Lecture 2
Advanced MATLAB:
Graphics

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CME 292
Advanced MATLAB for Scientific Computing
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Outline

Overview

- Graphics objects
  - Basic drawing elements used by MATLAB to display data
  - Each object *instance* has unique identifier, *handle*
    - Stored as a double
  - Objects organized in *hierarchy*

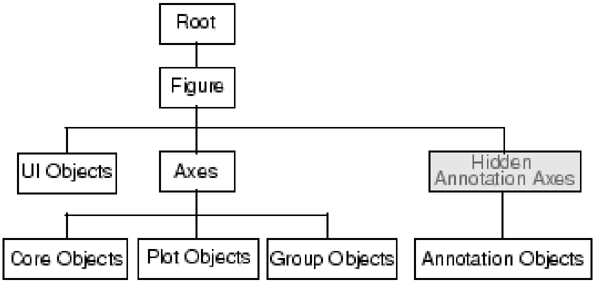


Figure: Organization of Graphics Objects (MathWorks `http://www.mathworks.com/help/matlab/creating_plots/organization-of-graphics-objects.html`)

Graphics Objects

Two basic types of graphics objects

- Core graphics object
  - `axes`, `image`, `light`, `line`, `patch`, `rectangle`, `surface`
- Composite graphics object
  - Plot objects
    - `areaseries`, `barseries`, `contourgroup`, `errorbarseries`, `lineseries`, `quivergroup`, `scattergroup`, `staircase`, `stemseries`, `surfaceplot`
  - Annotation objects
    - arrow, doublearrow, ellipse, line, rectangle, textarrow, textbox
  - Group objects
    - `hggroup`, `hgtransform`
  - User Interface objects

Graphics Handle

- Similar to *pointers* in that they contain a *reference* to a particular graphics object
  - `h1 = figure(2); h2 = h1;`
  - Both `h1`, `h2` point to figure 2
- Best way to obtain graphics handle is *from the call that creates the graphics object*, i.e.
  - `figH = figure('pos',[141,258,869,523]);`
  - `axH = axes();`
  - `ax1H = subplot(2,2,3);`
  - `sinH = plot(sin(linspace(0,2*pi,100)))`
  - `[c,contH] = contour(peaks);`
- Alternatively, obtain graphics handle manually
  - Select figure/axes/object of interest with mouse
  - Use `gcf`, `gca`, `gco`
- Graphics handles stored as `double`

Specifying Figure or Axes to Use

Handles can be used to specify which figure or axes is used when new graphics objects generated

- Specify figure in which to create new axes object
  - `for i = 1:10, fHan(i)=figure(); end`
  - `ax = axes('Parent',fHan(4))`
- Specify axes in which to create new graphics object
  - Most, if not all, plotting commands accept an axes handle as the *first* argument
  - Graphics object generated in axes object corresponding to handle passed
  - If axes handle not specified, `gca` used
  - `[C,objHan] = contourf(ax,peaks)`
- By default, MATLAB uses `gcf` (handle of current figure) or `gca` (handle of current axes)

Exercise

- You are provided a fairly useless piece of code below (`which_plot_ex.m`)
- Your task is to alter the code below such that
  - `sin(k*x)` is plotted vs `x` for `k` even in a single figure
  - `sin(k*x)` is plotted vs `x` for `k` odd in a single figure (different figure from the one above)

```
figure;
axes(); hold on;

figure;
axes(); hold on;

x = linspace(0,2*pi,1000);
for k = 1:10
    plot(x,sin(k*x));
end
```

Working with Graphics Objects

Command	Description
`gca`	Return handle of current axes
`gcf`	Return handle of current figure
`gco`	Return handle of current object
`get`	Query values of object's properties
`ishandle`	True if value is valid object handle
`set`	Set values of an object's properties

Query/Modify Graphics Object Properties

- `get` to query properties and values for any graphics handle
  - `get(han)`
    - Display all properties and values to screen
  - `get(han,'Property')`
    - Display `Property` value to screen
  - `V = get(han)`
    - Store all properties-value pairs in structure `V`
  - `V = get(han,'Property')`
    - Store `Property` value in `V`
- `set` to set properties for any graphics handle
  - `set(han,'Prop−1',Val−1,'Prop−2',Val−2...)`
    - Set `Prop−j`'s value to `Val−j`
  - `set(han,s) %s structure`
    - Set property-value pairs from `s`
  - `set(han,pn,pv) %pn, pv cell arrays`
    - Set value of property `pn{i}` to `pv{i}`

Properties Common to All Objects

Command	Description
`BeingDeleted`	`on` when object's `DeleteFcn` called
`BusyAction`	Control callback routine interruption
`ButtonDownFcn`	Callback routine that executes when button pressed
`Children`	Handles of all object's child objects
`Clipping`	Enables/disables clipping
`CreateFcn`	Callback routine that executes when object created
`DeleteFcn`	Callback routine that executes when object deleted

Properties Common to All Objects

Command	Description
`HandleVisibility`	Allows control over object handle's visibility (command line and callbacks)
`HitTest`	Determines if object selectable via mouse click
`Interruptible`	Determines whether callback can be interrupted by subsequently called callback
`Parent`	The object's parent
`Selected`	Indicates whether object is selected

Properties Common to All Objects

Command	Description
`SelectionHighlight`	Specifies whether object visually indicates selection state
`Tag`	User-specified object label
`Type`	The type of object
`UserData`	Any data user associates with object
`Visible`	Determines whether object is visible

Figure, Axes, and Plot Objects

- Figure window
  - `get(gcf)` to see all properties of Figure object and defaults
  - `Colormap`, `Position`, `PaperPositionMode`
- Axes Object
  - Axes objects contain the lines, surfaces, and other objects that represent the data visualized in a graph
  - `get(gca)` to see all properties of Axes object and defaults
  - `XLim`, `YLim`, `ZLim`, `CLim`, `XGrid`, `YGrid`, `ZGrid`, `XTick`, `XTickLabel`, `YTick`, `YTickLabel`, `ZTick`, `ZTickLabel`, `XScale`, `YScale`, `ZScale`
- Plot Objects
  - Plot objects are composite graphics objects composed of one or more core objects in a group
  - `XData`, `YData`, `ZData`, `Color`, `LineStyle`, `LineWidth`

Legend

- Probably familiar with basic legend syntax
  - `legend('First plotted','Second ... plotted','Location','Northwest')`
- What if legend based on order of objects plotted is not sufficient?
  - Use handles for fine grained control
  - `legend(h,'h(1)label','h(2)label')`
- Legend handle
  - Get handle by `leg = legend( )`
  - Use handle to control size/location (more control than `'Location'`)
  - Font size/style, interpreter, line style, etc

Callback Routines

- Function associated with graphics handle that gets called in response to a specific action applied to the associated graphics object
  - Object creation, deletion
  - Mouse motion, mouse press, mouse release, scroll wheel
  - Key press, key release
  - More here
- All callback routines automatically passed two inputs
  - Handle of component whose callback is being executed
  - Event data
- Callback routines specified in many possible forms
  - String
    - Expression evaluated in *base* workspace
  - Function handle
  - Cell arrays to pass additional arguments to callback routine

Demo & In-Class Assignment

`graphics_obj_han_ex.m`

Outline

Line plots

Command	Description
`plot`	2D line plot
`plotyy`	2D line plot, y-axes both sides
`plot3`	3D line plot
`loglog`	2D line plot: x- and y-axis log scale
`semilogx`	2D line plot, x-axis log, y-axis linear
`semilogy`	2D line plot, x-axis linear, y-axis log
`errorbar`	Error bars along 2D line plot
`fplot`	Plot function between specified limits
`ezplot`	Function plotter
`ezplot3`	2D parametric curve plotter

Examples: `plotyy`, `errorbar`

Figure: `plotyy` Plot

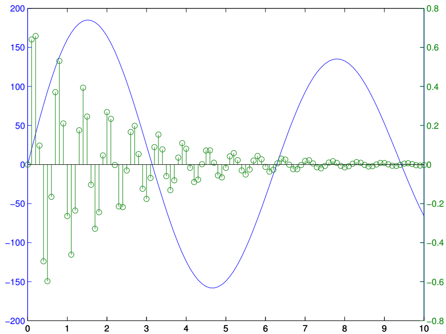
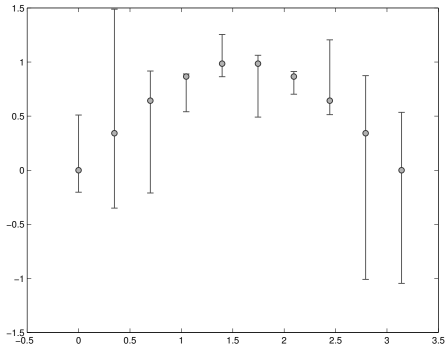


Figure: `errorbar` Plot



- Code: `advanced_plotting_ex.m`

Pie Charts, Bar Plots, and Histograms

Command	Description
`bar, barh`	Vertical, horizontal bar graph
`bar3, bar3h`	Vertical, horizontal 3D bar graph
`hist`	Histogram
`histc`	Histogram bin count (no plot)
`rose`	Angle histogram
`pareto`	Pareto chart
`area`	Filled area 2D plot
`pie, pie3`	2D, 3D pie chart

Examples: `hist`, `bar`, `barh`, `pie3`

Figure: `hist/bar/barh` Plot

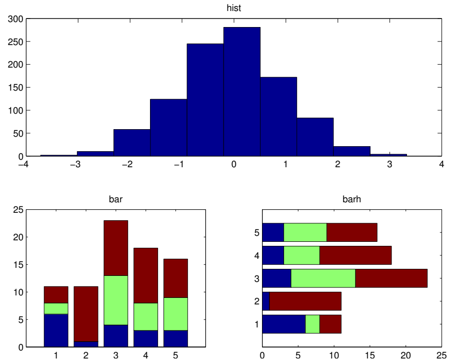
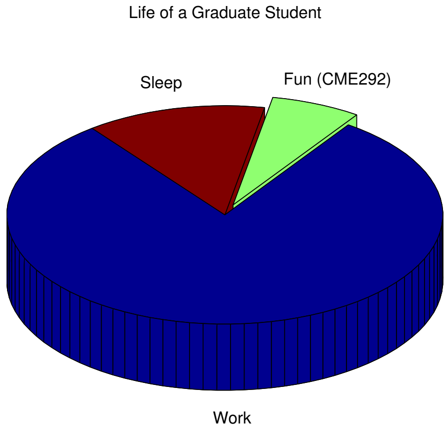


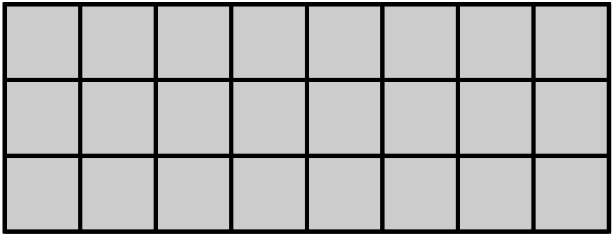
Figure: `pie3` Plot



- Code: `advanced_plotting_ex.m`

Generating Grid Data

- MATLAB graphics commands work primarily in terms of N-D grids



- Use `meshgrid` to define grid compatible with 2D, 3D MATLAB plotting commands from discretization in each dimension
  - `[X,Y] = meshgrid(x,y)`
  - `[X,Y,Z] = meshgrid(x,y,z)`

meshgrid

- Generate 2D grid: `[X,Y] = meshgrid(x,y)`
  - Relationships
    - `X(i,:)=` `x` for all i
    - `Y(:,j)=` `y` for all j
    - `X(:,i)=` `x(i)` for all i
    - `Y(j,:)=` `y(j)` for all j
- Generate 3D grid: `[X,Y,Z] = meshgrid(x,y,z)`
  - Relationships
    - `X(i,:,k)=` `x` for all i, k
    - `Y(:,j,k)=` `y` for all j, k
    - `Z(i,j,:)=` `z` for all i, j
    - `X(:,i,:)=` `x(i)` for all i,
    - `Y(j,:,:)=` `y(j)` for all j
    - `Z(:,:,k)=` `z(k)` for all k

`meshgrid` and Plotting Functions

- In MATLAB Help documentation, grid or domain data inputs/outputs usually refer to output of `meshgrid` or `meshgrid` or `ndgrid`

surfnorm

R2014a

Compute and display 3-D surface normals

expand all in page

Syntax

```
surfnorm(Z)
surfnorm(X,Y,Z)
surfnorm(axes_handle,__)
surfnorm(__,Name,Value)
[Nx,Ny,Nz] = surfnorm(__)
```

Description

`surfnorm(Z)` plots a surface of the matrix `Z` with `surf` and displays its surface normals as radiating vectors.

`surfnorm(X,Y,Z)` plots a surface and its surface normals from the vectors or matrices `X`, `Y`, and matrix `Z`. `X`, `Y`, and `Z` must be the same size.

`surfnorm(axes_handle,__)` plots into `axes_handle` instead of `gca` and it can include any of the input arguments in previous syntaxes.

`surfnorm(__,Name,Value)` can be used to set the value of the specified `Surface Properties`.

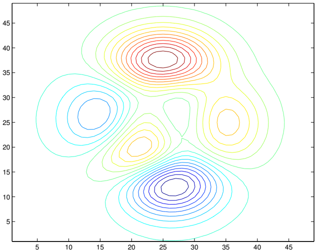
`[Nx,Ny,Nz] = surfnorm(__)` returns the components of the 3-D surface normals for the surface without plotting the surface or surface normals.

Contour Plots

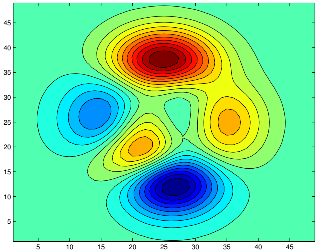
- Plot scalar-valued function of two variables as lines of constant value.
  - Visualize $f(x, y) \in \mathbb{R}$ by displaying lines where $f(x, y) = c$ for various values of c

Command	Description
`contour`	Contour plot
`contourf`	Filled contour plot
`contourc`	Contour plot computation (no plot)
`contour3`	3D contour plot
`contourslice`	Draw contours in volume slice planes
`ezcontour`	Contour plotter
`ezcontourf`	Filled contour plotter

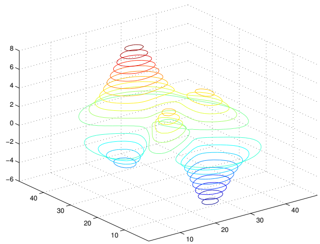
Contour Plots



(a) `contour`



(b) `contourf`



(c) `contour3`

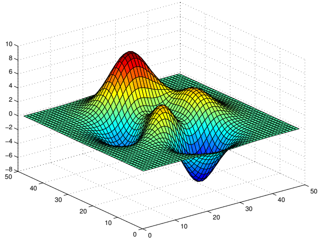
Code for plots generated in the remainder of the section:
`advanced_plotting_ex.m` or `lec_figs.m`

Surface and Mesh Plots

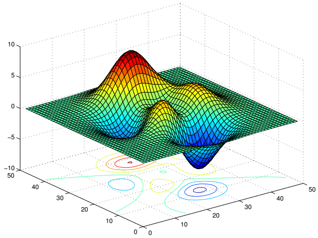
- Plot scalar-valued function of two variables $f(x, y) \in \mathbb{R}$

Command	Description
`surf`	3D shaded surface plot
`surfc`	Contour plot under `surf` plot
`surfl`	Surface plot with colormap lighting
`surfnorm`	Compute/plot 3D surface normals
`mesh`	Mesh plot
`meshc`	Contour plot under `mesh` plot
`waterfall`	Waterfall plot
`ribbon`	Ribbon plot
`ezsurf`, `ezsurfc`	Colored surface plotters
`ezmesh`,`ezmeshc`	Mesh plotters

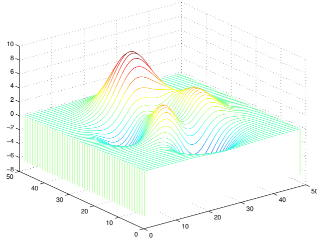
Surface/Mesh Plots



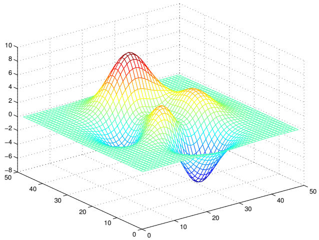
(d) surf



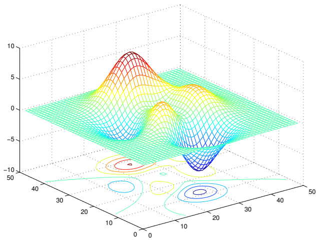
(e) surfc



(f) waterfall



(g) mesh



(h) meshc

Contour/Surface/Mesh Plots

- `[C,h] = contour_func(Z)`
  - Contour plot of matrix `Z`
- `[C,h] = contour_func(Z,n)`
  - Contour plot of matrix `Z` with `n` contour levels
- `[C,h] = contour_func(Z,v)`
  - Contour plot of matrix `Z` with contour lines corresponding to the values in `v`
- `[C,h] = contour_func(X,Y,Z)`
  - Contour plot of matrix `Z` over domain `X`, `Y`
- `[C,h] = contour_func(X,Y,Z,n)`
  - Contour plot of matrix `Z` over domain `X`, `Y` with `n` levels
- `[C,h] = contour_func(X,Y,Z,v)`
  - Contour plot of matrix `Z` over domain `X`, `Y` with contour lines corresponding to the values in `v`
- Similar for surface/mesh plots

Vector Fields

- Visualize vector-valued function of two or three variables $\mathbf{F}(x, y) \in \mathbb{R}^2$ or $\mathbf{F}(x, y, z) \in \mathbb{R}^3$

Command	Description
`feather`	Plot velocity vectors along horizontal
`quiver`, `quiver3`	Plot 2D, 3D velocity vectors from specified points
`compass`	Plot arrows emanating from origin
`streamslice`	Plot streamlines in slice planes
`streamline`	Plot streamlines of 2D, 3D vector data

Vector Fields

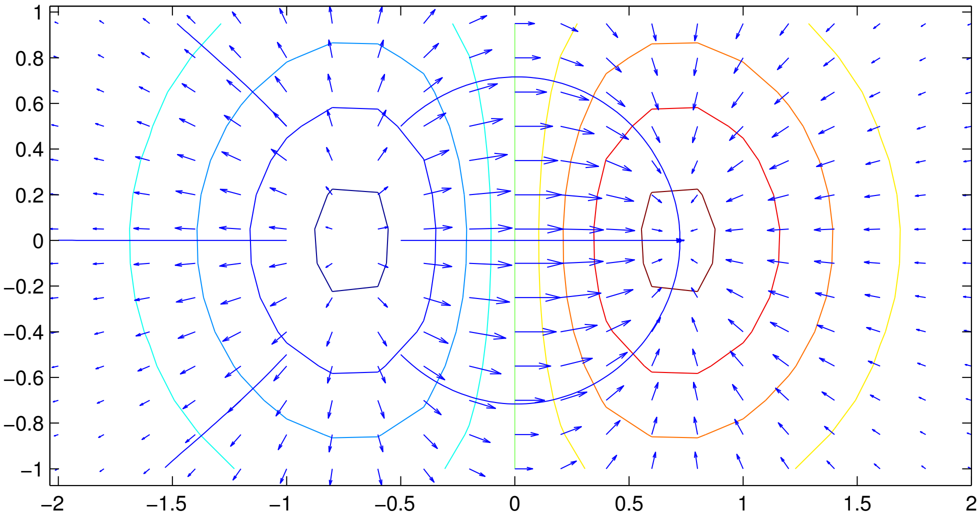


Figure: `contour`, `quiver`, `streamline`

Vector fields: `quiver`, `feather`, `compass`

- Quiver plots
  - `h = quiver(X,Y,U,V)`
    - Displays velocity vectors as arrows with components `(u,v)` at the point `(x,y)`
    - `X,Y` generated with meshgrid
    - Additional call syntaxes to control display
  - `h = quiver3(X,Y,Z,U,V,W)`
    - Displays velocity vectors as arrows with components `(u,v,w)` at the point `(x,y,z)`
    - `X,Y,Z` generated with meshgrid
    - Additional call syntaxes to control display
  - `Quivergroup Properties`
- `feather`, `compass` similar, but simpler (don't require `X`, `Y`)

Streamline-type plots

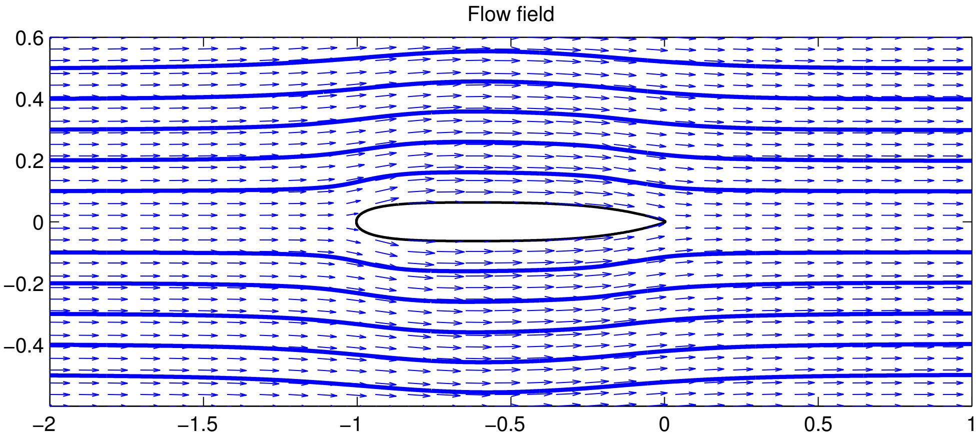


Figure: `quiver`, `streamline`, `fill` plots

Streamline-type plots

- `streamline`, `stream2`, `stream3`
- Relevant for vector-valued functions of 2 or 3 variables ($\mathbf{F}(x, y)$ or $\mathbf{F}(x, y, z)$)
- Requires points to initialize streamlines
- Plot the trajectory of a particle through a vector field that was placed at a given position
  - `han=streamline(X,Y,Z,F1,F2,F3,StX,StY,StZ)`
    - `X, Y, Z` - grid generated with `meshgrid`
    - `F1,F2,F3` - vector components of $\mathbf{F}$ over grid
    - `StX, StY, StZ` - vectors (of the same size) specifying the starting location of the particles to trace

Assignment

- Define `s = linspace(0,2*pi,100)`
- Plot $f(x, y) = \sin(xy)$ for $x, y \in [0, 2\pi]$ using any contour function
  - Make sure there are contour lines at $[-1.0, -0.75, -0.5, -0.25, 0, 0.25, 0.5, 0.75, 1.0]$
  - Use any colormap except `jet` (the default)
    - `autumn`, `bone`, `colorcube`, `cool`, `copper`, `flag`, `gray`, `hot`, `hsv`, `jet`, `lines`, `pink`, `prism`, `spring`, `summer`, `white`, `winter`
  - Use a colorbar
- Numerically compute $\nabla f(x, y)$ as `[Fx,Fy] = gradient(F)`
  - Make a `quiver` plot of $\nabla f(x, y)$
  - Plot streamline of $\nabla f(x, y)$ vector field, beginning at the point $(2, 2)$

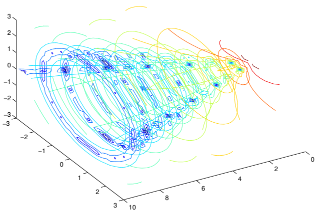
Volume Visualization - Scalar Data

- Visualize scalar-valued function of two or three variables $f(x, y, z) \in \mathbb{R}$

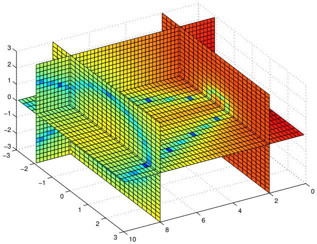
Command	Description
`contourslice`	Draw contours in volume slice planes
`flow`	Simple function of three variables
`isocaps`	Compute isosurface end-cap geometry
`isocolors`	Compute isosurface and patch colors
`isonormals`	Compute normals of isosurface vertices
`isosurface`	Extract isosurface data from volume data
`slice`	Volumetric slice plot

Volume Visualization - Scalar Data

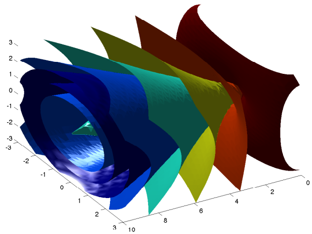
- Visualize scalar data defined over a volume.



(a) `contourslice`



(b) `slice`



(c) `isosurface`

Slice-type plots

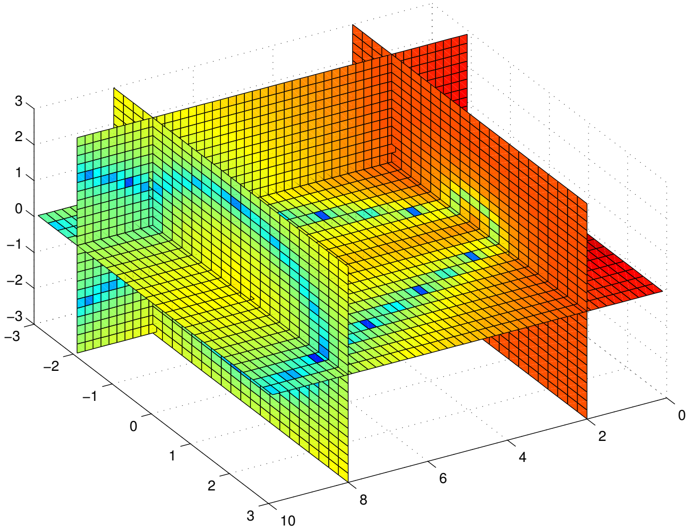


Figure: slice

Slice-type plots

- `slice`, `contourslice`, `streamslice`
- Relevant for scalar- or vector-valued volume functions ($f(x, y, z)$ or $\mathbf{F}(x, y, z)$)
- Plot information in planar slices of the volumetric domain
  - `han = slice(X,Y,Z,F,Sx,Sy,Sz)`
    - `X`, `Y`, `Z` - grid generated by meshgrid
    - `F` = $\mathbf{F}$(X,Y,Z)
    - `Sx`, `Sy`, `Sz` vectors specifying location of slice planes in the $y-z$, $x-z$, and $x-y$ planes
  - `han = slice(X,Y,Z,F,XI,YI,ZI)`
    - `XI`, `YI`, `ZI` define *surface* (i.e. that could be plotted with surf) on which to plot `F`

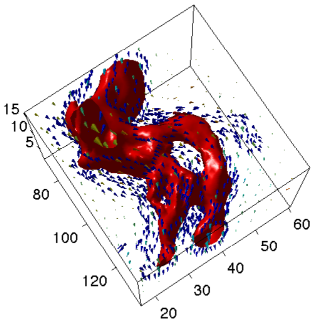
Volume Visualization - Vector Data

- Visualize vector-valued function of three variables $\mathbf{F}(x, y, z) \in \mathbb{R}^3$

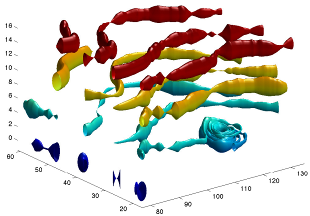
Command	Description
`coneplot`	Plot velocity vectors as cone
`interpstreamspeed`	Interpolate stream-line vertices from flow speed
`stream2, stream3`	Compute 2D, 3D streamline data
`streamline`	Plot streamlines of 2D, 3D vector data
`streamparticles`	Plot stream particles
`streamribbon`	3D stream ribbon plot
`streamslice`	Plot streamlines in slice planes
`streamtube`	Create 3D stream tube plot

Volume Visualization - Vector Data

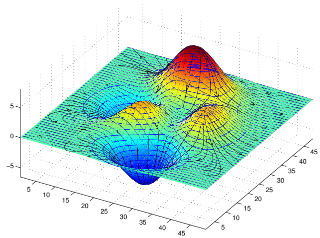
- Visualize vector data defined over a volume.



(a) `coneplot`



(b) `streamtube`



(c) `streamslice`

Outline

MATLAB File Exchange

The MATLAB File Exchange is a very useful forum for finding solutions to many MATLAB-related problems

- 3D Visualization
- Data Analysis
- Data Import/Export
- Desktop Tools and Develepment Environment
- External Interfaces
- GUI Development
- Graphics
- Mathematics
- Object-Oriented Programming
- Programming and Data Types

MATLAB File Exchange

The MATLAB File Exchange is a very useful forum for sharing solutions to many MATLAB-related problems

- Clean integration of MATLAB figures in LaTeX documents
  - `matlabfrag`, `figuremaker`, `export_fig`, `mcode`, `matrix2latex`, `matlab2tikz`
- Plot formatting and manipulation
  - `xticklabel_rotate`, `tight_subplot`
- Interfacing to iPhone, iPad, Android, Kinect devices
- Interfacing to Google Earth and Maps
- Much more

Outline

Motivation

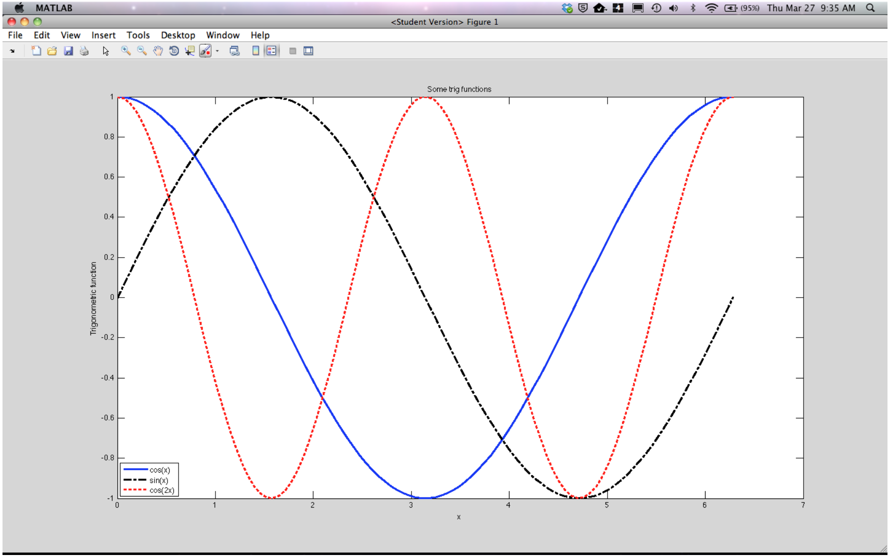
- Generating publication quality plots in MATLAB is not a trivial task
  - Plot annotation to match font size/style of document
  - Esthetic - dependent on type of publication
  - Legends can be difficult to work with
  - MATLAB figures not WYSIWYG by default
- Three fundamental approaches to generate plots for publications using MATLAB
  - Generate *plots* in MATLAB and import into document
    - Graphics handles to deal with esthetics
    - MATLAB File Exchange to integrate figures with LaTeX
  - Generate *data* in MATLAB and *plot* in document
    - TikZ/PGF popular choice for LaTeX
  - Hybrid (`matlab2tikz`)
- `high_quality_ex.m`

WYSIWYG

MATLAB is not *What You See Is What You Get* (WYSIWYG) by default, when it comes to plotting

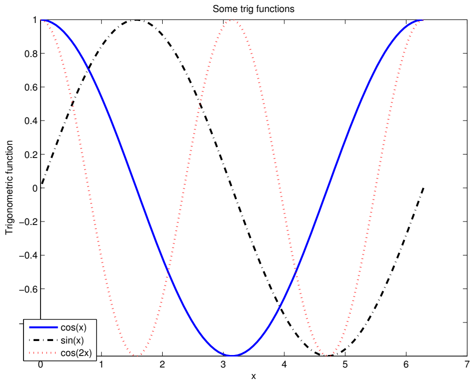
- Spend time making plot look exactly as you want
- Doesn't look the same when saved to file
  - Legend particularly annoying
  - Issues amplified when figure resized
- Very frustrating
- Force WYSIWYG
  - `set(gcf, 'PaperPositionMode', 'auto');`

WYSIWYG Example

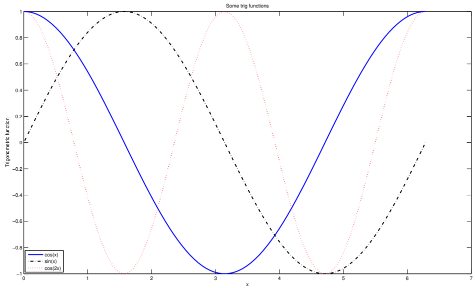


WYSIWYG Example

(d) Without WYSIWYG



(e) With WYSIWYG



High-Quality Graphics

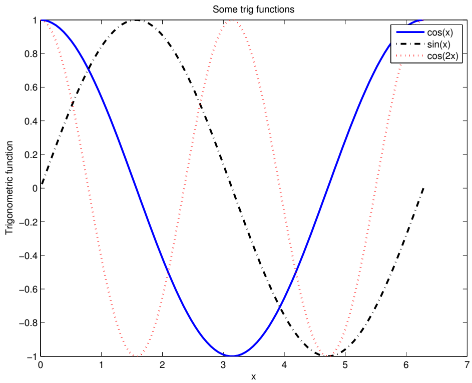
This information is based on websites here and here.

- Generate plot with all lines/labels/annotations/legends/etc
- Set properties (graphics handles or interactively)
  - Figure width/height
  - Axes line width, object line width, marker size
  - Font sizes
- Save to figure to file
  - WYSIWYG
    - `set(gcf, 'PaperPositionMode', 'auto');`
  - Print to file for inclusion in document
    - `print(gcf,'-depsc2',filename)`
    - `matlabfrag(filename)`
    - `matlab2tikz(filename)`
- Fixing EPS file
  - Esthetics of dashed and dotted lines
  - `fixPSlinestyle`

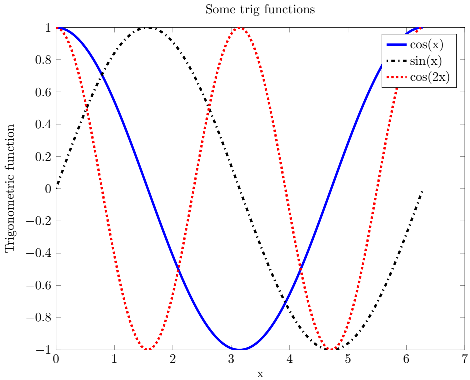
matlab2tikz

- `matlab2tikz(FileName,...)`
    - Save figure in native LaTeX (TikZ/Pgfplots).
    - Import file in LaTeX (`\input` or `\includegraphics`)

(f) without `matlab2tikz`



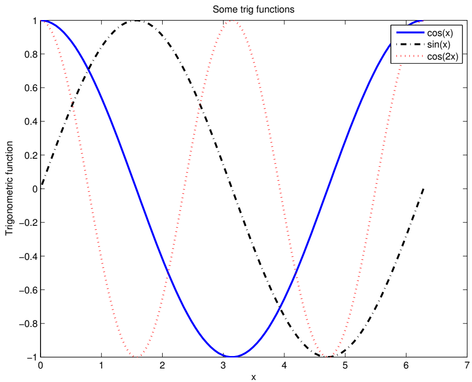
(g) with `matlab2tikz`



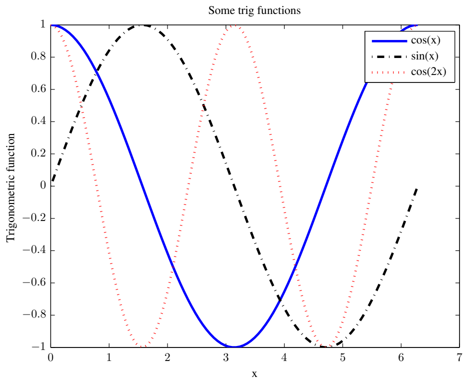
matlabfrag

- `matlabfrag(FileName,OPTIONS)`
  - Exports a matlab figure to an .eps file and a .tex file for use with psfrag in LaTeX.
  - Doesn't seem to work well with beamer

(h) without `matlabfrag`

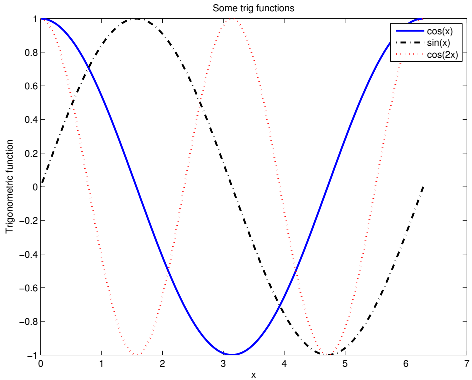


(i) with `matlabfrag`

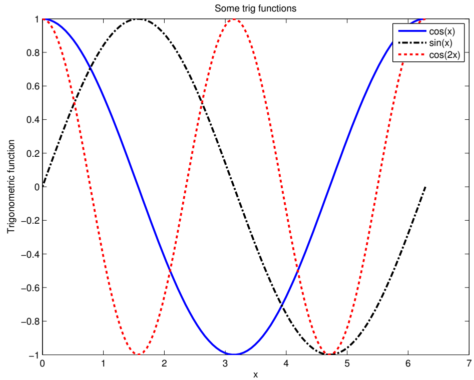


fixPSlinestyle

(j) without fixPSlinestyle



(k) with fixPSlinestyle



`fixPSlinestyle` syntax

- `fixPSlinestyle(fname)`
- `fixPSlinestyle(old_fname,new_fname)`

Show Mcode

Two options to modify appearance of figure

- Interactively via MATLAB Figure GUI
  - Simplest and most popular
  - Not repeatable/automated
- Command line control via graphics handles
  - Less intuitive than interactive approach
  - Highly automated
  - Annoying trial/error when it comes to positioning/sizing

A hybrid approach that combines the above options is available

- Use GUI to interactively modify appearance of figure
- `Show Mcode` option to print underlying graphics handle operations to file
- Copy/paste into script for repeatability
- Demo: `show_mcode_ex.m`

Outline

Animation

Two main types of animation

- Interactive animation
  - Generate and display animation during execution of code
- Animation movies
  - Save animation in movie format

Interactive Animation

- Generated by calling plot commands inside a loop with new data generated at each iteration
  - Before entering loop
    - Create figure and axes
    - Modify using handles to achieve desired appearance
    - Use command `set(gca,'nextplot','replacechildren')` to ensure only *children* of axes object will be replaced upon next plot command (will not modify axes properties)
  - During loop
    - Plotting command to generate data on plot
    - Modify object using handle to achieve desired appearance
    - Use command `drawnow` to draw object, otherwise will not be drawn until execution is complete (MATLAB optimization as plotting is expensive)
- Alternatively, modify `XData`, `YData`, `ZData` properties of initial plot object

Interactive Animation

- Additionally, save sequence of plotting command as frames (`getframe`) and play back from MATLAB window (`movie`)
- animate_ex.m

Approach 1

```
fig=figure();
ax=axes();
obj=plot(..);
set(ax,'nextplot',...
    'replacechildren');
for j = 1:N
   obj=plot(..);
   drawnow;
end
```

Approach 2

```
fig=figure();
ax=axes();
obj=plot(..);
set(ax,'xlim',..,'ylim',..);
for j = 1:N
    set(obj,'xdata',..);
    set(obj,'ydata',..);
    drawnow;
end
```

Animation Movies

Saving animations as movie files can be accomplished using `VideoWriter` class (`video_writer_ex.m`)

- `VideoWriter` enables creation of video files from MATLAB figures, still images, or MATLAB movies

```
writerObj = VideoWriter('my_movie.avi');  %Video obj
set(writerObj, 'FrameRate',10);  % Set the FPS
open(writerObj); % Open the video object
% Prepare the movie
figure; set(gca,'NextPlot','replaceChildren')
th = linspace(0,2*pi,100);
for j = th
    plot(sin(th),cos(th),'k-');  hold on;
    plot(sin(j),cos(j),'ro');
    writeVideo( writerObj, getframe );
end
close(writerObj); % Close the video object
```

VideoWriter

- List of `VideoWriter` properties
  - Here on MathWorks website
  - `FrameRate` - rate of playback (cannot change after `open`)
  - `Quality` - integer between 0, 100
- `VideoWriter` methods
  - `open` - Open file for writing video data
  - `writeVideo` - Write video data to file
  - `close` - Close file after writing video data