6.057
Introduction to programming in MATLAB

Lecture 2: Visualization and Programming

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IAP 2019

Homework 1 Recap

Some things that came up:

- Plotting a straight line

```
» x = 1:10
» plot(x, 0)
```

  - ➢ Not an error, but probably not what you meant

- Use of semicolon – never required if one command per line. You can also put multiple commands on one line; in this case, a semicolon is necessary to separate commands:

```
» x=1:10; y=(x-5).^2; z = x.*y;
```

Plotting

- Example

```
» x=linspace(0,4*pi,10);
» y=sin(x);
```

- Plot values against their index

```
» plot(y);
```

- Usually we want to plot y versus x

```
» plot(x,y);
```

MATLAB makes visualizing data fun and easy!

What does plot do?

- **plot** generates dots at each (x,y) pair and then connects the dots with a line
- To make plot of a function look smoother, evaluate at more points

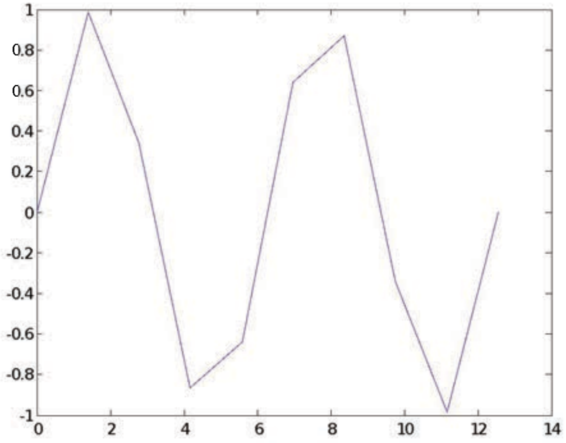
```
» x=linspace(0,4*pi,1000);
» plot(x,sin(x));
```

- x and y vectors must be same size or else you'll get an error

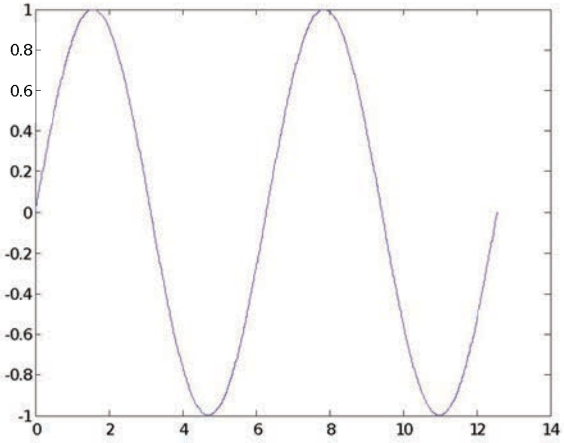
```
» plot([1 2], [1 2 3])
```

  ➢ error!!

10 x values:



1000 x values:



Exercise: Plotting

Plot the learning trajectory

- In helloWorld.m, open a new figure (use `figure`)
- Plot knowledge trajectory using `tVec` and `knowledgeVec`
- When plotting, convert `tVec` to days by using `secPerDay`
- Zoom in on the plot to verify that `halfTime` was calculated correctly

Outline for Lec 2

(1) **Functions**

(2) Flow Control

(3) Line Plots

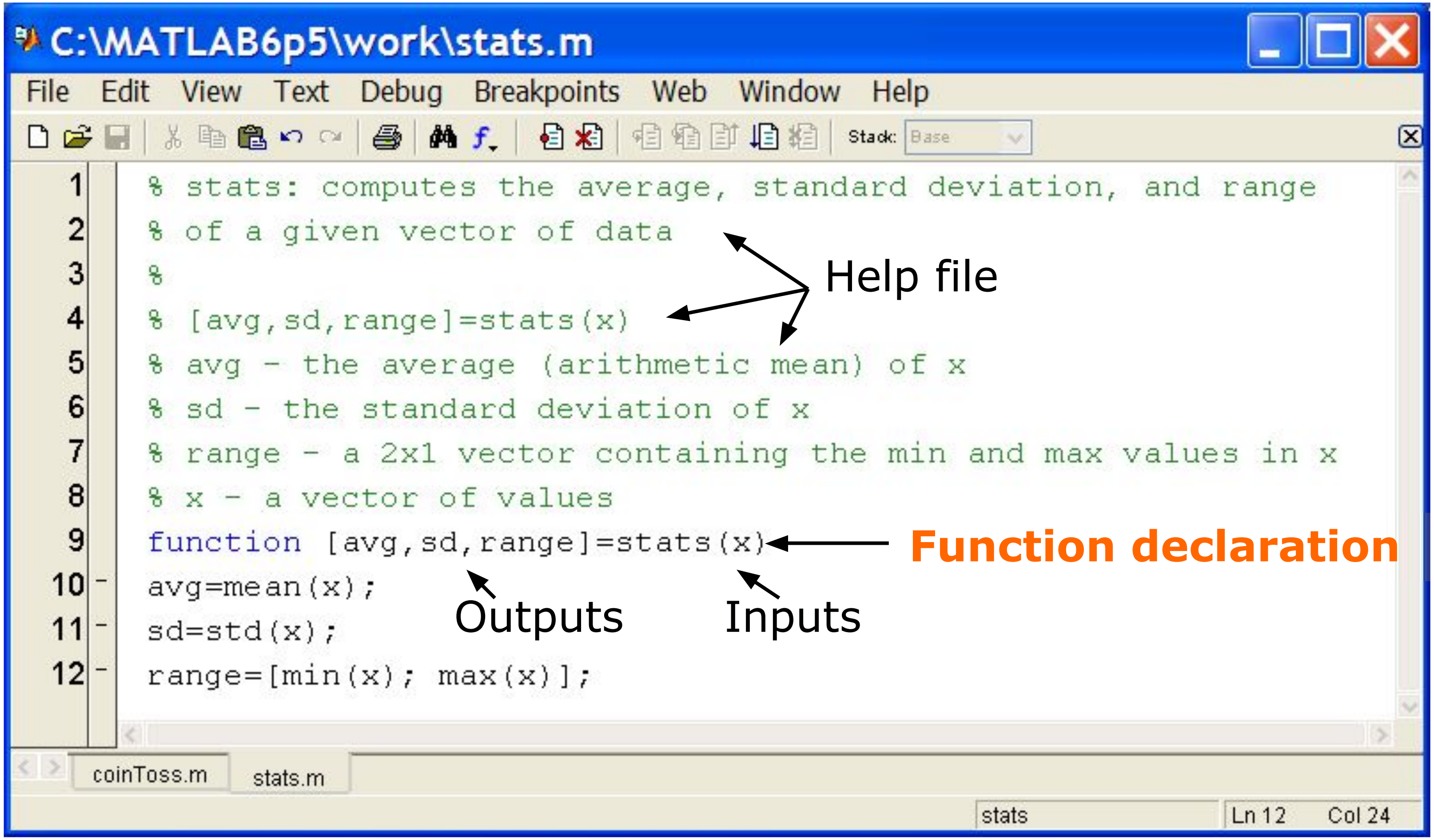
(4) Image/Surface Plots

(5) Efficient Codes

(6) Debugging

User-defined Functions

- Functions look exactly like scripts, but for **ONE** difference
  - ➢ Functions must have a function declaration


C:\MATLAB6p5\work\stats.m
File Edit View Text Debug Breakpoints Web Window Help
Stack: Base
coinToss.m
stats.m
stats
Ln 12
Col 24

```
% stats: computes the average, standard deviation, and range
% of a given vector of data
%
% [avg,sd,range]=stats(x)
% avg - the average (arithmetic mean) of x
% sd - the standard deviation of x
% range - a 2x1 vector containing the min and max values in x
% x - a vector of values
function [avg,sd,range]=stats(x)
avg=mean(x);
sd=std(x);
range=[min(x); max(x)];
```

Help file

Function declaration

Outputs

Inputs

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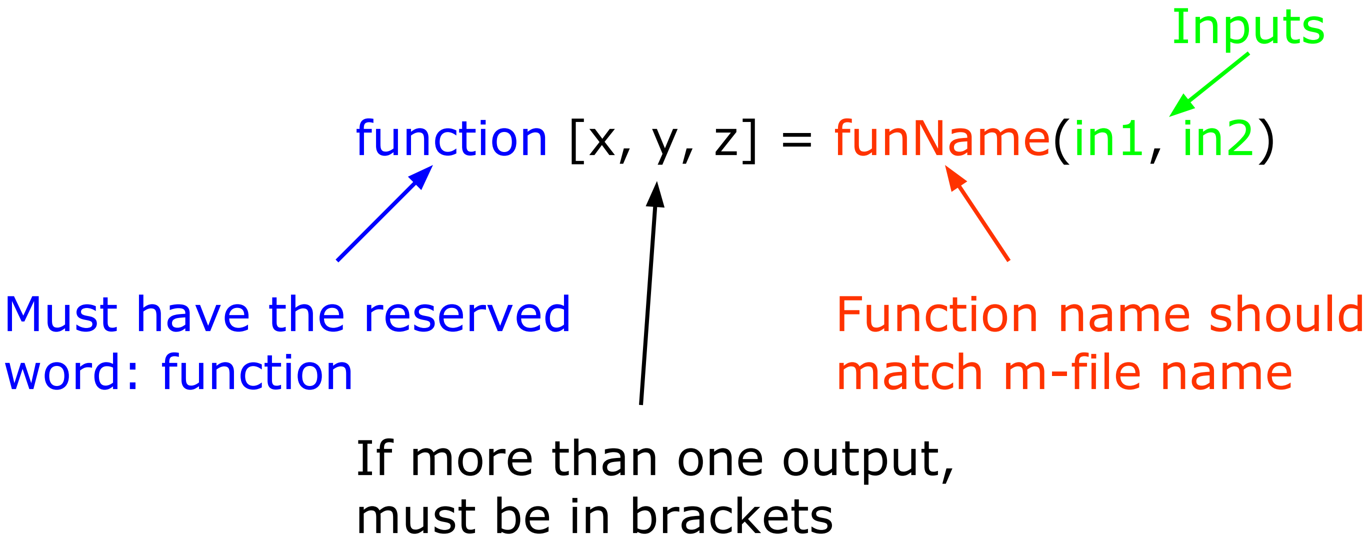
User-defined Functions

- Some comments about the function declaration



Inputs

```
function [x, y, z] = funName(in1, in2)
```

Must have the reserved word: function

Function name should match m-file name

If more than one output, must be in brackets

- No need for return: MATLAB 'returns' the variables whose names match those in the function declaration (though, you can use **`return`** to break and go back to invoking function)
- Variable scope: Any variable created within the function but not returned disappears after the function stops running (They're called "local variables")

Functions: overloading

- We're familiar with
  - » `zeros`
  - » `size`
  - » `length`
  - » `sum`

- Look at the help file for size by typing
  - » `help size`

- The help file describes several ways to invoke the function
    - ➢ D = SIZE(X)
    - ➢ [M,N] = SIZE(X)
    - ➢ [M1,M2,M3,...,MN] = SIZE(X)
    - ➢ M = SIZE(X,DIM)

Functions: overloading

- MATLAB functions are generally overloaded
  - ➢ Can take a variable number of inputs
  - ➢ Can return a variable number of outputs

- What would the following commands return:

```
» a=zeros(2,4,8); %n-dimensional matrices are OK
» D=size(a)
» [m,n]=size(a)
» [x,y,z]=size(a)
» m2=size(a,2)
```

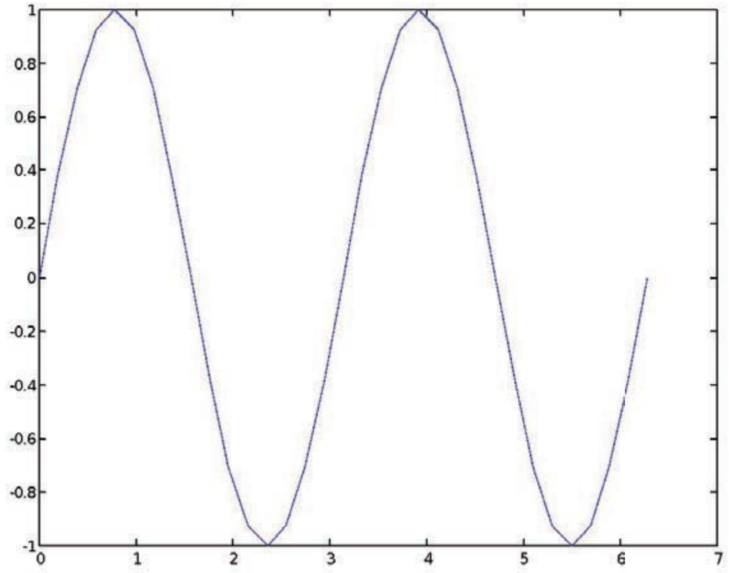
- You can overload your own functions by having variable number of input and output arguments (see **`varargin`**, **`nargin`**, **`varargout`**, **`nargout`**)

Functions: Exercise

- Write a function with the following declaration:
  `function plotSin(f1)`

- In the function, plot a sine wave with frequency f1, on the interval [0,2π]: $\sin(f_1 x)$

- To get good sampling, use 16 points per period.



Outline

(1) Functions

(2) Flow Control

(3) Line Plots

(4) Image/Surface Plots

(5) Efficient Codes

(6) Debugging

Relational Operators

- MATLAB uses *mostly* standard relational operators

equal	==
not equal	~=
greater than	>
less than	<
greater or equal	>=
less or equal	<=

Logical operators	elementwise	short-circuit (scalars)
And	&	&&
Or	|	||
Not	~	
Xor	xor	
All true	all	
Any true	any	

- Boolean values: zero is false, nonzero is true
- See **help .** for a detailed list of operators

if/else/elseif

- Basic flow-control, common to all languages
- MATLAB syntax is somewhat unique

IF

```
if cond
    commands
end
```

Conditional statement: evaluates to true or false

ELSE

```
if cond
    commands1
else
    commands2
end
```

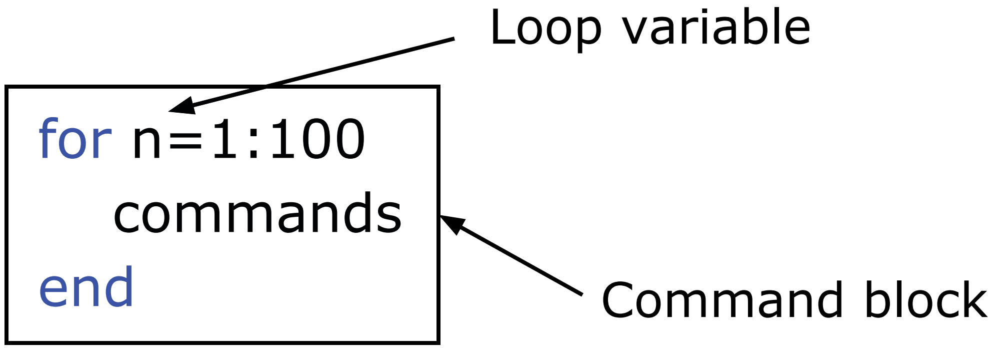
ELSEIF

```
if cond1
    commands1
elseif cond2
    commands2
else
    commands3
end
```

- No need for parentheses: command blocks are between reserved words
- Lots of `elseif`'s? consider using `switch`

for

- **for** loops: use for a known number of iterations
- MATLAB syntax:



```
for n=1:100
    commands
end
```

Loop variable

Command block

- The loop variable
  - ➢ Is defined as a vector
  - ➢ Is a scalar within the command block
  - ➢ Does not have to have consecutive values (but it's usually cleaner if they're consecutive)
- The command block
  - ➢ Anything between the **for** line and the **end**

while

- The while is like a more general for loop:
  - ➢ No need to know number of iterations

WHILE

```
while cond
    commands
end
```

- The command block will execute while the conditional expression is true
- Beware of infinite loops! CTRL+C?!
- You can use `break` to exit a loop

Exercise: Conditionals

- Modify your `plotSin(f1)` function to take two inputs: `plotSin(f1,f2)`

- If the number of input arguments is 1, execute the plot command you wrote before. Otherwise, display the line `'Two inputs were given'`
- Hint: the number of input arguments is stored in the built-in variable `nargin`

Outline

(1) Functions

(2) Flow Control

(3) **Line Plots**

(4) Image/Surface Plots

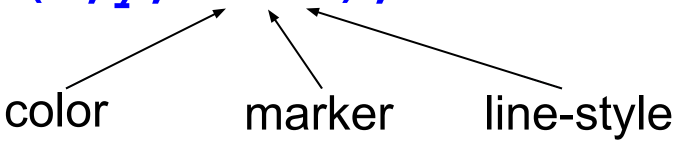
(5) Efficient Codes

(6) Debugging

Plot Options

- Can change the line color, marker style, and line style by adding a string argument

```
» plot(x,y,’k.-’);
```

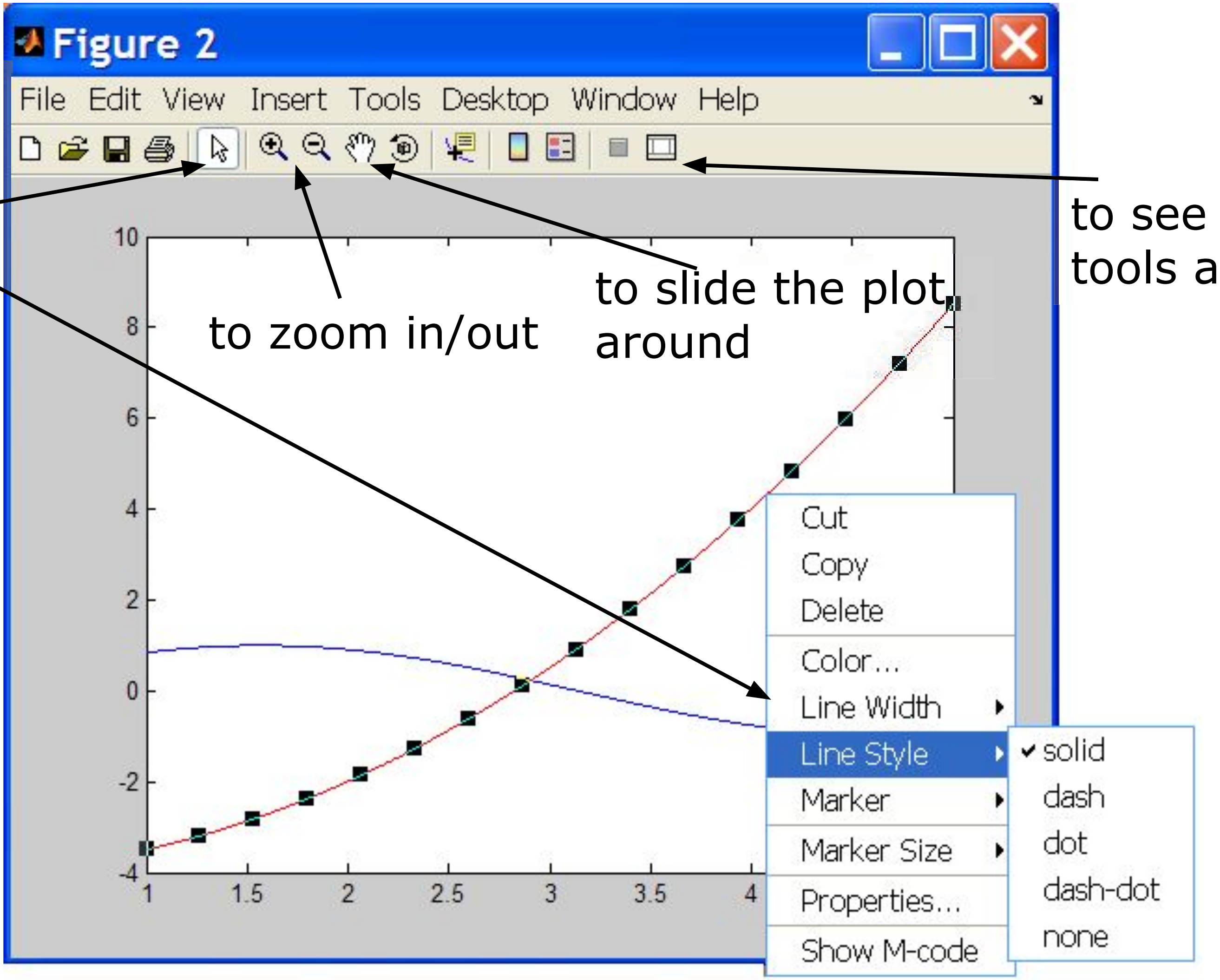


- Can plot without connecting the dots by omitting line style argument

```
» plot(x,y,’.’)
```

- Look at **help plot** for a full list of colors, markers, and line styles

Playing with the Plot



to select lines and delete or change properties

to zoom in/out

to slide the plot around

to see all plot tools at once

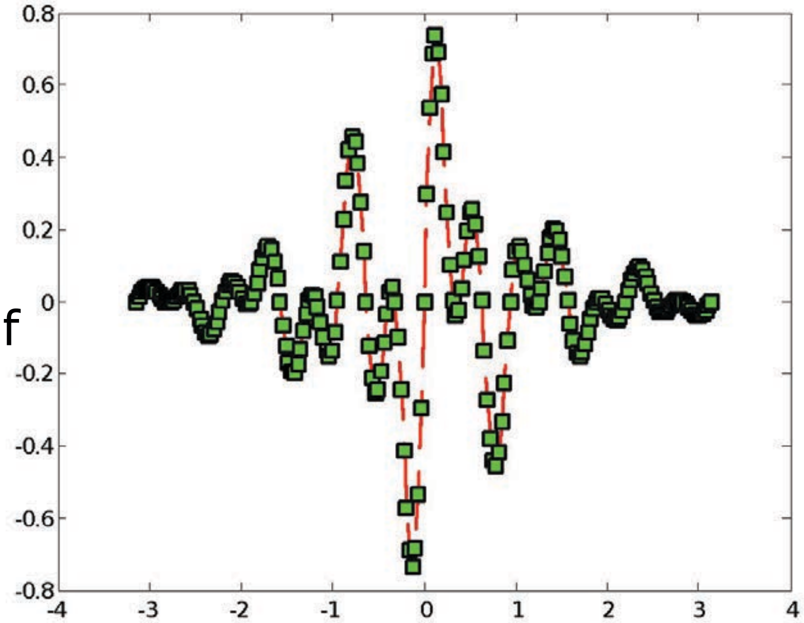
Line and Marker Options

- Everything on a line can be customized

```
» plot(x,y,'s--','LineWidth',2,...
            'Color', [1 0 0], ...
            'MarkerEdgeColor','k',...
            'MarkerFaceColor','g',...
            'MarkerSize',10)
```

You can set colors by using a vector of [R G B] values or a predefined color character like 'g', 'k', etc.

- See **doc line_props** for a full list of properties that can be specified



Cartesian Plots

- We have already seen the plot function

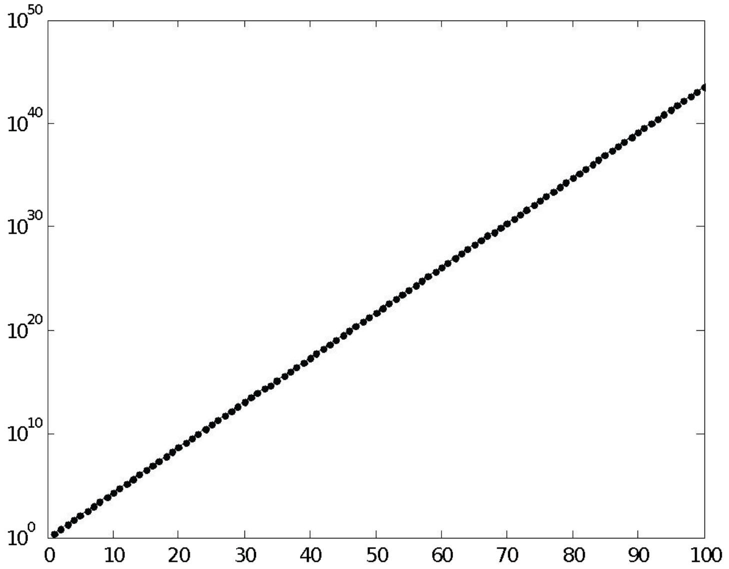
```
» x=-pi:pi/100:pi;
» y=cos(4*x).*sin(10*x).*exp(-abs(x));
» plot(x,y,'k-');
```

- The same syntax applies for semilog and loglog plots

```
» semilogx(x,y,'k');
» semilogy(y,'r.-');
» loglog(x,y);
```

- For example:

```
» x=0:100;
» semilogy(x,exp(x),'k.-');
```



3D Line Plots

- We can plot in 3 dimensions just as easily as in 2D

```
» time=0:0.001:4*pi;
» x=sin(time);
» y=cos(time);
» z=time;
» plot3(x,y,z,'k','LineWidth',2);
» zlabel('Time');
```

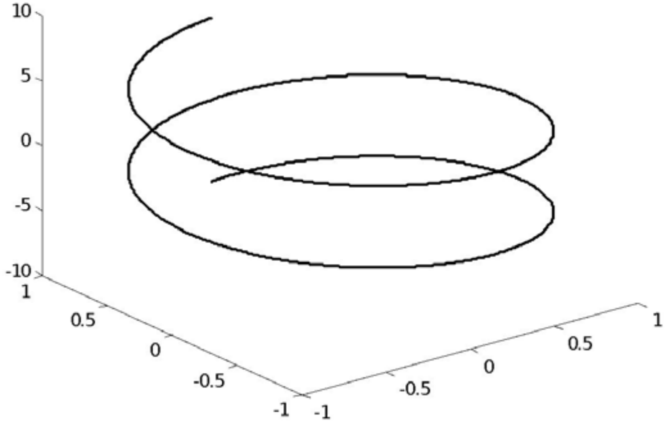
3D Line Plots

- We can plot in 3 dimensions just as easily as in 2D

```
» time=0:0.001:4*pi;
» x=sin(time);
» y=cos(time);
» z=time;
» plot3(x,y,z,'k','LineWidth',2);
» zlabel('Time');
```

- Use tools on figure to rotate it
- Can set limits on all 3 axes

```
» xlim, ylim, zlim
```



Axis Modes

- Built-in axis modes (see `doc axis` for more modes)

» `axis square`

➢ makes the current axis look like a square box

» `axis tight`

➢ fits axes to data

» `axis equal`

➢ makes x and y scales the same

» `axis xy`

➢ puts the origin in the lower left corner (default for plots)

» `axis ij`

➢ puts the origin in the upper left corner (default for matrices/images)

Multiple Plots in one Figure

- To have multiple axes in one figure
  - » `subplot(2,3,1)`
    - ➢ makes a figure with 2 rows and 3 columns of axes, and activates the first axis for plotting
    - ➢ each axis can have labels, a legend, and a title
  - » `subplot(2,3,4:6)`
    - ➢ activates a range of axes and fuses them into one

- To close existing figures
  - » `close([1 3])`
    - ➢ closes figures 1 and 3
  - » `close all`
    - ➢ closes all figures (useful in scripts)

Copy/Paste Figures

- Figures can be pasted into other apps (word, ppt, etc)
- *Edit→ copy options→ figure copy template*
  - ➢ Change font sizes, line properties; presets for word and ppt
- *Edit→ copy figure* to copy figure
- Paste into document of interest

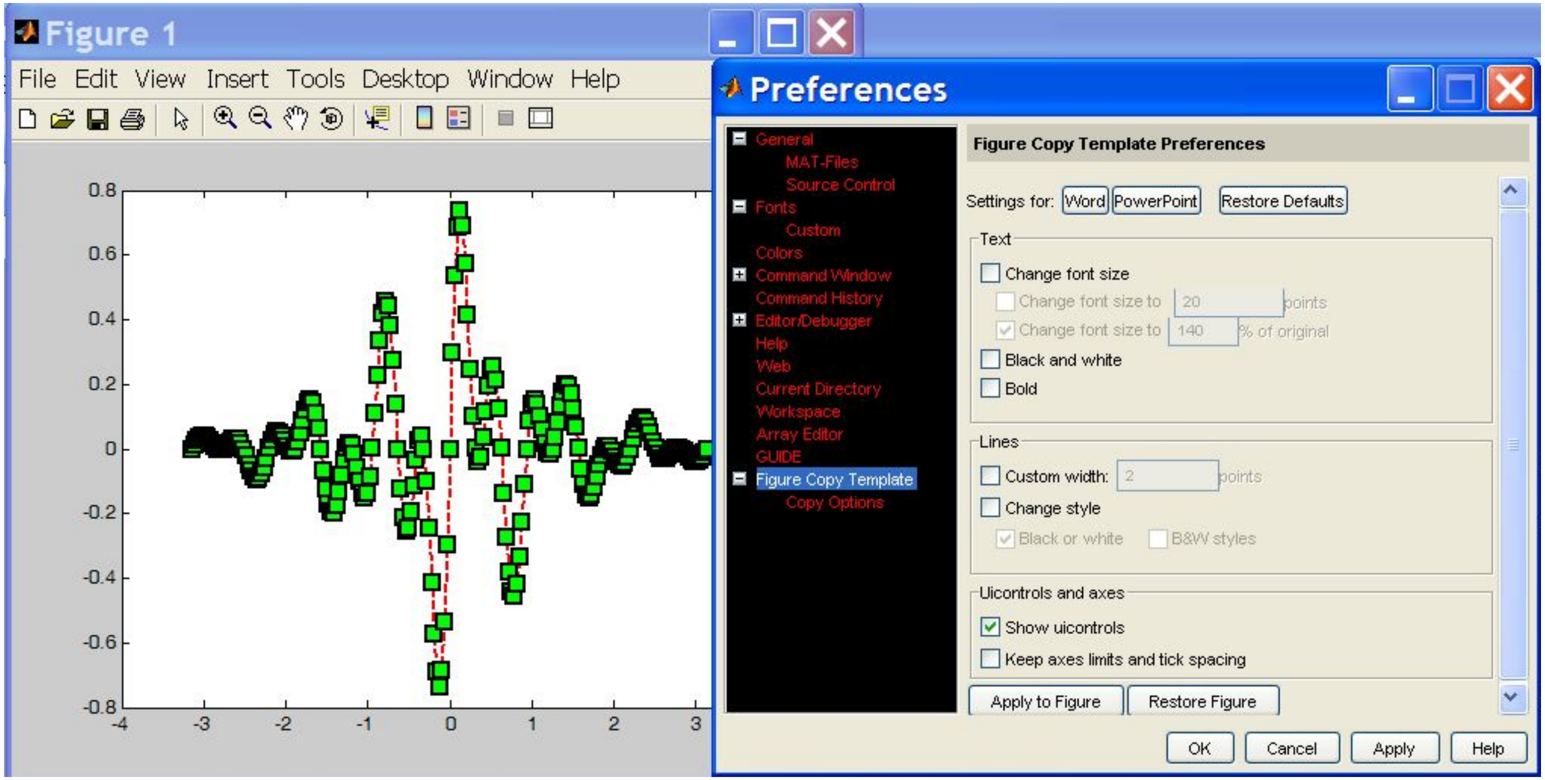


Figure Copy Template Preferences

Settings for: Word PowerPoint Restore Defaults

Text

☐ Change font size

☐ Change font size to 20 points

☑ Change font size to 140 % of original

☐ Black and white

☐ Bold

Lines

☐ Custom width: 2 points

☐ Change style

☑ Black or white ☐ B&W styles

Uicontrols and axes

☑ Show uicontrols

☐ Keep axes limits and tick spacing

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Saving Figures

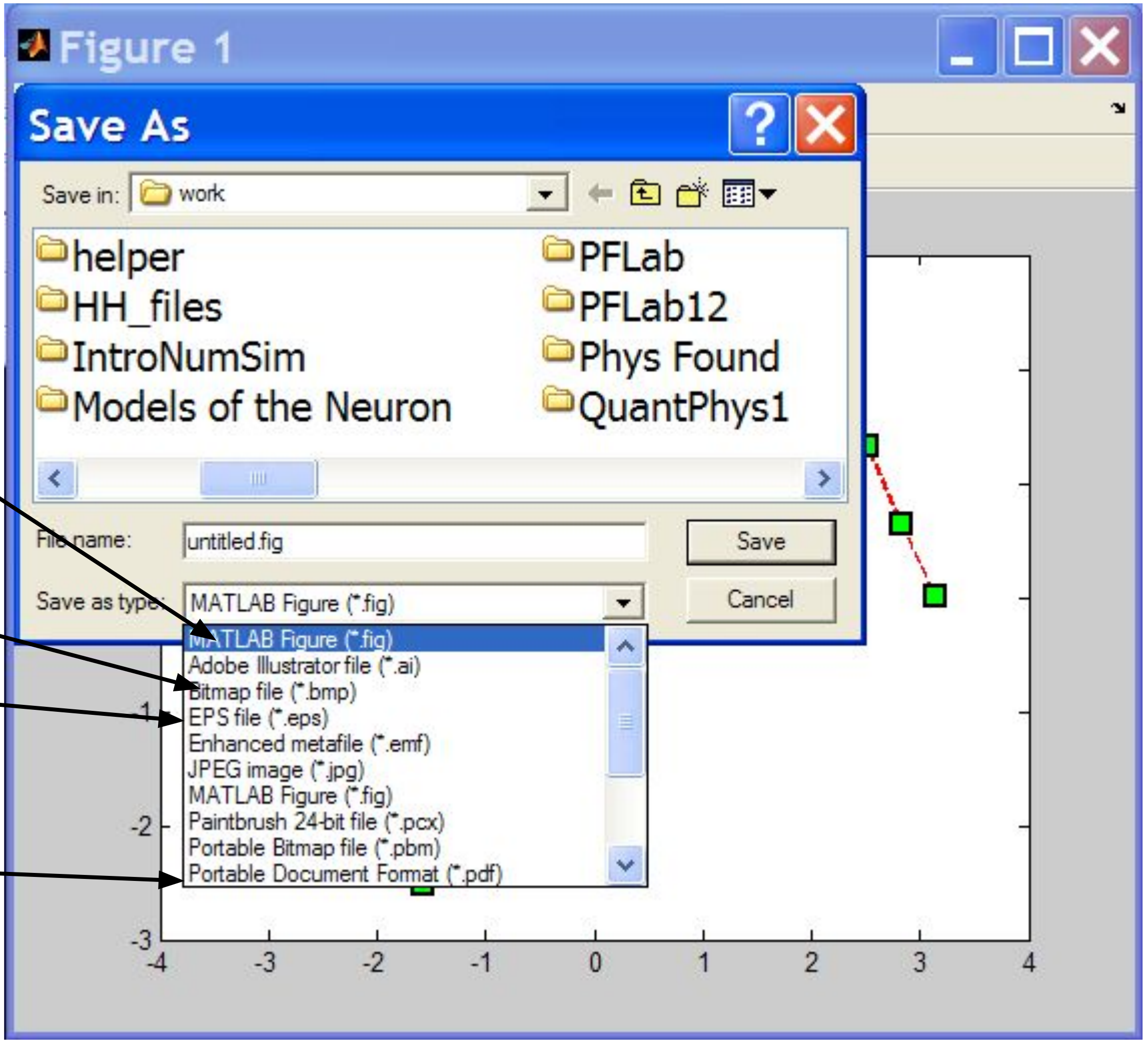
- Figures can be saved in many formats. The common ones are:

.fig preserves all information

.bmp uncompressed image

.eps high-quality scaleable format

.pdf compressed image



File name: untitled.fig

Save as type: MATLAB Figure (*.fig)

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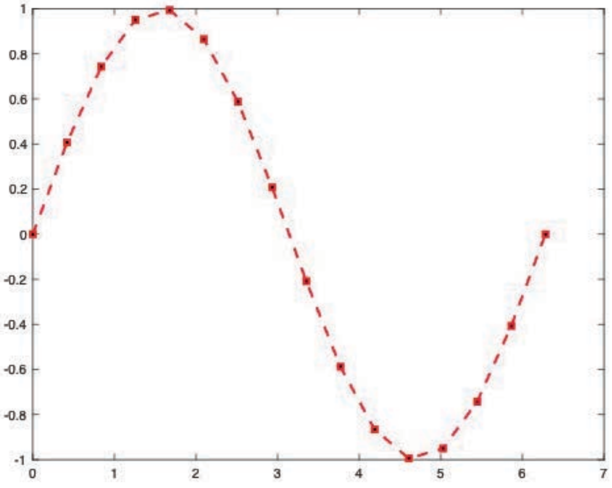
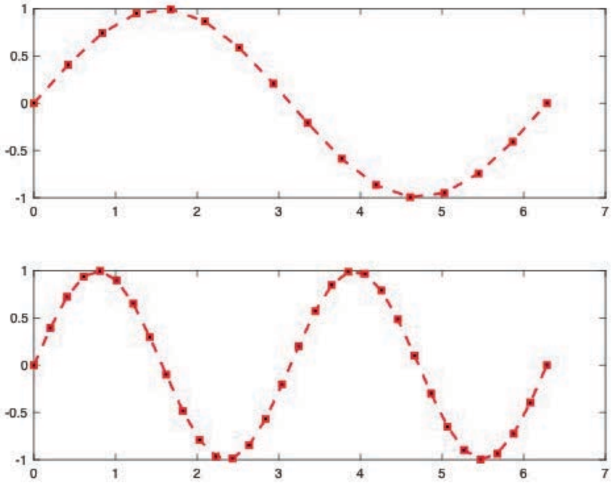
Advanced Plotting: Exercise

- Modify the plot command in your plotSin function to use **squares** as markers and a **dashed red** line of **thickness** 2 as the line. Set the marker face color to be **black** (properties are `LineWidth`, `MarkerFaceColor`)
- If there are 2 inputs, open a new figure with 2 axes, one on top of the other (not side by side), and plot both frequencies (`subplot`)

`plotSin(6)`



`plotSin(1,2)`



Outline

(1) Functions

(2) Flow Control

(3) Line Plots

(4) **Image/Surface Plots**

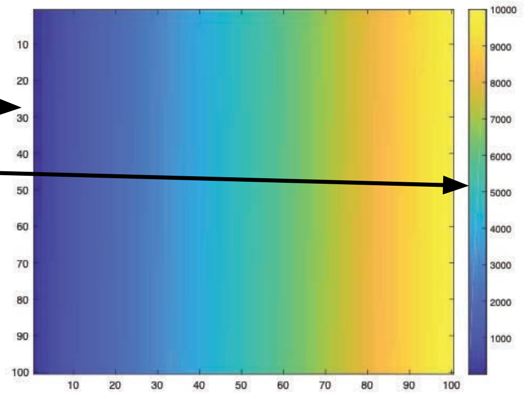
(5) Efficient Codes

(6) Debugging

Visualizing matrices

- Any matrix can be visualized as an image

```
» mat=reshape(1:10000,100,100);
» imagesc(mat);
» colorbar
```



- **imagesc** automatically scales the values to span the entire colormap

- Can set limits for the color axis (analogous to `xlim`, `ylim`)

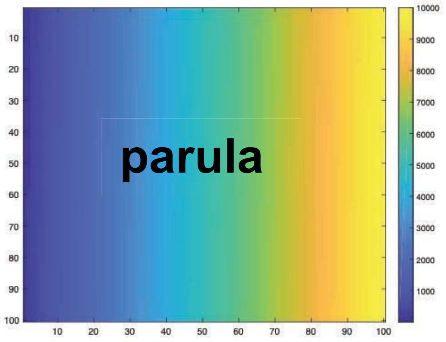
```
» caxis([3000 7000])
```

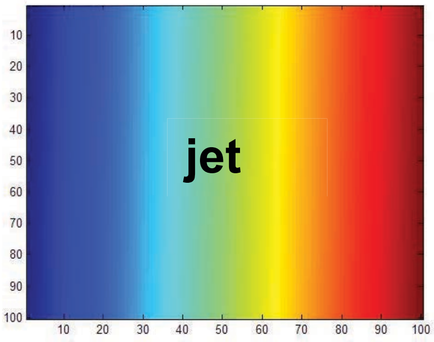
Colormaps

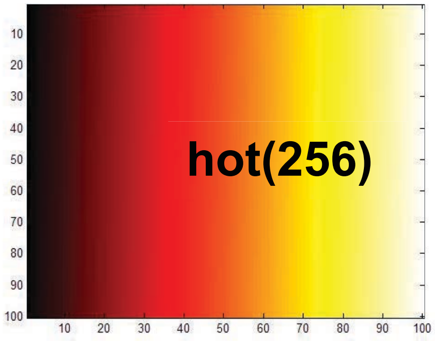
- You can change the colormap:
  - » `imagesc(mat)`
    - ➢ default map is parula
  - » `colormap(gray)`
  - » `colormap(cool)`
  - » `colormap(hot(256))`

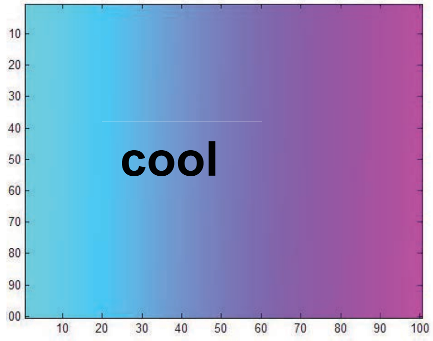
- See `help hot` for a list

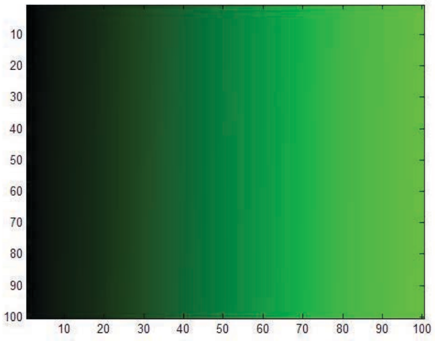
- Can define custom color-map
  - » `map=zeros(256,3);`
  - » `map(:,2)=(0:255)/255;`
  - » `colormap(map);`

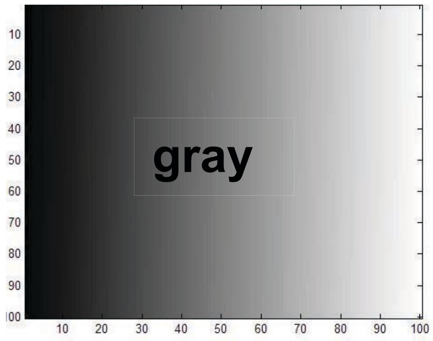












Surface Plots

- It is more common to visualize *surfaces* in 3D

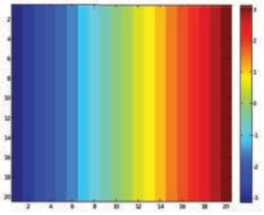
- Example:

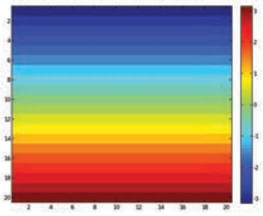
$$\boxed{\begin{array}{l} f(x,y) = sin(x)cos(y) \\ x \in [-\pi,\pi];\, y \in [-\pi,\pi] \end{array}}$$

- **surf** puts vertices at specified points in space x,y,z, and connects all the vertices to make a surface

- The vertices can be denoted by matrices X,Y,Z

- How can we make these matrices
  - ➢ built-in function: **meshgrid**





surf

- Make the x and y vectors

```
» x=-pi:0.1:pi;
» y=-pi:0.1:pi;
```

- Use meshgrid to make matrices

```
» [X,Y]=meshgrid(x,y);
```

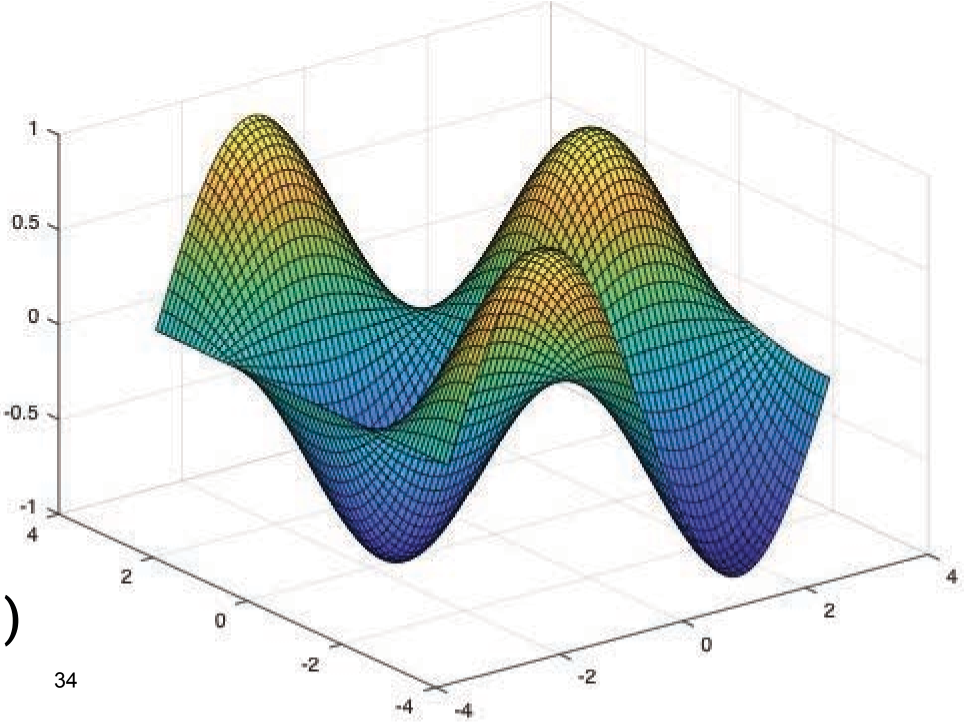
- To get function values, evaluate the matrices

```
» Z =sin(X).*cos(Y);
```

- Plot the surface

```
» surf(X,Y,Z)
» surf(x,y,Z);
```

*Try typing `surf(membrane)`



surf Options

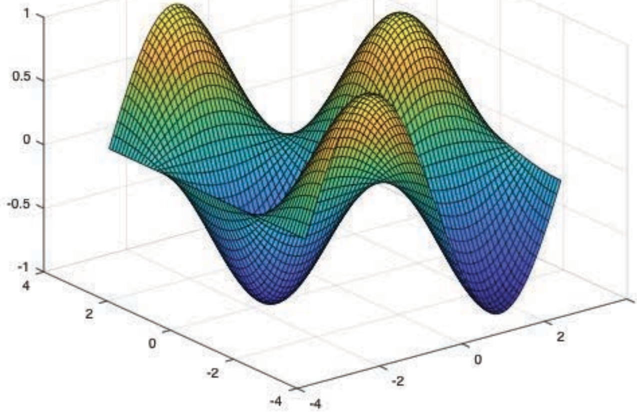
- See **help surf** for more options
- There are three types of surface shading

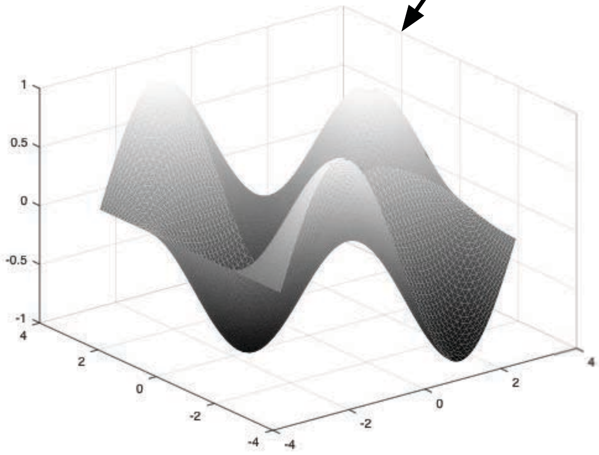
```
» shading faceted
» shading flat
» shading interp
```

- You can also change the colormap

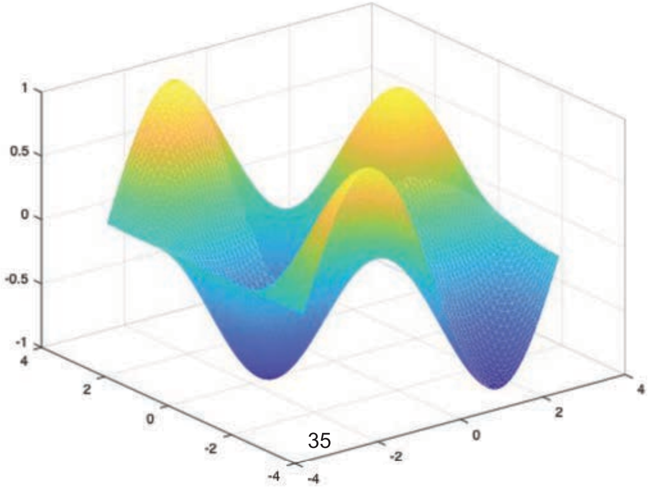
```
» colormap(gray)
```

faceted

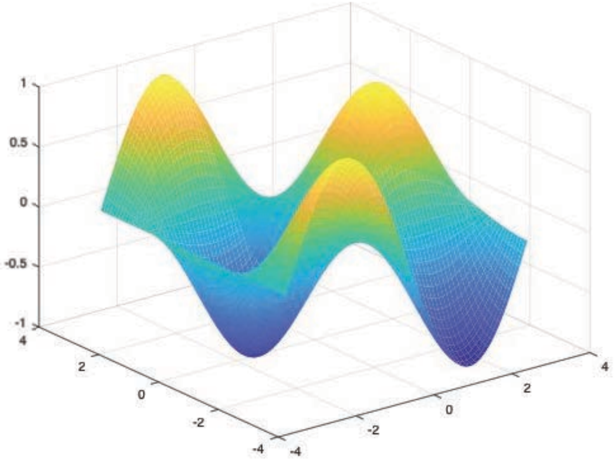




interp



flat



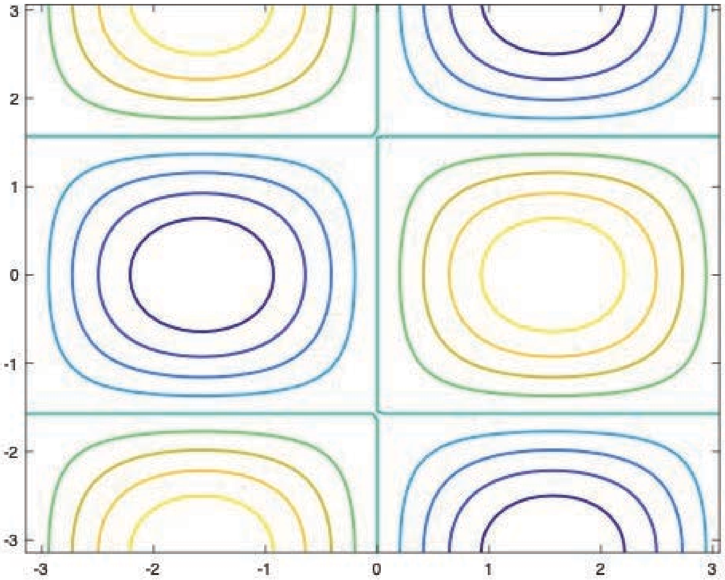
contour

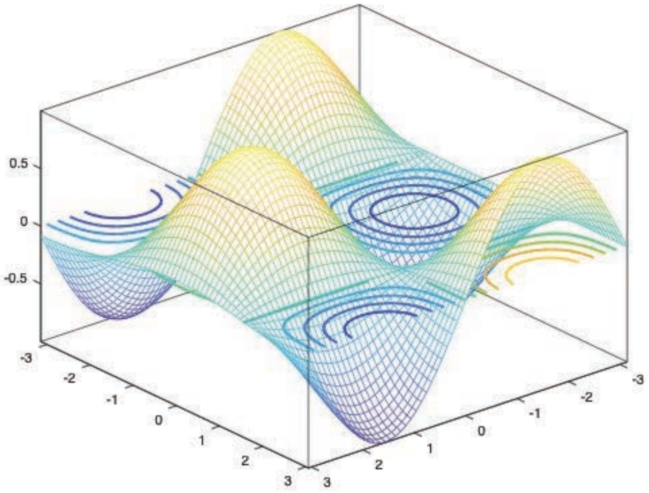
- You can make surfaces two-dimensional by using contour

```
» contour(X,Y,Z,'LineWidth',2)
```

  - ➢ takes same arguments as surf
  - ➢ color indicates height
  - ➢ can modify linestyle properties
  - ➢ can set colormap

```
» hold on
» mesh(X,Y,Z)
```





Exercise: 3-D Plots

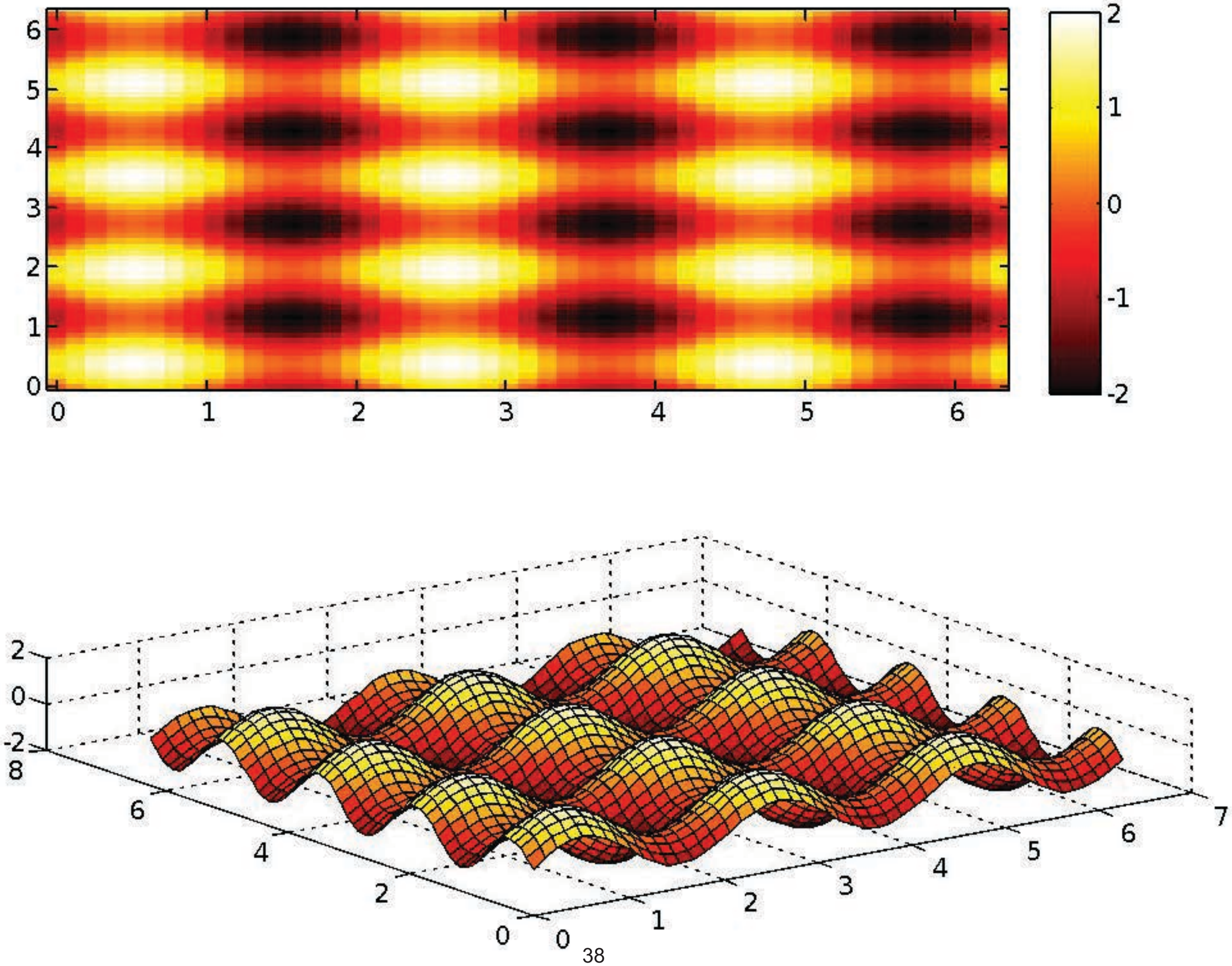
- Modify **plotSin** to do the following:
- If two inputs are given, evaluate the following function:

$$Z = \sin\left(f_1 x\right) + \sin\left(f_2 y\right)$$

- y should be just like x, but using f2. (use **meshgrid** to get the X and Y matrices)
- In the top axis of your subplot, display an image of the Z matrix. Display the colorbar and use a **hot** colormap. Set the axis to xy (**imagesc**, **colormap**, **colorbar**, **axis**)
- In the bottom axis of the subplot, plot the 3-D surface of Z (**surf**)

Exercise: 3-D Plots

`plotSin(3,4)` generates this figure



Specialized Plotting Functions

- MATLAB has a lot of specialized plotting functions
- **polar**-to make polar plots
  ```
  » polar(0:0.01:2*pi,cos((0:0.01:2*pi)*2))
  ```
- **bar**-to make bar graphs
  ```
  » bar(1:10,rand(1,10));
  ```
- **quiver**-to add velocity vectors to a plot
  ```
  » [X,Y]=meshgrid(1:10,1:10);
  » quiver(X,Y,rand(10),rand(10));
  ```
- **stairs**-plot piecewise constant functions
  ```
  » stairs(1:10,rand(1,10));
  ```
- **fill**-draws and fills a polygon with specified vertices
  ```
  » fill([0 1 0.5],[0 0 1],'r');
  ```
- see help on these functions for syntax
- **doc specgraph** – for a complete list

Outline

(1) Functions

(2) Flow Control

(3) Line Plots

(4) Image/Surface Plots

(5) **Efficient codes**

(6) Debugging

find

- **find** is a very important function
  - ➢ Returns indices of nonzero values
  - ➢ Can simplify code and help avoid loops

- Basic syntax: index=find(cond)

```
» x=rand(1,100);
» inds = find(x>0.4 & x<0.6);
```

`inds` contains the indices at which x has values between 0.4 and 0.6. This is what happens:

x>0.4 returns a vector with 1 where true and 0 where false

x<0.6 returns a similar vector

& combines the two vectors using logical **and** operator

find returns the indices of the 1's

Example: Avoiding Loops

- Given x= sin(linspace(0,10*pi,100)), how many of the entries are positive?

Using a loop and if/else

```
count=0;
for n=1:length(x)
    if x(n)>0
        count=count+1;
    end
end
```

Being more clever

```
count=length(find(x>0));
```

Is there a better way?!

length(x)	Loop time	Find time
100	0.01	0
10,000	0.1	0
100,000	0.22	0
1,000,000	1.5	0.04

- Avoid loops!
- Built-in functions will make it faster to write and execute

Vectorization

- Avoid loops
    - ➢ This is referred to as vectorization
- Vectorized code is more efficient for MATLAB
- Use indexing and matrix operations to avoid loops
- For instance, to add every two consecutive terms:

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- For instance, to add every two consecutive terms:

```
» a=rand(1,100);
» b=zeros(1,100);
» for n=1:100
»     if n==1
»         b(n)=a(n);
»     else
»         b(n)=a(n-1)+a(n);
»     end
» end
```

- ➢ Slow and complicated

Vectorization

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- Vectorized code is more efficient for MATLAB
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»     end
» end
```

➢ Slow and complicated

```
» a=rand(1,100);
» b=[0 a(1:end-1)]+a;
```

➢ Efficient and clean. Can also do this using `conv`

Preallocation

- Avoid variables growing inside a loop
- Re-allocation of memory is time consuming
- Preallocate the required memory by initializing the array to a default value
- For example:

```
» for n=1:100
»     res = % Very complex calculation %
»     a(n) = res;
» end
```

  - ➢ Variable `a` needs to be resized at every loop iteration

Preallocation

- Avoid variables growing inside a loop
- Re-allocation of memory is time consuming
- Preallocate the required memory by initializing the array to a default value
- For example:

```
» a = zeros(1, 100);
» for n=1:100
»     res = % Very complex calculation %
»     a(n) = res;
» end
```

➢ Variable **a** is only assigned new values. No new memory is allocated

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Display

- When debugging functions, use **disp** to print messages

```
» disp('starting loop')
» disp('loop is over')
```

  - ➢ `disp` prints the given string to the command window

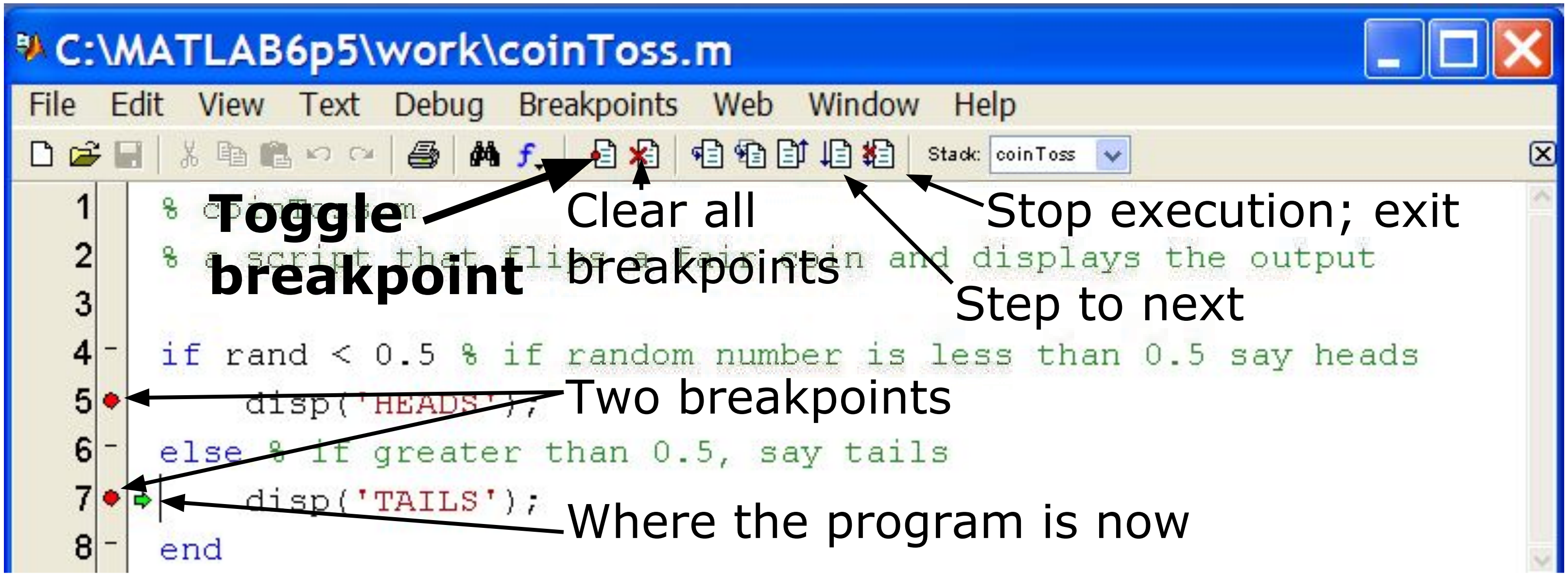
- It's also helpful to show variable values

```
» disp(['loop iteration ' num2str(n)]);
```

  - ➢ Sometimes it's easier to just remove some semicolons

Debugging

- To use the debugger, set breakpoints
  - ➢ Click on – next to line numbers in m-files
  - ➢ Each red dot that appears is a breakpoint
  - ➢ Run the program
  - ➢ The program pauses when it reaches a breakpoint
  - ➢ Use the command window to probe variables
  - ➢ Use the debugging buttons to control debugger



```
% coinToss.m
% a script that flips a fair coin and displays the output

if rand < 0.5 % if random number is less than 0.5 say heads
    disp('HEADS');
else % if greater than 0.5, say tails
    disp('TAILS');
end
```

Toggle breakpoint

Clear all breakpoints

Stop execution; exit

Step to next

Two breakpoints

Where the program is now

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Performance Measures

- It can be useful to know how long your code takes to run
  - ➢ To predict how long a loop will take
  - ➢ To pinpoint inefficient code

- You can time operations using **tic**/**toc**:

```
» tic
» Mystery1;
» a=toc;
» Mystery2;
» b=toc;
```

  - ➢ tic resets the timer
  - ➢ Each toc returns the current value in seconds
  - ➢ Can have multiple tocs per tic

Performance Measures

- Example: Sparse matrices

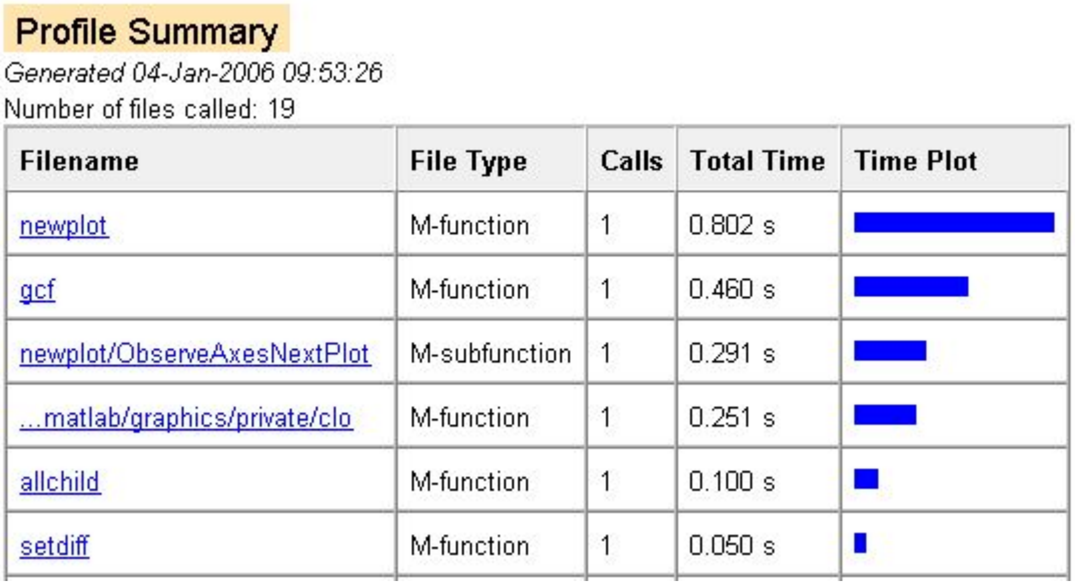
```
» A=zeros(10000); A(1,3)=10; A(21,5)=pi;
» B=sparse(A);
» inv(A);   % what happens?
» inv(B);   % what about now?
```

- If system is sparse, can lead to large memory/time savings

```
» A=zeros(1000); A(1,3)=10; A(21,5)=pi;
» B=sparse(A);
» C=rand(1000,1);
» tic; A\C; toc;   % slow!
» tic; B\C; toc;   % much faster!
```

Performance Measures

- For more complicated programs, use the profiler
  - » `profile on`
    - ➢ Turns on the profiler. Follow this with function calls
  - » `profile viewer`
    - ➢ Displays gui with stats on how long each subfunction took



Profile Summary

Generated 04-Jan-2006 09:53:26

Number of files called: 19

Filename	File Type	Calls	Total Time	Time Plot
newplot	M-function	1	0.802 s	▬▬▬▬▬▬▬▬
gcf	M-function	1	0.460 s	▬▬▬▬▬
newplot/ObserveAxesNextPlot	M-subfunction	1	0.291 s	▬▬▬
...matlab/graphics/private/clo	M-function	1	0.251 s	▬▬▬
allchild	M-function	1	0.100 s	▬
setdiff	M-function	1	0.050 s	▮

End of Lecture 2

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Vectorization makes coding fun!

6.057 Introduction to MATLAB
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