2 … 1]**. One can include a null element if desired, e.g. **t(2) = [ ];**. If you don't want to determine a nice **dt** to yield an integer **N**, use:

```
t = linspace(t0,tf,N-1);           % equally-spaced time array, alternate
```

Two useful functions to automatically determine the array dimensions are **size** and **length**:

```
>> size(t)
ans =
     1    11

>> length(t)
ans =
    11
```

To obtain an element of an array, use the **(i)** notation. For example:

```
>> t(3)
ans =
    0.2000
```

To obtain a contiguous subset of an array, use the **(i:j)** notation. For example:

```
>> t(3:7)
ans =
    0.2000    0.3000    0.4000    0.5000    0.6000
```

Most functions can accept arrays as inputs, for example **cos(t)**. However, the multiply (*****) and square (**^2**) operators will not work with arrays since matrix multiplication is impossible with (**1xn**)(**1xn**) dimensions:

```
>> t(3:7)^2
??? Error using ==> ^
Matrix must be square.
```

If you want to perform element-by-element operations on arrays, use the dot notation:

```
>> t(3:7).^2
ans =
    0.0400    0.0900    0.1600    0.2500    0.3600
```

The dot notation also works with element-by-element multiplication and division:

```
.^          % array element-by-element exponentiation

.*          % array element-by-element multiplication

./          % array element-by-element division

.\          % array element-by-element left division
```

The following functions apply to statistical array calculations:

```
max, min, mean, median, std, sort, sum, diff, prod
```

It is very convenient to use the array power of MATLAB in programming (see the section on Programming). For example, here are two ways to define the identical time array:

```
1.   dt = 0.1;
     for i = 1:11,
          t(i) = (i-1)*dt;
     end

2.   t = [0:0.1:1];
```

Both yield the array **`t = [0 0.1 0.2 … 1]`**. Then here are two alternative ways to perform a function calculation for all array values:

```
1.   for j = 1:11,
          f(j) = cos(t(j));
     end

2.   f = cos(t);
```

Both methods yield the same array **`f`**, the cosine of all **`t`** values. Clearly method **`2`** is preferable in both cases for brevity and readability.

10. Plotting

Generating 2D plots in MATLAB is easy:

```
plot(x,y);                  % plot dependent variable y versus independent variable x
```

Where **y** is plotted on the ordinate axis and **x** is plotted on the abscissa axis. **x** and **y** must both be arrays of equal sizes (1 x *n* or *n* x 1). To plot multiple curves on the same graph:

```
plot(x,y1,x,y2,x,y3);
```

To distinguish between the curves one may use different colors, linetypes, markers, or combinations of these. The default colors are:

yellow (**y**), magenta (**m**), cyan (**c**), red (**r**), green (**g**), blue (**b**), white (**w**), black (**k**)

The possible linetypes are:

solid (**-**)	dashed (**--**)	dotted (**:**)	dashed-dot (**-.**)

The possible markers are:

point (**.**)	plus (**+**)	star (*****)	circle (**o**)	ex (**x**)
down triangle (**v**)	up triangle (**^**)	left triangle (**<**)	right triangle (**>**)	
square (**s**)	diamond (**d**)	pengtagram (**p**)	hexagram (**h**)	

We can combine curve characteristics. For example:

```
plot(x,y1,'r--',x,y2,'g:',x,y3,'b-.');
```

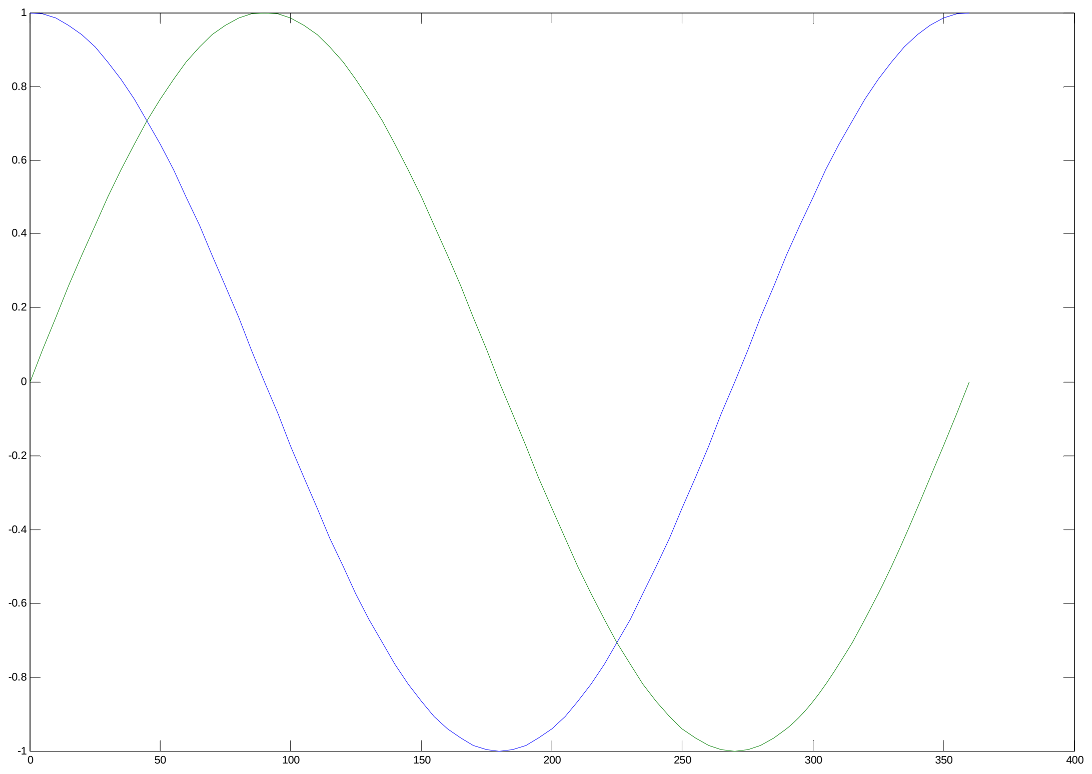
To plot a sine and cosine function on the same graph is straight-forward (see the first plot below):

```
ph = [0:5:360];  y1 = cosd(ph);  y2 = sind(ph);
figure;  plot(ph,y1,ph,y2);
```

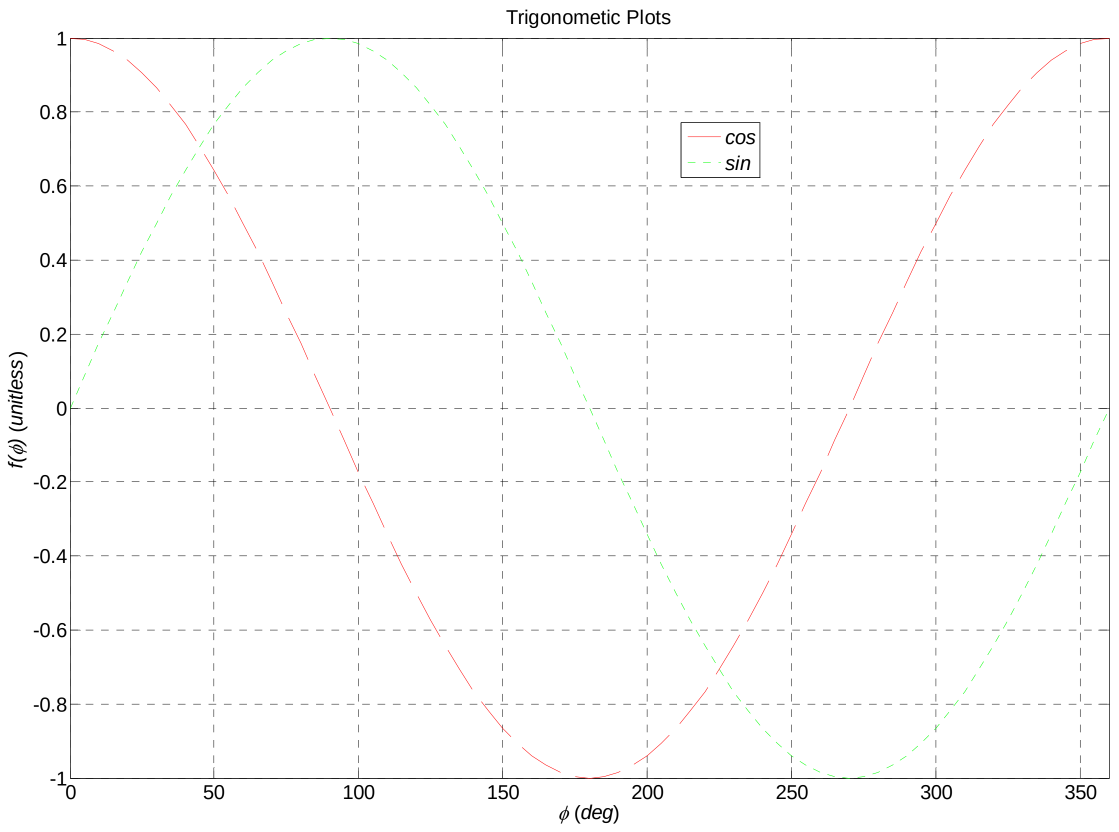
To plot a more professional graph requires bigger font, a title, axis labels and units, a grid, a legend, controlled color and linetypes, and controlled axis limits (see the second, improved plot below):

```
figure;
plot(ph,y1,'r--',ph,y2,'g:'); grid; axis([0 360 -1 1]);
set(gca,'FontSize',18);
xlabel('{\it\phi} ({\itdeg})');
ylabel('{\itf(\phi)} ({\itunitless})');
legend('{\itcos}', '{\itsin}');  title('Trigonometic Plots');
```

The plot legend may be dragged to a more convenient location with the mouse, to avoid covering plots.



Trig Plots



Improved Trig Plots

Here are some general plot commands:

`figure;`	% creates an empty figure window for graphics
`clf;`	% clear current figure
`close all;`	% close all open figure windows – this is useful if your m-file generates a lot of plots, enter this command prior to running the program again.
`fplot;`	% plot user-defined function
`text(x,y,'string');`	% position the text **`string`** at **`x,y`** in the current graphics window
`gtext('string');`	% position text **`string`** interactively in current graphics window
`[x,y] = ginput;`	% collect graphical input from mouse in **`x`** and **`y`** arrays. Press **`<Enter>`** to quit collecting
`hold;`	% hold current graph – **`hold on`** and **`hold off`** to release
`axis('square');`	% specify square axes
`axis([xmin xmax ymin ymax]);`	% specify axis limits
`axis('equal');`	% specify axes with equal **`x`** and **`y`** ranges

Here are some other 2D plot options:

```
polar, bar, hist, loglog, semilogx, semilogy
```

To draw lines, again use **`plot(x,y);`** where **`x`** and **`y`** are now arrays containing the endpoint of the line to draw. For example:

```
x = [0 L*cos(th)];
y = [0 L*sin(th)];
```

The above will draw a single rotating link of length **`L`** at a snapshot with angle **`th`**. This single link can be animated by incrementing **`th`** and plotting the line within a **`for`** loop (see **`MATEx2.m`**). The animation will zip right by without seeing it unless you use **`pause(dt);`** where **`dt`** is the pause time in seconds (approximately real-time).

I do a lot of MATLAB animations for visualizing the simulated motion of various mechanisms and robots, both planar and spatial. The default line width is marginal for representing real-world mechanical devices so I use the `'LineWidth'` switch in the plot command as follows (the default thin width is 1 and I have used up to 5 for thick lines):

```
plot(x,y,'g','LineWidth',3);    % draw a green link with a thicker line width
```

To draw solid polygons, use:

```
patch(x,y);
```

where **x** and **y** are now arrays containing the vertex coordinates of the polygon. Note you needn't go back to vertex 1, but MATLAB closes the polygon for you. For example:

```
x = [x1  x2  x3  ...  xn];
y = [y1  y2  y3  ...  yn];
```

3D plots in MATLAB are similar to 2D plots:

```
plot3(x,y,z);          % 3D plot x vs. y vs. z
```

Where **x**, **y**, and **z** must all be arrays of equal sizes (1 x *n* or *n* x 1). Again, one can plot multiple curves on the same graph. To control the viewing angle via azimuth **az** and elevation **el**:

```
view(az,el);
```

Here are some other 3D plot options:

```
surf, contour3, cylinder, sphere, peaks (MATLAB logo)
```

Plots may be saved in **name.fig** format via the menus on each figure window:

```
File →   Save As...
```

name.fig can then be retrieved later using the MATLAB open file icon or

```
File →   Open...
```

Plots may be copied to the clipboard for other Windows applications via the menus on each figure window:

```
Edit →   Copy Figure
```

First, if necessary, one can change the options via the same menu (the default works well):

```
Edit →   Copy Options...
```

After generating a plot there are many useful annotations and editing capabilities available via mouse interaction with the figure menus. I don't tend to use these a lot since I would rather do the same functions in automated m-files which I can re-use for ensuing projects.

See the Appendix for a description of interactive MATLAB plot tools.

One can generate a grid of plots using MATLAB function **`subplot`**:

```
subplot(mni)
```

will generate the *ith* plot in an *m* x *n* array of plots in the same figure window. Here is a specific example for a 2 x 2 subplot arrangement. Note that any useful plot annotation commands can still be used, plot by plot, with a subplot approach.

```
figure;
subplot(221)
plot(t,x1); grid;
set(gca,'FontSize',18);  ylabel('\itx_1 (m)');
subplot(222)
plot(t,x2); grid;
set(gca,'FontSize',18);  ylabel('\itx_2 (m)');
subplot(223)
plot(t,x3); grid;
set(gca,'FontSize',18);  ylabel('\itx_3 (m/s)');
xlabel('\ittime (\itsec)'); ;
subplot(224)
plot(t,x4); grid;
set(gca,'FontSize',18);  ylabel('\itx_4 (m/s)');
xlabel('\ittime (\itsec)'); ;
```

No spaces or commas are necessary in the **`subplot(mni)`** command, though these can be used if desired. The subplots will be filled in row-wise, i.e. the upper-left, upper-right, lower-left, and lower-right locations correspond to the **`(221)`**, **`(222)`**, **`(223)`**, and **`(224)`** designations, respectively. In this example these further correspond to the x_1, x_2, x_3, and x_4 variables, respectively.

The following code structure and functions may be used to save your MATLAB animation to an AVI movie file that can be played later independently of MATLAB (see the Programming chapter and also MatEx2.m).

```
for i=1:N,
     plot(...);
     Moov(i) = getframe;
end

movie2avi(Moov,'Name.avi')
```

11. Nonlinear Equations Solution

MATLAB has functions for solving systems of non-linear algebraic equations. Here are a few common ones:

`fzero`	% numeric solution of a nonlinear algebraic equation in one variable
`fminsearch`	% numeric solution of nonlinear algebraic equations in multiple variables
`solve`	% symbolic solution of nonlinear algebraic equations

12. Differential Equations Solution

MATLAB has many functions for solving differential equations. Here are a few common ones:

`ode23`	% 2nd-3rd order Runge-Kutta numerical solution
`ode45`	% 4th-5th order Runge-Kutta numerical solution
`dsolve`	% symbolic solution for differential equations
`impulse`	% numerical differential equation solution for an impulse input $\delta(t)$
`step`	% numerical differential equation solution for a unit step input
`lsim`	% numerical differential equation solution for any input

MATLAB can perform numerical (or symbolic) differentiation and integration:

`diff`	% numerical difference and approximate derivative or symbolic derivative
`quad`	% numerical integration
`dblquad`	% numerical double integration
`triplequad`	% numerical triple integration
`int`	% symbolic integration

13. Polynomials

A general polynomial has the form:

$$a_n s^n + a_{n-1} s^{n-1} + \cdots + a_2 s^2 + a_1 s + a_0$$

Here the independent variable is *s*, the Laplace frequency variable, but the independent variable could be *t*, *x*, or anything you want, MATLAB doesn't care. To define a polynomial in MATLAB enter an array with the *n*+1 numerical polynomial coefficients, in descending order of *s*-powers:

```
GenPoly = [an  anm1  . . .  a2  a1  a0];
                                  % enter a general polynomial via its coefficients
```

Here is a specific example for a 4th-order polynomial ($n = 4$): $s^4 + 10s^3 + 35s^2 + 50s + 24$

```
Poly4th = [1 10 35 50 24];        % enter a 4th-order polynomial via its coefficients
```

To find the roots of a polynomial:

```
PolyRoots = roots(GenPoly)        % to find the roots of a polynomial

>> roots(Poly4th)
ans =
   -4.0000
   -3.0000
   -2.0000
   -1.0000
```

To generate a polynomial from its roots (which are contained in array **`PolyRoots`**):

```
poly(PolyRoots)                   % build a polynomial from its roots


>> bob = poly(ans)
bob =
    1.0000   10.0000   35.0000   50.0000   24.0000
```

Here are some other useful polynomial functions:

```
conv           % multiply factors to obtain a polynomial product

deconv         % divide a polynomial by specified factors to obtain a polynomial
               quotient; synthetic division with remainder

polyval        % evaluate a polynomial numerically for an independent variable array

polyfit        % best polynomial fit to numerical data

polyder        % polynomial derivative
```

14. Vectors

Vectors are 1-dimensional arrays. To enter vectors use:

```
v1 = [1 2 3];                  % enter a 1x3 row vector
v2 = [1;2;3];                  % enter a 3x1 column vector
```

To separate elements on a row use spaces (or commas); to separate elements in a column use a semi-colon. Vector addition or subtraction is simply accomplished using the standard **+** and **–** operators.

To obtain an element of a vector, use the **(i)** notation. For example:

```
>> v1(3)
ans =
    3.0000
```

To obtain a contiguous subset of a vector, use the **(i:j)** notation. For example:

```
>> v2(2:3)
ans =
    2.0000
    3.0000
```

The following are useful vector functions:

```
dot(a,b)                       % vector dot product

cross(a,b)                     % vector cross product

transpose(a)                   % transpose of a vector

a'                             % transpose of a vector, shorthand notation

norm(a)                        % length (Euclidean norm) of a vector

[th,r] = cart2pol(x,y);        % convert Cartesian to polar vector description

[x,y] = pol2cart(th,r);        % convert polar to Cartesian vector description

[th,phi,r] = cart2sph(x,y,z);  % convert Cartesian to 3D spherical description

[x,y,z] = sph2cart(th,phi,r);  % convert 3D spherical to Cartesian description
```

The dot product is applicable to any equal-sized vectors and is identical to **a'*b**. The vector cross product is only applicable to **3x1** (or **1x3**) vectors; planar vectors need a zero **z** component.

The **size** and **length** functions introduced earlier under arrays apply to vectors.

15. Matrices and Linear Algebra

Matrices are 2-dimensional arrays. To enter matrices use:

```
A = [1 2 3 4;5 6 7 8; 9 10 11 12]; % enter a 3x4 matrix

A = [1  2  3  4;                   % enter a 3x4 matrix, alternate
     5  6  7  8;
     9 10 11 12];
```

Clearly the second method to enter the same matrix is more readable. To separate elements on a row use spaces (or commas); to separate rows from each other use a semi-colon. Matrix addition or subtraction is simply accomplished using the standard **+** and **–** operators. Matrix multiplication with appropriate dimensions is accomplished using the standard ***** operator.

To obtain an element of a matrix, use the **(i,j)** notation, where **i** refers to the row index and **j** the column index. For example:

```
>> A(2,3)
ans =
    7.0000
```

To obtain a contiguous subset of a matrix, use the **(i:j,k:l)** notation. For example:

```
>> A(1:2,2:3)
ans =
    2.0000  3.0000
    6.0000  7.0000
```

To obtain an entire row **i** of a matrix, use the **(i,:)** notation. That is, if the indices are omitted with the **:** notation, MATLAB just assumes you want the entire column range. For example:

```
>> A(2,:)
ans =
    5.0000  6.0000  7.0000  8.0000
```

To obtain an entire column **j** of a matrix, use the **(:,j)** notation. That is, if the indices are omitted with the **:** notation, MATLAB just assumes you want the entire row range. For example:

```
>> A(:,3)
ans =
    3.0000
    7.0000
   11.0000
```

The following are matrix functions:

`eye(n)`	% create an *n* x *n* identity matrix I_n
`zeros(m,n)`	% create a *m* x *n* matrix of zeros
`ones(m,n)`	% create a *m* x *n* matrix of ones
`diag(v)`	% create a diagonal matrix with vector **`v`** on the diagonal
`diag(A)`	% extracts the a diagonal terms of matrix **`A`** into a vector
`transpose(A)`	% transpose of matrix **`A`**
`A’`	% transpose of matrix **`A`**, shorthand notation
`inv(A)`	% inverse of matrix **`A`**
`pinv(A)`	% pseudoinverse of matrix **`A`**
`x = A\b;`	% Gaussian elimination to solve **`A x = b`**
`eig(A)`	% find the eigenvalues of **`A`**
`[v,d] = eig(A)`	% find the eigenvectors and eigenvalues of **`A`**
`rank(A)`	% calculate the rank of matrix **`A`**
`det(A)`	% calculate the determinant of square matrix **`A`**
`norm(A)`	% return the norm of matrix **`A, many options`**
`cond(A)`	% return the condition number of matrix **`A`**
`trace(A)`	% calculate the trace of matrix **`A`**

The **`size`** and **`length`** functions introduced earlier under arrays and vectors also apply to matrices.

MATLAB allows 3D arrays, i.e. sets of matrices. This feature is very useful in robotics, where the pose (position and orientation) of one Cartesian frame with respect to another is represented by 4x4 homogeneous transformation matrices. In a given robot there are many of these 4x4 matrices to describe the pose of all joints/links within the robot.

16. Workspace Data Archiving

One can save and recall the MATLAB workspace. That is, variables that you created and manipulated in one MATLAB session can be saved for later recall and future work.

`save`	% saves all user-created variables in the binary file **`matlab.mat`**
`save filename`	% saves all user-created variables in the binary file **`filename.mat`**
`save filename x y z`	% saves the user-created variables **`x`**, **`y`**, and **`z`** in the binary file **`filename.mat`**

There are many options for data formatting – enter **`help save`** to learn these.

To recall MATLAB data saved earlier using the above commands, use:

`load`	% loads all user-created variables from the binary file **`matlab.mat`**
`load filename`	% loads all user-created variables from the binary file **`filename.mat`**
`load filename x y z`	% loads the user-created variables **`x`**, **`y`**, and **`z`** from the binary file **`filename.mat`**

To save all the text that transpires in the command window during a MATLAB session, both input and output, use:

`diary filename`	% copy all command window input and output to the file **`filename`**.
`diary off`	% suspend copying the command window input and output.
`diary on`	% resume copying the command window input and output.

For MATLAB to write/read data files for Excel and other external programs, use:

`csvwrite / csvread`	% write / read a comma-separated data file
`dlmwrite / dlmread`	% write / read an ASCII-delimited data file

17. User Input

For user input data typed from the keyboard and choices from the mouse, use the **`input`**, **`menu`**, **`inputdlg`**, and **`ginput`** commands:

```
name = input('string')
```

% The **`input`** command displays a text message **`string`** to the user, prompting for input; the data entered from the keyboard are then written to the variable **`name`**. This data can be a scalar, vector, matrix, or string as the programmer desires.

Example:

```
R     = input('Enter [r1  r2  r3  r4] (length units):  ');
r1    = R(1); r2 = R(2); r3 = R(3); r4 = R(4);
```

Upon execution, for example the user can type the following in the MATLAB command window in response to the prompt:

```
Enter [r1  r2  r3  r4] (length units):  [10 20 30 40]
```

and press the Enter key in order to ensure that MATLAB assigns:

```
r1 = 10   r2 = 20   r3 = 30   r4 = 40
```

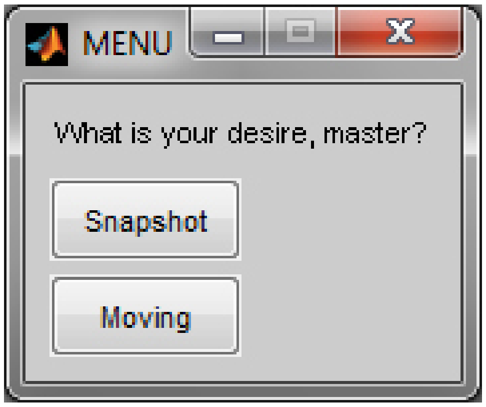
```
var = menu('Message','Choice1','Choice2','Choice3',...)
```

% The **`menu`** command displays a window on the screen, with the text **`Message`** prompting the user to click their choice. Here the programmer types desired text in **`Choicei`**, which is written to the screen menu. Then the result of the user's clicking is written as integer 1, 2, 3, … into the variable **`var`**, which can then be used for ensuing logical programming.

Example:

```
choose = menu('What is your desire, master?','Snapshot','Moving');
```

will display the following menu on the screen for the user to click one choice with the mouse:



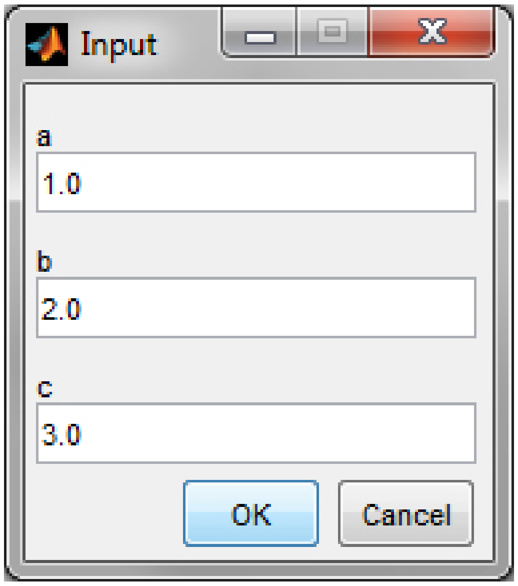
When the user clicks **`Snapshot`**, the variable **`choose`** is assigned the value **`1`** (causing the program to execute the Snapshot code, not shown), and when the user clicks **`Moving`**, the logical variable **`choose`** is assigned the value **`2`** (causing the program to execute the Moving animation code, not shown).

The MATLAB **`inputdlg`** command (input dialog) is very useful for convenient user data entry into a program, with built-in default values.

Example:

```
name    = 'Input';
values  = {'a','b','c'};
default = {'1.0','2.0','3.0'};
vars    = inputdlg(values,name,1,default);
a = str2num(vars{1});  b = str2num(vars{2});  c = str2num(vars{3});
```

This MATLAB code will display the following dialog box on the screen for the user to click with the mouse and enter data as desired, clicking **OK** to proceed in the program when finished entering data. If the default values are acceptable, the user need only click **OK** to proceed.



Note that strings are used in the above code to enter the Name, values, and default values. This is why the `str2num` function is required, to convert strings to numerical values MATLAB can compute with. As such, it is critical to use the curly brackets `{ }` as shown and not square brackets nor parentheses in their place.

The MATLAB **`ginput`** command is very useful for convenient user data entry into a program, via clicking the mouse in the current graphics window.

`[X,Y,BUTTON] = ginput(N)`

% The **`ginput`** command allows the user to click in the current graphics window and enter the data into the **`X`**, **`Y`**, and **`BUTTON`** arrays. **`X`** and **`Y`** are the coordinates chosen by the user's mouse and **`BUTTON`** is 1, 2, or 3 for the left, middle, or right mouse buttons, respectively. **`N`** is the number of points to be collected and entered into the data arrays. If **`N`** is omitted, the user keeps clicking and saving points until the return key is pressed.

`ginput` example:

```
%---------------------------------------------------------------------------
%   Mousey.m
%       use ginput to get x,y,button data from the mouse in a graphics window
%           Dr. Bob 11/2013
%---------------------------------------------------------------------------
clear; clc;

figure;
axis('square'); axis([-10 10 -10 10]); grid;
set(gca,'FontSize',18);
xlabel('\itX (m)'); ylabel('\itY (m)');

N = 4;
disp('please choose the following number of points in the figure window'); N
[X,Y,BUTT] = ginput(4);

for i = 1:N,
    [X(i) Y(i) BUTT(i)]
end
```

18. Programming

This section discusses MATLAB programming. MATLAB programs are written using the MATLAB Editor/Debugger, saved in m-files, and executed by typing the filename at the MATLAB Command Window or by using the save-and-run button from the Editor. In either case, the m-file must reside on disk within the MATLAB file search path.

MATLAB code is interpretive like the standard Basic programming language. That is, there is no compiling and statements are executed line-by-line in serial fashion. There is an optional compiler available to run MATLAB code more efficiently in standard C or C++ for real-time applications.

Even though normal MATLAB is not compiled, a program may not run if MATLAB sees an error later in the m-file. MATLAB error statements (in red in the Command Window after attempted m-file execution) are usually very helpful, including a clear statement of the problem and the row and column numbers where the error occurs. MATLAB will only display one error at a time, either prior to execution or when the error is encountered during interpretive execution. Therefore, I usually must fix each error one at a time and then keep re-executing and re-fixing new errors until the entire program runs correctly.

Always use good programming techniques, like with any programming language. Use appropriate tabs (in the MATALB editor, try **`right-click`** → **`Smart Indent`**), and include generous line and character spacing to make the program more readable and logical. Use plenty of comments **`%`** with in-line or separate lines or blocks of comments. Often I will need to temporarily remove one or more lines of code to test various issues – in the MATALB editor, highlight the desired code line(s) and use **`right-click`** → **`Comment`** (or **`Uncomment`**).

Almost all of my m-files start with the commands:

```
clear; clc;
```

to erase any previously-defined user-created MATLAB variables (**`clear`**) and to clear the screen and move the cursor to the top of the Command Window (**`clc`**).

Three useful programming constructs are the **for** loop, the **while** loop, and the **if** logical condition. These are familiar from other programming languages and the MATLAB syntax is:

```
for i = 1:N,
     put loop statements here
     using (i) notation to pick off and save single array values
end


while (condition)
     put statements here
     to execute while condition is true
end


if (condition1)
     put statements here to execute for condition1 is true
elseif (condition2)
     put statements here to execute for condition2 is true
...
end
```

N is the number of times to execute the **for** loop. Any number of **elseif** conditions may be included, or none at all. One can have nested loops and logical conditions in any program. Again, use **right-click** → **Smart Indent** to make more readable m-file programs.

In the **while** and **if** / **elseif** statements above, the **condition** and **condition1** / **condition2** can be compound conditions, i.e. using the Booleans below.

The comparatives for the **condition** statements are standard:

<	% less than
>	% greater than
<=	% less than or equal to
>=	% greater than or equal to
==	% exactly equal to
~=	% not equal to

The Booleans in MATLAB again are standard:

&	% AND
|	% OR
~	% NOT

The following two commands are useful for halting execution until the user wants to resume:

```
pause;                 % stop execution until the <Enter> key is pressed

waitforbuttonpress;    % stop execution until a mouse button or keyboard key is pressed
                       over a figure window
```

For instance, I routinely use:

```
if i==1
     pause;            % user presses <Enter> to continue
end
```

inside a **for** loop when there is graphics and animation so that the user may see the initial mechanism or robot rendering, get acclimated to the view, and re-size the window prior to hitting **<Enter>** to continue the program and display the ensuing animation. Also, for animations, I use the following pause inside the **for** loop, otherwise the animation will zip right by without the user seeing anything:

```
pause(dt);             % program pauses for dt seconds for
                       animation purposes
```

This is approximately real-time and it unpauses automatically after **dt** has elapsed.

In large, complicated programs I regularly use sub-m-files to simplify the programming. That is, I put a series of commands into a different m-file and then call it by typing the sub-m-file name in the calling m-file. This is not a subroutine or a function (see next section) but merely cutting lines which logically belong together, and which may need to be repeated, into a separate file. Then upon running the main program, the interpretive execution proceeds as if all commands were in the same file.

Here are four program flow commands that I have never used in my life, but you may want to:

```
break                  % stop execution of a for or while loop

continue               % go to the next iteration of a for or while loop

keyboard               % pause m-file execution for user keyboard input

return                 % return to invoking function; also terminate keyboard mode
```

For more advanced interactive applications, one may wish to create a GUI (graphical user interface). MATLAB has a very general and powerful GUI facility called **GUIDE**. To invoke it, either click the **GUIDE** button on the MATLAB toolbar, or simply type **>>guide** in the MATLAB command window.

To get started with **GUIDE**, run the demo (**Help** → **Demos** → **MATLAB** → **Creating Graphical User Interfaces** → **Creating a GUI with GUIDE**).

19. Functions

MATLAB comes with many useful built-in functions, many of which are covered in this primer. One can also write user-defined functions to perform specific calculations that you may need repeatedly.

Here is an example user-created function to calculate the mobility M (number of degrees-of-freedom, dof) for planar jointed mechanical devices (structures, mechanisms, and robots), using Kutzbach's planar mobility equation:

$$M = 3(N-1) - 2J_1 - J_2$$

```
% Function for calculating planar mobility
%   Dr. Bob

function M = dof(N,J1,J2)

M = 3*(N-1) - 2*J1 - 1*J2;
```

Create the above function within the MATLAB editor and name it **`dof.m`**.

Usage:
```
    mob = dof(4,4,0);   % for 4-bar and slider-crank mechanisms
```

Result:
```
    mob = 1
```

The command **`mob = dof(4,4,0);`** may be invoked either from MATLAB's command window or from within another m-file. In either case, the file **`dof.m`** containing the function **`dof`** must be in the MATLAB file search path.

For simple user-created functions, one can use **`inline`**:

```
    g = inline('x.^2 + 2*x + 3','x');  % create an in-line function
```

This yields the function $g(x) = x^2 + 2x + 3$. To use it, simply enter **`g(4)`** and so on. Note that this function will work with scalar or array input due to our use of the **`.^`** term-by-term exponentiation. The **`.*`** term-by-term multiplication is not required since the scalar multiplication of 2 works with arrays or scalars.

20. Editor/Debugger

This section presents the MATLAB Editor/Debugger.

In the MATLAB editor, comments **`%`** appear in **`green`**, text strings appear in **`violet`**, and logical operators and other reserved programming words such as looping words appear in **`blue`**. Errors in the command window appear in **`red`**.

Press the new file button from the Command Window to invoke the MATLAB Editor/Debugger – a new window will open for you to enter your m-file. Be sure to **`Save As filename.m`**, in a folder that is in the MATLAB file search path. Alternatively, you may add the folder where you save the m-file to the search path.

Use generous in-line and between-line spacing, and appropriate tabbing (**`right-click`** → **`Smart Indent`**), to make the program more readable and logical. Use lots of comments **`%`**, at the end of lines and in separate lines and blocks of comments (**`right-click`** → **`Comment`** or **`Uncomment`**).

The MATLAB editor conveniently numbers the m-file lines consecutively from 1. The columns are not numbered, but if you place the cursor anywhere in the m-file using the mouse by single-clicking, the line and column numbers are displayed in the editor screen to the lower right (e.g. **`Ln 3  Col 15`**).

There is a convenient button to save and run the m-file in the active editor window. Multiple m-files from different directories may be open simultaneously, as long as no two have the same **`filename`**.

After running an m-file, place the cursor over different variables in the m-file inside the MATLAB Editor/Debugger to see the values.

MATLAB has a powerful debugging capability within the Editor. Honestly I have not found the need to learn this so far. It is certainly recommended to the interested student, especially for more advanced programming. Debugging is critical when using functions extensively since their variables are not global.

Use the **`profile on`** command to track the execution times of your m-file execution.

21. m-files management

MATLAB uses a Unix-like directory structure and commands to access and manage m-files.

`pwd`	% show the current directory (folder)
`dir`	% list all files in the current directory
`dir *.m`	% list all m-files in the current directory
`dir *.mdl`	% list all Simulink models in the current directory
`chdir pathname`	% change the current directory to **`pathname`**
`chdir`	% show the current directory (just like **`pwd`**)
`cd`	% shorthand for **`chdir`**
`what`	% list all MATLAB files in the current directory
`which` ***`fname`***	% displays the path name of the function **`fname.m`**.
`path`	% prints the current MATLAB file search path to the screen
`addpath`	% add another directory to the current MATLAB file search path
`rmpath`	% remove a directory from the current MATLAB file search path
`why`	% responds with funny answers – many possibilities

22. Toolboxes

MATLAB has been expanded significantly over the years to include many fields besides control systems engineering, the initial MATLAB focus. Below is a ***partial*** list of available MATLAB toolboxes to expand the base MATLAB software capability. Ohio University does not have a license for all of these toolboxes.

I especially recommend Simulink, the Control Systems Toolbox, Real-time Workshop, SimMechanics, the Symbolic Math Toolbox, and the Virtual Reality Toolbox.

- Aerospace Blockset
- Aerospace Toolbox
- Communications Toolbox
- Control System Toolbox
- Curve Fitting Toolbox
- Data Acquisition Toolbox
- Filter Design Toolbox
- Financial Toolbox
- Fuzzy Logic Toolbox
- Genetic Algorithm Toolbox
- Image Processing Toolbox
- MATLAB Compiler
- Model Predictive Control Toolbox
- Neural Network Toolbox
- Optimization Toolbox
- Parallel Computing Toolbox
- Partial Differential Equation Toolbox
- Real-Time Workshop
- Robust Control Toolbox
- Signal Processing Toolbox
- SimBiology
- SimMechanics
- Simulink
- Simulink 3D Animation
- Simulink Control Design
- Simulink Design Optimization
- Spline Toolbox
- Stateflow
- Statistics Toolbox
- Symbolic Math Toolbox
- System Identification Toolbox
- Virtual Reality Toolbox

23. Simulink Tutorial

Simulink is the Graphical User Interface (GUI) for MATLAB. This section presents a brief tutorial on how to use `simulink` to create an open-loop block diagram. Then the model can easily be run, i.e. asking `simulink` to numerically solve the associated IVP ODE for you and plot the results vs. time.

1. Start **MATLAB** and at the prompt type `simulink` (all lower case).

2. If installed, the **Simulink Library Browser** will soon pop up.

3. Click on the new icon, identical to a MS Word new file icon. That is your space to work in. After creating a model it can be saved (using the save icon).

4. To build simulation models, you will be creating block diagrams just like we draw by hand. In general all blocks are double-clickable to change the values within. In general you can connect the ports on each block via arrows easily via clicking and dragging with the mouse. You can also double-click any arrow (these are the controls variables) to label what it is. Same with all block labels (`simulink` will give a default name that you can change).

5. `simulink` uses EE lingo. Sources are inputs and sinks are outputs. If you click around in the Simulink Library Browser, you will see the possible sources, blocks, and sinks you have at your disposal.

6. Now let us create a simple one-block transfer function and simulate it subject to a unit step input. The given open-loop transfer function is $G(s)=\dfrac{1}{s^2+2s+8}$.

   a. Click the **new icon** in the **Simulink Library Browser** to get a window to work in (**untitled** with the `simulink` logo).

   b. Double-click the **Continuous** button in the **Simulink Library Browser** to see what blocks are provided for continuous control systems. Grab and slide the **Transfer Fcn** block to your workspace. Double-click the block in your workspace and enter **`[1]`** in **Numerator coefficients** and **`[1 2 8]`** in **Denominator coefficients** and close by clicking OK. Simulink will update the transfer function in the block, both mathematically and visually.

   c. Go ahead and save your model on your flash drive as **`name.mdl`** (whatever **`name`** you want, as long as it is not a reserved MATLAB word).

   d. Click the **Sources** tab in the **Simulink Library Browser** to see what source blocks are provided. You will find a Step, Ramp, Sine Wave, etc. (but no Dirac Delta – see Dr. Bob's on-line ME 3012 NotesBook Supplement to see how to make that type on input in Simulink, three alternate methods). Grab and slide the **Step** block to your workspace. Double-click the Step block in your workspace and ensure **1** is already entered as the final value (for a unit step) and that **0** is the Initial value. Close by clicking OK.

e. Draw an arrow from the Step block to the Transfer Fcn block by using the mouse. Float the mouse near the Step port (> symbol) and you will get a large + mouse avatar. Click and drag to the input port of the Transfer Fcn block; when you see a double-plus, let go and the arrow will be connected.

f. Click the **Sinks** tab in the **Simulink Library Browser** to see what sink blocks are provided. Grab and slide the **Scope** block to your workspace.

g. Draw an arrow from the Transfer Fcn block to the Scope block by using the mouse, the same method as before.

h. To run the model (solve the associated differential equation numerically and plot the output results vs. time automatically), simply push **`play`** (the solid black triangle button in your workspace window).

i. After it runs, double-click on your Scope to display the results. Click the binoculars icon to zoom in automatically.

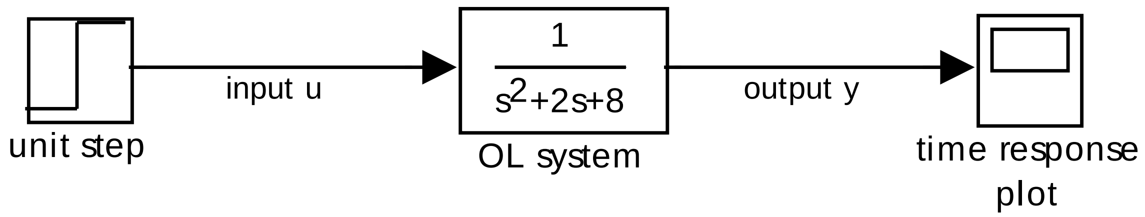
j. When I perform these steps, there are two immediate problems: i. the plot does not start until *t* = 1 sec and ii. the plot is too choppy. These are easy to fix:

   i. Double-click the Step block and change the Start time to **0** from the default **1** sec, then click **OK**. Re-run and ensure the plot now starts at *t* = 0.

   ii. In your workspace window click Simulation -> Configuration Parameters -> Data Import/Export. Look for Refine output in the window and change the Refine factor from **1** to **10**, then click **OK**. Re-run and ensure the plot is now acceptably smooth.

k. Finally in this open-loop simulation example, it appears that 10 sec final time is a bit too much. Near the play button in your workspace is an unidentified number 10.0. This is the default final time. Change it to 8.0, re-run, and ensure the plot now ends at *t* = 8. If you reduce final time less than 8.0 you will lose some transient response detail.

Your final model will look like this (be sure to be a control freak like Dr. Bob and line up all the arrows and blocks in a rectangular grid). I also renamed the blocks and labeled the variables.



Open-loop simulation example Simulink model

Feel free to play around to your heart's content and see what you can learn. Simulink is fast, easy, and fun! But it is a bad black box on top of the black box of MATLAB.

Another group of simulink blocks you may use a lot is under **Math Operations** in the **Simulink Library Browser**. In particular, we use the **Sum** (summing junction) and **Gain** (multiplication by a constant) a lot in controls.

In addition I find the **Mux** (multiplexer) and **Demux** (demultiplexer) very useful, especially the **Mux** to combine two or more variables for plotting on a common scope. These are found under **Signal Routing** in the **Simulink Library Browser**.

Assignment: update your above model by yourself to include negative unity feedback (sensor transfer H(s) = 1), with no specific controller (G_C(s) = 1, just a straight line with no block). Plot both open- and closed-loop unit step responses and compare and discuss.

Hint: put a summing junction between the Step input and the OL system transfer function. Double-click the sum to make the correct signs (i.e. + and -). Then pull an arrow down from the negative summing port, turn the corner without letting go. Then you will have to let go, but click immediately without moving the mouse and hover it over the output y line. When you get the double-plus, let go and you have just made a pickoff point, for the output y feedback.

24. Pitfalls

This section contains some pitfalls that many MATLAB newbies encounter.

Be sure to use proper m-file filenames. There can be no leading number, i.e. **`4bar.m`** is an invalid filename in MATLAB, even though the MATLAB editor will let you name it as such. There can be no spaces in your filename, i.e. MATLAB will interpret the filename **`four bar.m`** as two separate text strings, even though Windows stupidly allows spaces in filenames. You can use the underbar instead of spaces and you can use numerical characters as long as they are not the leading character.

MATLAB is case-sensitive, which means that variables **`a`** and **`A`** are different. Also, generally MATLAB functions and commands are all lower-case. If you type a MATLAB command in all CAPS by mistake, such as **`WHOS`** instead of **`whos`**, this will fail – the MATLAB response is:

```
>> WHOS
??? Undefined function or variable 'WHOS'.
```

However, if you want to run an m-file **`name.m`** and type in **`NAME`** in all capitals by mistake, instead of **`name`**, MATLAB generally says the following and will run your m-file anyway:

```
Warning: Could not find an exact (case-sensitive) match for 'NAME'.
```

MATLAB sample program **`MATEx2.m`**, given later, requires user-typed input from the keyboard to proceed:

```
the = input('Enter [th0 dth thf] (deg):  ')        %  User types input
```

I created the text inside the input function – be sure to type the data in square brackets exactly as I specify in the text string above (without the **`(deg)`** which is for info only), and then hit **`<Enter>`**:

```
     Enter [th0 dth thf] (deg):  [0 5 360]
```

If you just cannot get the input function to work, skip it for now and just hard-code the data:

```
     th0 = 0;  dth = 5;  thf = 360;
```

Be sure to comment out the **`input`** and following line in this case.

If you are doing planar vector operations, the **`dot`** product will work:

```
     >> a = [1;2];  b = [3;4];
     >> dot(a,b)
     ans =
         11
```

But the **`cross`** product will fail, until you augment the planar vectors with zero in the **`z`** component.

```
     >> cross(a,b)
     ??? Error using ==> cross
     A and B must have at least one dimension of length 3.
```

```
>> a = [1;2;0];  b = [3;4;0];
>> cross(a,b)
ans =
     0
     0
    -2
```

Multiplying these two planar vectors will fail since the indices do not line up properly for matrix multiplication (**`2x1`** times **`2x1`** and **`3x1`** times **`3x1`** will both fail since the inner matrix dimensions are not the same – for matrix multiplication, the number of columns in the left matrix must match the number of rows in the right matrix).

```
>> a*b
??? Error using ==> mtimes
Inner matrix dimensions must agree.
```

Another way to perform the dot product is to transpose the first vector and use multiplication:

```
>> a'*b
ans =
    11
```

Now this matrix multiplication succeeds since the inner matrix dimensions match (**`1x3`** times **`3x1`**).

A similar common error arises when an **`nx1`** (or **`1xn`**) array is squared:

```
>> b^2
??? Error using ==> mpower
Matrix must be square.
```

There are two potential fixes for this error. If you are inside an **`i`** loop and only intended to square one individual component, use the **`(i)`** notation:

```
>> b(2)^2
ans =
     16
```

If you wanted to square each component of the original array and place the result in an equal-sized array, use the **`.^`** element-by-element notation:

```
>> b.^2
ans =
     9
    16
     0
```

When using the 2D plot command **`plot(x,y)`** both arrays **`x`** and **`y`** must be of the exact same dimension:

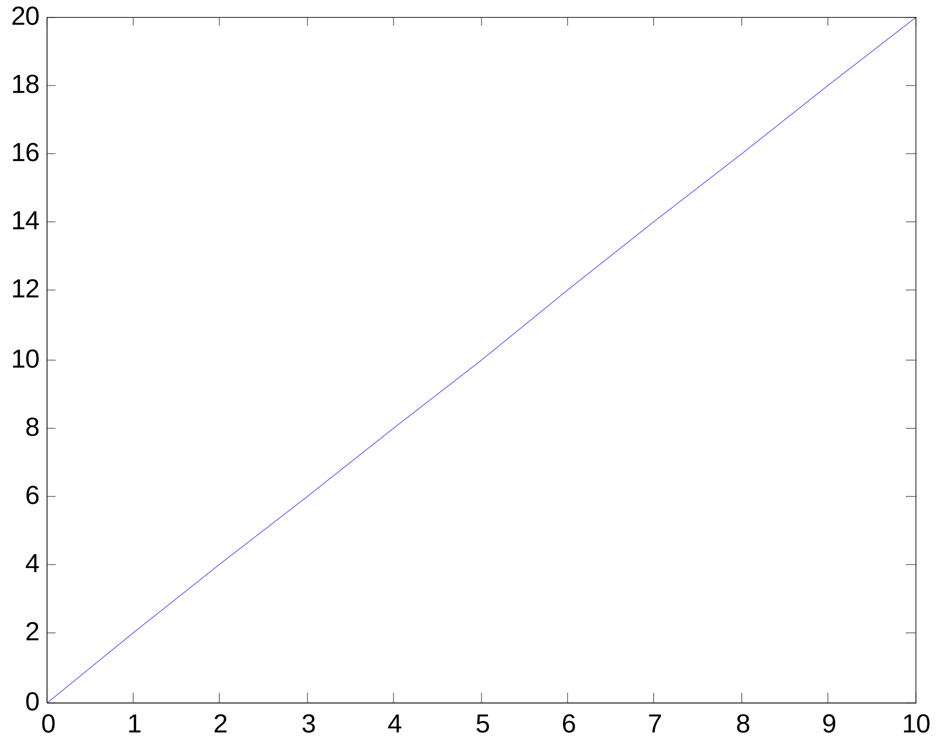
```
>> x = [0:1:10];  y = [2:2:20];
>> plot(x,y)
??? Error using ==> plot
Vectors must be the same lengths.
```

To fix this case use **whos** to see the problem:

```
>> whos
  Name        Size                Bytes  Class
  x           1x11                   88  double
  y           1x10                   80  double
```

We see that **x** is **1x11** and **y** is only **1x10**. The same information could have been determined from **length(x)**, **length(y)** (or **size(x)**, **size(y)**). To fix this error:

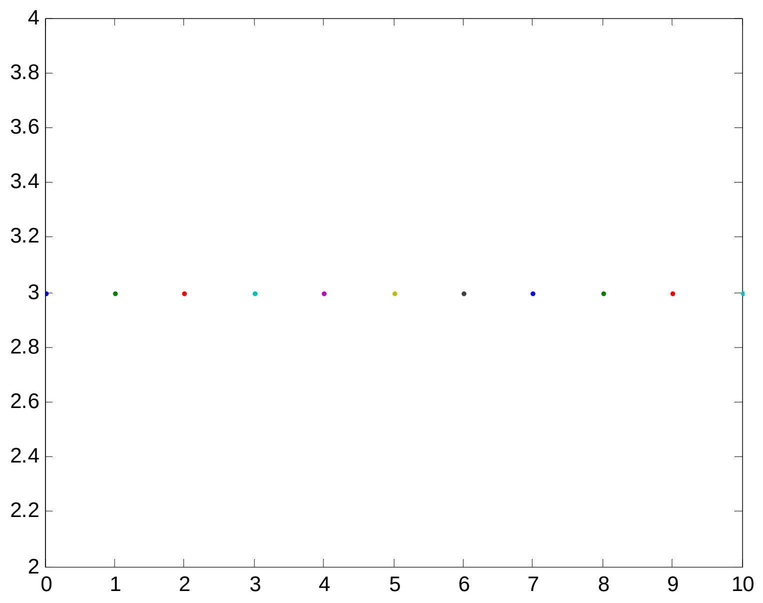
```
>> x = [0:1:10];  y = [0:2:20];
>> plot(x,y)
```



Actually, the two arrays need not be of the exact same dimension – **y** of **1xn** may be plotted vs. **x** of **nx1** and vice versa.

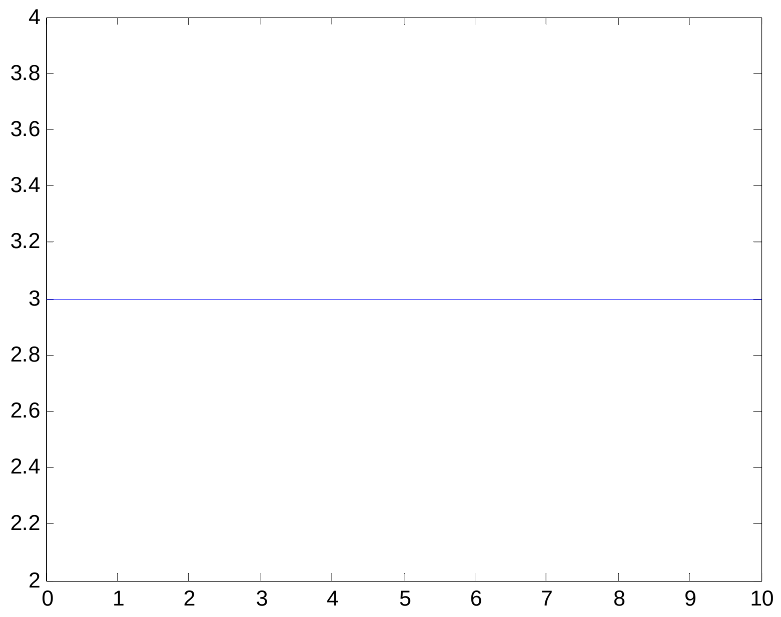
A common plotting error with newbies is when the user wants to plot an entire array vs. the independent variable array. By mistake, the user only plots a single scalar. In older versions of MATLAB this used to fail. Now MATLAB plots the following, barely visible:

```
>> c = 3;
>> plot(x,c)
```



If you want to plot a constant scalar vs. the independent variable array:

```
    plot(x,c*ones(1,length(x)))
```



An alternate approach, yielding the same plot:

```
    plot(x,c*ones(size(x)))
```

Here are some more common errors I have seen with students and myself over the years.

As in any programming, one must take care that your parentheses and brackets line up correctly, as you intended, and with proper left/right balancing:

```
>> sqrt(cos(t)
??? sqrt(cos(t)
               |
Error: Expression or statement is incorrect--possibly unbalanced
(, {, or [.
```

Whereas the C language starts indices at 0, and MATLAB is based on the C language, all MATLAB indices must start at 1:

```
>> b(0) = 10
??? Subscript indices must either be real positive integers or
logicals.
```

If you intended to define an array **w2**, but instead made a scalar **w2**, then if you try to access that variable **w2** inside a loop for **i** greater than 1 you will get this error:

```
>> w2 = 5
>> w2(2)
??? Index exceeds matrix dimensions.
```

If you attempt to set a matrix equal to a left-hand-side array you will get this error:

```
>> b = rand(2);     %  generate a random 2x2 matrix b
>> a(1) = b
???  In an assignment  A(I) = B, the number of elements in B and
 I must be the same.
```

The fix for this error is to drop the **(i)** notation on the left-hand side. In general, if you are within a loop, only use the **(i)** notation on the left-hand side when you want to save that particular variable for later plotting or other operations. If the variable is intermediate and you don't care about it, drop the **(i)** notation and then it will be overwritten the next time through the loop.

If you intended to make an animation of robot or mechanism motion in a **for** loop of N steps but instead got N separate plot windows, you must move the **figure;** statement to outside the **for** loop. Then use **close all;** to kill the unwanted N figures on your screen prior to trying the program again.

Remember to run an m-file **`name.m`** from the MATLAB command prompt, DO NOT type **`name.m`**, only **`name`**. Otherwise you will get the following error, since MATLAB thinks you are trying to access a data structure with **`.m`** in its name:

```
>> name.m
??? Undefined variable "name" or class "name.m".
```

25. Sample m-files

The following example **`m-files`** are given on the following pages.

1) **`MATEx1.m`**	matrix and vector definition, multiplication, transpose, and solution of linear equations
2) **`MATEx2.m`**	input, programming, plots, animation
3) **`MATEx3.m`**	complex numbers, polynomials, plotting

```
%-------------------------------------------------------------
%  MATLAB Example Program 1:  MATEx1.m
%     Matrix and Vector examples
%        Dr. Bob, Ohio University
%-------------------------------------------------------------
clear;  clc;         % clear any previously defined variables and the cursor

%
%  Matrix and Vector definition, multiplication, and transpose
%
A1  = [1  2 3; ...   % define 2x3 matrix [A1] (... is continuation line)
       1 -1 1];
x1  = [1;2;3];       % define 3x1 vector {x1}

v  = A1*x1;          % 2x1 vector {v} is the product of [A1] times {x1}

A1T = A1';           % transpose of matrix [A1]
vT = v';             % transpose of vector {v}

%
%  Solution of linear equations Ax=b
%
A2    = [1  2  3; ...% define matrix [A2] to be a 3x3 coefficient matrix
         1 -1  1; ...
         8  2 10];

b     = [3;2;1];     % define right-hand side vector of knowns {b}

detA2  = det(A2);    % first check to see if det(A) is near zero

x2     = inv(A2)*b;  % calculate {x2} to be the solution of Ax=b by inversion

check = A2*x2;       % check results

z     = b - check;   % must be zero

%
%  Display the user-created variables (who), with dimensions (whos)
%
who
whos

%
%  Display some of the results
%
v, x2, z

%  More vectors and matrices functions
v1 = [1;2;3];
v2 = [3;2;1];
s3 =   dot(v1,v2);
v4 = cross(v1,v2);
A  = rand(3);
v5 = A*v1;
At = A';
Ainv = inv(A);
i1 = A*Ainv;
i2 = Ainv*A;
dA = det(A);
```

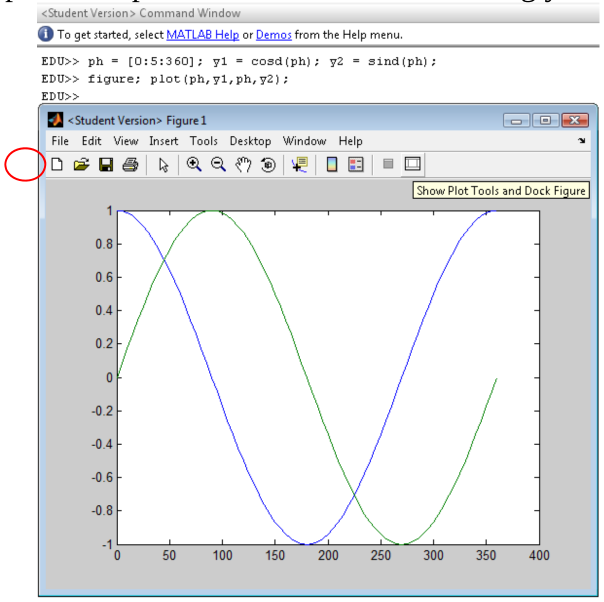
```
%-----------------------------------------------------------------
%  MATLAB Example Program 2:  MATEx2.m
%     Menu, Input, FOR loop, IF logic, Animation, and Plotting
%        Dr. Bob, Ohio University
%-----------------------------------------------------------------

clear;  clc;         %  clear any previously defined variables and the cursor

r  = 1;  L  = 2;  DR = pi/180;                      % constants

%
%  Input
%
anim = menu('Animate Single Link?','Yes','No')      % menu to screen
the = input('Enter [th0 dth thf] (deg):  ')         % user types input
th0 = the(1)*DR; dth = the(2)*DR; thf = the(3)*DR; % initial, delta, final thetas
th  = [th0:dth:thf];                                % assign theta array
N   = (thf-th0)/dth + 1;                            % number of iterations for loop

%
%  Animate single link
%
if anim == 1                                        % animate if user wants to
   figure;                                          % give a blank graphics window
   for i = 1:N;                                     % for loop to animate
      x2 = [0     L*cos(th(i))];                    % single link coordinates
      y2 = [0     L*sin(th(i))];
      plot(x2,y2); grid;                            % animate to screen
      set(gca,'FontSize',18);
      xlabel('\itX (\itm)'); ylabel('\itY (\itm)');
      axis('square'); axis([-2 2 -2 2]);            % define square plot limits
      pause(1/4);                                   % pause to see animation
      if i==1                                       % pause to maximize window
         pause;                                     % user hits Enter to continue
      end
   end
end

%
%  Calculate circle coordinates and cosine function
%
xc = r*cos(th);                               % circle coordinates
yc = r*sin(th);
f1 = cos(th);                                 % cosine function of theta
f2 = sin(th);                                 %  sine  function of theta

%
%  Plots
%
figure;                                       % co-plot cosine and sine functions
plot(th/DR,f1,'r',th/DR,f2,'g'); grid; set(gca,'FontSize',18);
legend('Cosine','Sine');
axis([0 360 -1 1]); title('Functions of \it\theta');
xlabel('\it\theta (\itdeg)'); ylabel('Functions of \it\theta');

figure;                                       %  plot circle
plot(xc,yc,'b'); grid; set(gca,'FontSize',18);
axis('square'); axis([-1.5 1.5 -1.5 1.5]); title('Circle');
xlabel('\itX (\itm)'); ylabel('\itY (\itm)');
```

```
%----------------------------------------------------------------------
%     MATLAB Example Program 3:  MATEx3.m
%           Complex Numbers, Polynomials, and Plotting
%                 Dr. Bob, Ohio University
%----------------------------------------------------------------------

clear;  clc;            % clear any previously defined variables and the cursor


%  Complex numbers
x  = 3 + 4*i;           % define some complex numbers; can use j too
y  = 4 - 2*i;
z  = 1 +   i;
w1 = x + y + z;         % operations with complex numbers
w2 = x*y;
w3 = x/y;
w4 = (x+y)/z;
re =  real(w4);         % real and imaginary parts
im =  imag(w4);
mg =   abs(w4);         % polar form
an = angle(w4);


%  Polynomials
p0 = [1];               % define 0th through 5th order polynomials
p1 = [1 2];
p2 = [1 2 3];
p3 = [1 2 3 4];
p4 = [1 2 3 4 5];
p5 = [1 2 3 4 5 6];

r0 = roots(p0);         % find roots of polynomials
r1 = roots(p1);
r2 = roots(p2);
r3 = roots(p3);
r4 = roots(p4);
r5 = roots(p5);

p9 = conv(p4,p5);       % multiply p4*p5
r9 = roots(p9);
q9 = poly(r9);          % reconstruct p9 from roots
m9 = real(q9);          % ignore spurious imaginary parts
q4 = deconv(p9,p5);     % divide p9/p5

x1 = [0:0.1:5];         % evaluate and plot a polynomial function
p  = [1 -10 35 -50 24];
rp = roots(p);
y1 = polyval(p,x1);

figure;
plot(x1,y1);grid; set(gca,'FontSize',18);
xlabel('\itX'); ylabel('\itY'); title('4^{th}-order polynomial plot');
```

Appendix. Interactive Plot Tools

This appendix on MATLAB interactive plotting tools, leading to automatic m-file generation to see how the resulting graphics can be generated, was contributed by Jesus Pagan, of the Ohio University Mechanical Engineering Department.

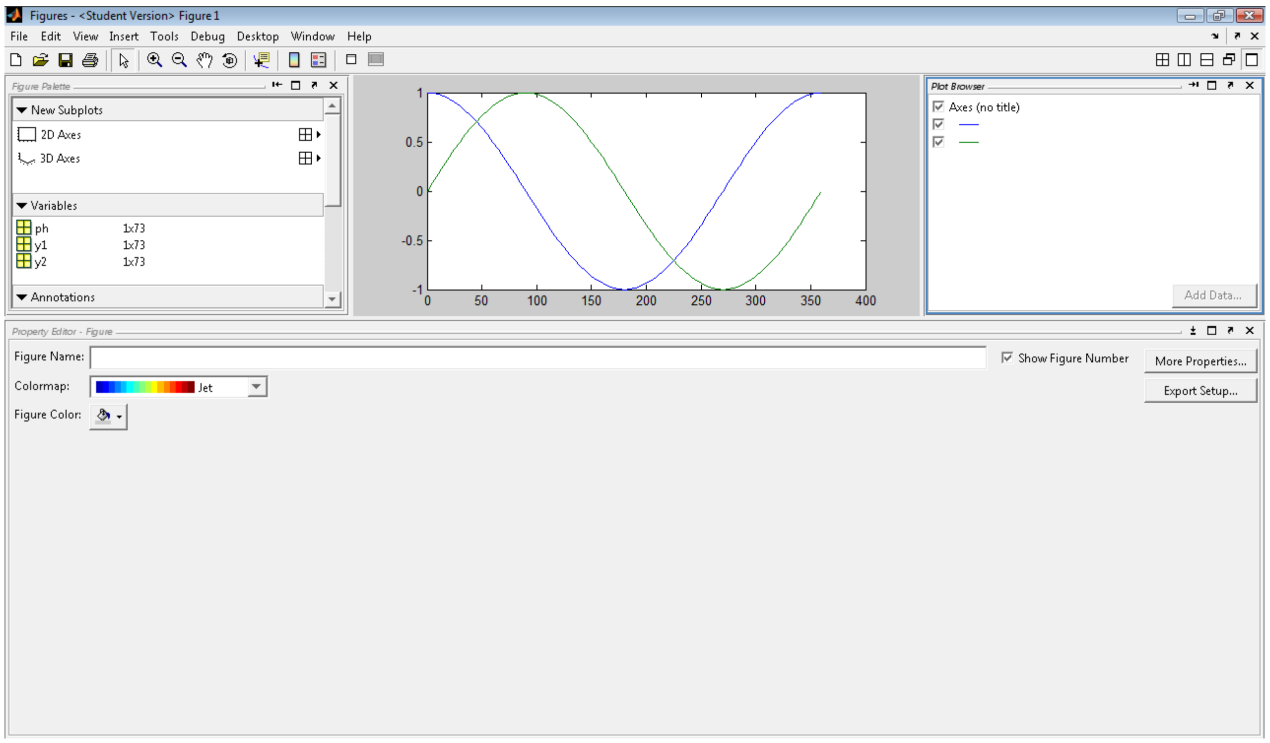
If you enter the first plot example from the section on Plotting you should get the following:



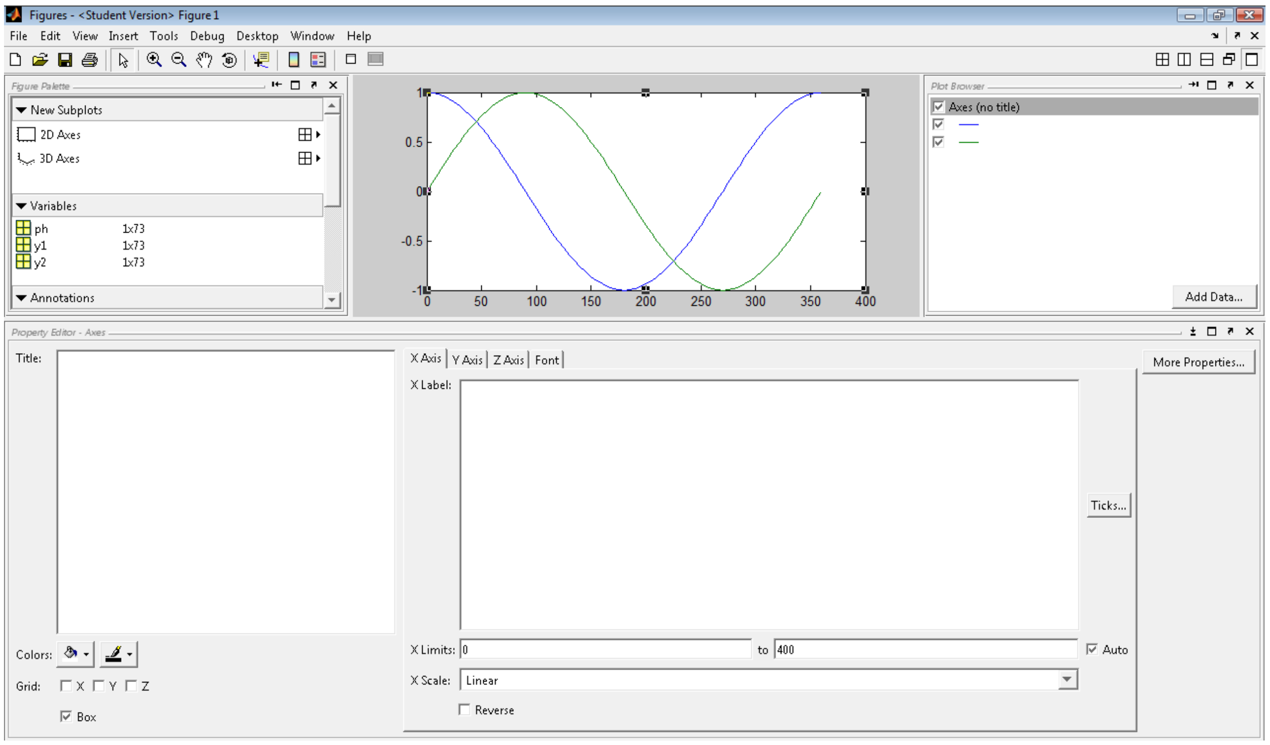
<Student Version> Command Window
To get started, select MATLAB Help or Demos from the Help menu.
<Student Version> Figure 1
File Edit View Insert Tools Desktop Window Help
Show Plot Tools and Dock Figure

```
EDU>> ph = [0:5:360]; y1 = cosd(ph); y2 = sind(ph);
EDU>> figure; plot(ph,y1,ph,y2);
EDU>>
```

You can then click on the icon **`Show Plot Tools and Dock Figure`** and you should get the following (after some manipulation of the window in the screen):



From this screen, you can now access many features to manipulate your plots by adding legends, titles, x-axis label, y-axis label, grids, limits in the x-axis and y-axis, and many others. Now, try to click somewhere on the chart to see **`Property Editor – Axes`** in the lower part of the window.



Title:

X Label:

X Limits: 0 to 400 ☑ Auto

X Scale: Linear

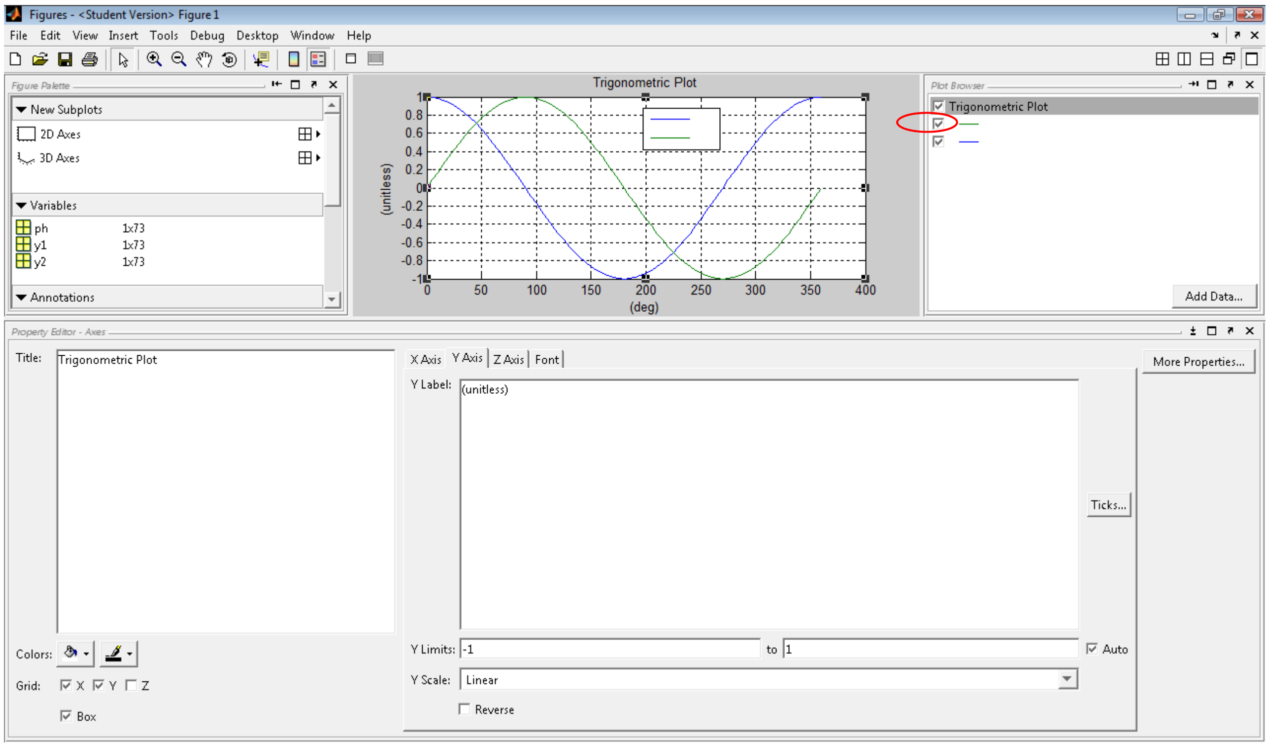
☐ Reverse

Grid: ☐ X ☐ Y ☐ Z

☑ Box

ph	1x73	
y1	1x73	
y2	1x73	

Go ahead and add some information. When you are finished making the desired changes, your plot could look like this:



ph	1x73	
y1	1x73	
y2	1x73	

Title: Trigonometric Plot

Y Label: (unitless)

Y Limits: -1 to 1 ☑ Auto

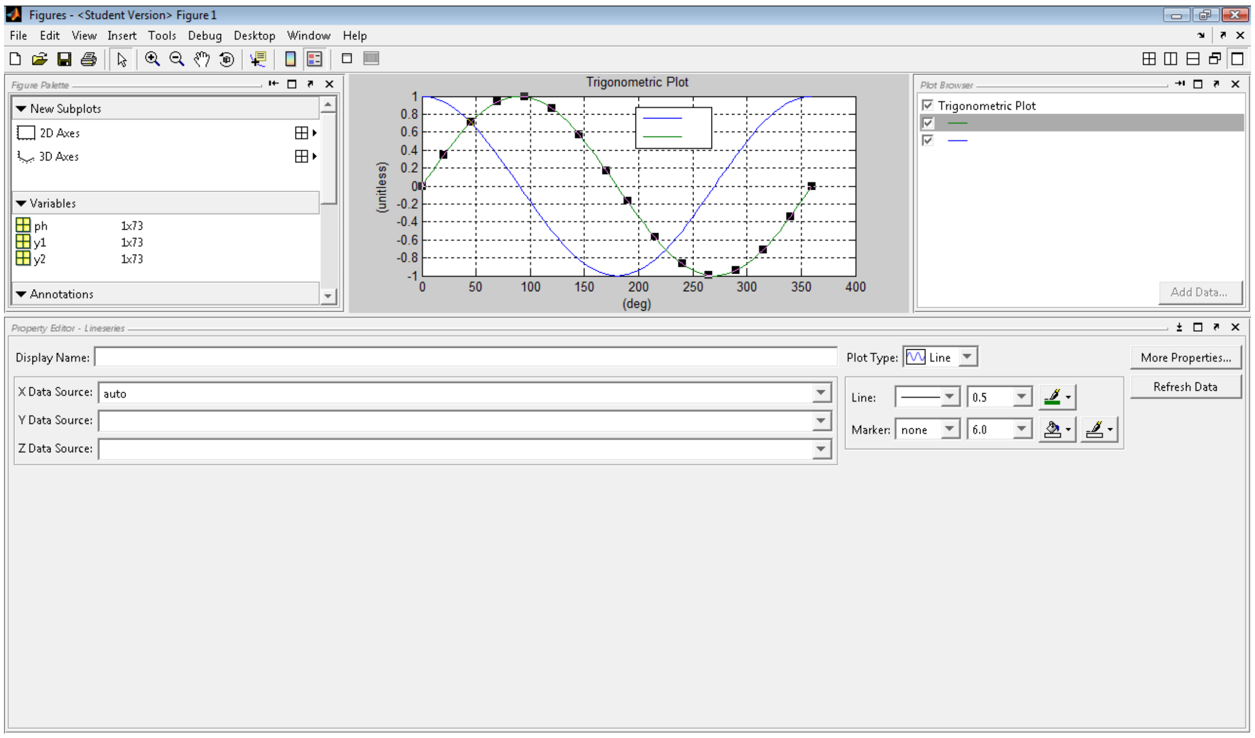
Y Scale: Linear

☐ Reverse

Grid: ☑ X ☑ Y ☐ Z

☑ Box

If you want to change the name of the **green** line series and format the lines and markers, you can click on the line shown above to get the **Property Editor – Lineseries** in the lower part of the window.



Variables: ph 1x73, y1 1x73, y2 1x73

Plot Browser: ☑ Trigonometric Plot

Display Name:

X Data Source: auto

Y Data Source:

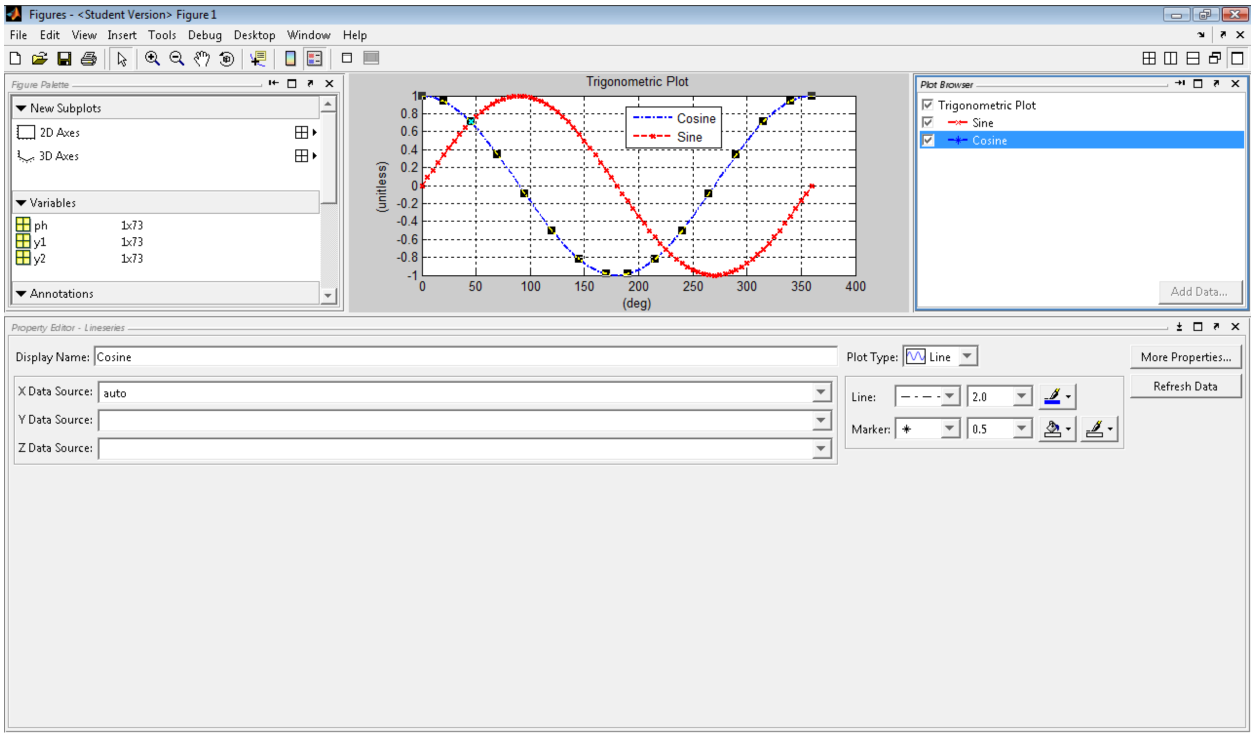
Z Data Source:

Plot Type: Line

Line: 0.5

Marker: none 6.0

After a few changes, the plot might look like this:



Variables: ph 1x73, y1 1x73, y2 1x73

Plot Browser: ☑ Trigonometric Plot, ☑ Sine, ☑ Cosine

Display Name: Cosine

X Data Source: auto

Y Data Source:

Z Data Source:

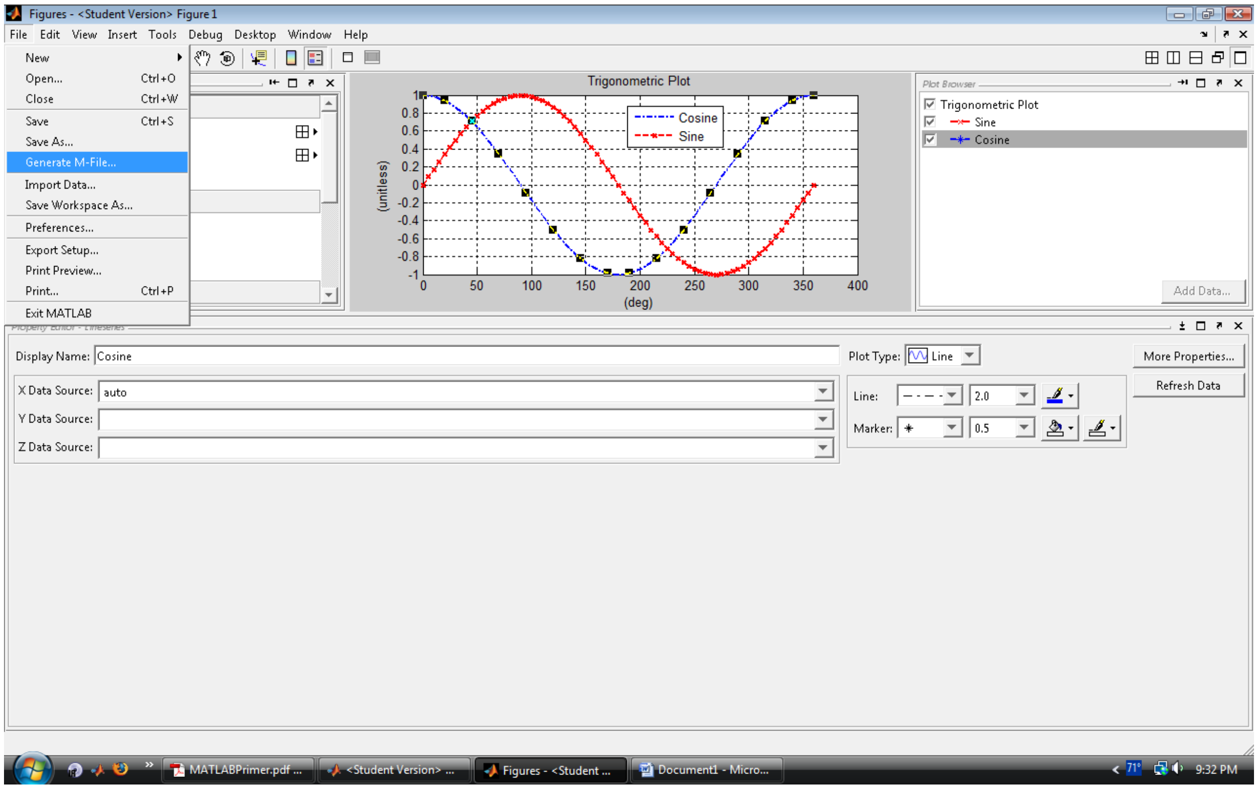
Plot Type: Line

Line: 2.0

Marker: 0.5

Let's say that we have done everything we wanted to do with this plot and that we are satisfied with the results. Now, we can generate the m-file for this figure by clicking on:

`File > Generate M-File…`



Display Name: Cosine

Plot Type: Line

X Data Source: auto

Y Data Source:

Z Data Source:

Line: – - – - 2.0

Marker: + 0.5

The editor window will open up with the generated m-file for your plot (see the following). You can either copy and paste what you want to use in your program or save the m-file as your own to be called from your other programs.

Automatically-generated m-file from this example

```
function createfigure(X1, YMatrix1)
%CREATEFIGURE(X1,YMATRIX1)
%  X1:  vector of x data
%  YMATRIX1:  matrix of y data

%  Auto-generated by MATLAB on 25-Jul-2009 21:33:42

% Create figure
figure1 = figure;

% Create axes
axes1 = axes('Parent',figure1,...
    'YTick',[-1 -0.8 -0.6 -0.4 -0.2 -5.551e-017 0.2 0.4 0.6 0.8 1],...
    'YGrid','on',...
    'XGrid','on');
box('on');
hold('all');

% Create multiple lines using matrix input to plot
plot1 = plot(X1,YMatrix1,'LineWidth',2);
set(plot1(1),'DisplayName','Cosine','MarkerSize',0.5,'Marker','*',...
    'LineStyle','-.');
set(plot1(2),'DisplayName','Sine','MarkerFaceColor','auto','Marker','x',...
    'LineStyle','--',...
    'Color',[1 0 0]);

% Create xlabel
xlabel('(deg)');

% Create ylabel
ylabel('(unitless)');

% Create title
title('Trigonometric Plot');

% Create light
light('Parent',axes1,'Position',[-0.9999 0.005773 0.00866]);

% Create light
light('Parent',axes1,'Style','local','Position',[-0.9999 0.00577 0.00866]);

% Create legend
legend1 = legend(axes1,'show');
set(legend1,'Position',[0.4945 0.6912 0.1704 0.1714]);
```