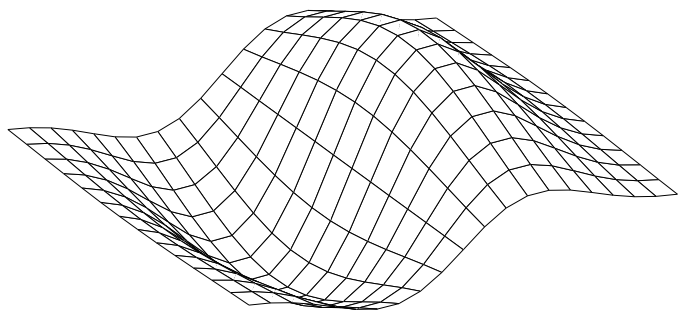
Matlab Tutorial

CS 475 - Computational Linear Algebra

Spring 2025

Outline

- Matlab Overview
- Useful Commands
- Matrix Construction and Flow Control
- Script/Function Files
- Basic Graphics



Getting to Matlab

- You can access MATLAB at `https://www.mathworks.com/academia/tah-portal/university-of-waterloo-31483447.html`
- Use your @uwaterloo.ca email to access MATLAB online, or to install on your local machine
- Problems: see consultants in MC3011

What is Matlab?

According to *The Mathworks*:

> MATLAB is an integrated technical computing environment that combines numeric computation, advanced graphics and visualization, and a high-level programming language.
>
> *MATLAB includes hundreds of functions for:*
>
> - *Data analysis and visualization*
> - *Numeric and symbolic computation*
> - *Engineering and scientific graphics*
> - *Modeling, simulation, and prototyping*
> - *Programming, application development, and GUI design*

Getting Started

- Web resources
  - www.mathworks.com
- Books
  - *Mastering Matlab 5/6/7*, D. Hanselman, B. Littlefield
  - *Introduction to Scientific Computing*, Van Loan
  - See also Course Web site for other sources

Running Matlab

- Macs/PCs (running Matlab locally)
  - Launch MATLAB from wherever you have installed it.
- If using xterm/remote from home: at the UNIX prompt:
  - *Don't type:* matlab
    - graphical desktop, slow
  - *Instead, type:* matlab -nodesktop -nosplash
    -text interface, faster
  - (other options: matlab -h)
- Reset the display permissions if you see the message

```
Xlib:  connection to "x.uwaterloo.ca:0.0" refused by
server
Xlib:  Client is not authorized to connect to Server
```

```
@rees[102]% matlab -nodesktop -nosplash

                                  < M A T L A B >
                      Copyright 1984-2002 The MathWorks, Inc.
                         VR2013b (8.2.0.701) 64-bit (glnxa64)
                                   August 13, 2013


  To get started, type one of these: helpwin, helpdesk, or demo.
  For product information, visit www.mathworks.com.

>>
```

How does Matlab work?

- Interactive environment
- Type commands at the prompt ('>>' typically)
- Case sensitive
- External programs/functions are in M-files (text files with a .m extension)
- Execute M-files by typing the filename (without the .m)
- Note: Almost everything in Matlab is an external function (use the which command to locate the source)

Basic Operations

- 'Matrix' (array) is the only main data type
  (everything is a matrix, although entries may be numeric, logical, char, etc.)
- Vectors are $1 \times N$ or $N \times 1$ matrices
- Scalars are 1×1 matrices
- Addition and subtraction operate entry-wise, while

  `*  ^ \  /`

  are matrix operations, *unless preceded by a dot*
- Entries are accessed via `(row index, column index)`
- Matrices and vectors are *1-offset*
  (rows/columns are numbered starting from 1, *not 0*)

Basic Example 1

```
>> A = [1 2 3 ; 4 5 6]
A =
     1     2     3
     4     5     6

>> test = A*A
??? Error using ==> *
Inner matrix dimensions must agree.

>> test = A*A'
test =
    14    32
    32    77
```

Basic Example 2

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

>> A^2
ans =
     7    10
    15    22

>> A.^2
ans =
     1     4
     9    16
```

Transposes

- Strictly, A' is *complex conjugate transpose* of A
- Usual (non-conjugate) transpose is A.'
- ```
  >> A = [1+i, 2+2i, 3+3i]
  A =
     1.0000 + 1.0000i   2.0000 + 2.0000i   3.0000 + 3.0000i
  >> A'
  ans =
     1.0000 - 1.0000i
     2.0000 - 2.0000i
     3.0000 - 3.0000i
  >> A.'
  ans =
     1.0000 + 1.0000i
     2.0000 + 2.0000i
     3.0000 + 3.0000i
  ```
  ```

More dots

```
>> A = [1 2; 3 5]
A =
     1     2
     3     5
>> B = [-5 2; 3 -1]
B =
    -5     2
     3    -1
>> A*B
ans =
     1     0
     0     1
>> A.*B
ans =
    -5     4
     9    -5
```

Basic Example 3 - Solving Ax=b

```
>> A = [1,15,4; 2,15,20; 3,30,9];
>> b = [1;22;9];
>> x=A\b

x =
    6.0667
   -0.5867
    0.9333

>> x=inv(A)*b

x =
    6.0667
   -0.5867
    0.9333
```

Useful commands

- `help` - Obtain help for a specific function
- `lookfor` - Keyword search of help text
- `more {on/off}` - Paging
- `clear` - Remove variables
- `close` - Close figure windows
- `whos` - List currently defined variables
- `format` - Set output format (e.g., number of digits)
- `%` - comment line in an M-file

help

- `help function` - Gives detailed information about 'function'
- Displays the comments at the top of the M-file
- Some of the help screens read like UNIX man pages
- Related items are listed at the end
- Despite the help text, all commands are lower case
- Useful command to use when you are stuck
- `help` - Provides a list of topics which can then be searched

lookfor

- First command to use when you are stuck
- `lookfor XYZ` - Searches the first comment line for the string XYZ
- Useful if you do not know the function name, but expect that the function exists
- Can be slow

more

- `more {on/off}`
- Turn screen paging on or off
- Works like the Unix more command

clear

- `clear X` - Remove the variable X
- `clear X*` - Remove all variables starting with string X
- `clear` - Remove all variables
- `clear all` - Removes everything (variables, functions, globals and MEX links)
- Often useful at the beginning of script files
- To clear command window: clc

close

- `close` - Close the current figure
- `close all` - Close all figure windows
- Useful at the start of script files

whos

- `who` - list all variables
- `whos` - list all variables, with size information

```
>> whos
  Name        Size              Bytes  Class

  ans         1x17                 34  char array
  x          14x21               2352  double array
  y          14x22               2464  double array
  z          14x21               2352  double array
Grand total is 913 elements using 7202 bytes
```

- Useful if you keep getting array size mismatches (remember that Matlab is 1-offset)

format

- ```
  >> 1/3
  ans =
     0.3333
  ```
- ```
  >> format long
  >> 1/3
  ans =
     0.33333333333333
  ```
- ```
  >> format short e
  >> 1/3
  ans =
     3.3333e-01
  ```
- help format
  ```

Command line tricks

- Up/Down arrow keys to cycle through commands
- Partially typing a command and hitting up arrow will search the command stack
- Can type multi-line commands, but each line is saved separately (ie. not very useful for re-entering loop commands)
- A command can span two lines by using ... at the end of the first line

Constructing Matrices

- Type in all the numbers directly (semi-colons or new lines create new rows)
- Use ones or zeros
- Use the colon notation
  - start:step:final (e.g. 3:2:7 = [3 5 7])
  - steps can be negative (e.g. 7:-2:3 = [7 5 3])
  - start:final assumes a step of 1
  - colon by itself means 'all' (eg. A(1,:) is all entries in row 1)
- A variety of other methods exist (load, algebra, other functions)
- Note that vectors and arrays are dynamic

Example

```
>> m1 = zeros(1,3)
m1 =
     0     0     0

>> m2 = ones(3)
m2 =
     1     1     1
     1     1     1
     1     1     1

>> m3(2:3,:) = [m2(3,:); [1:1:3]]
m3 =
     0     0     0
     1     1     1
     1     2     3
```

Dimensions of Matrices and Vectors

- size(A) for matrices, length(x) for vectors
-
```
>> A = [1 2 3; 4 5 6]
A =
     1     2     3
     4     5     6
>> [m n] = size(A)
m =
     2
n =
     3
>> x = [1 2 3 4]
x =
     1     2     3     4
>> length(x)
ans =
     4
```

Control Structures

- For statements:

```
for i = 1:n,
    for j = 1:n,
        A(i,j) = 1/(i+j-1);
    end
end
```

- While loops

```
while x > 1,
    x = x - 1;
end
```

Control Structures (cont.)

- IF statements

```
if <expression>
    <statements>
elseif <expression>
    <statements>
    .
    .
    .
else
    <statements>
end
```

Relational and Logical Operators

- Relational operators

```
<   <=   >   >=   ==   ~= (in C: !=)
```

- Logical operators

	Matlab	C
AND	&	&&
OR	|	||
NOT	~	!

-
```
>> A = 1:9
A =
     1     2     3     4     5     6     7     8     9
>> tf = (A>2)&(A<6)
tf =
     0     0     1     1     1     0     0     0     0
```

Vectorizing Loops

```
>> cs475marks = [24 36 11 42 33 55 30];
>> for i=1:length(cs475marks)
      cs475marks(i) = 10*cs475marks(i)^(1/2);
   end
>> cs475marks
cs475marks =
   48.9898   60.0000   33.1662   64.8074   57.4456
   74.1620   54.7723

>> cs475marks = [24 36 11 42 33 55 30];
>> cs475marks = 10*cs475marks.^(1/2)
cs475marks =
   48.9898   60.0000   33.1662   64.8074   57.4456
   74.1620   54.7723
```

Script files

- Matlab commands can be placed in text files with .m extensions
- The commands are interpreted/executed when the filename is typed at the Matlab prompt (no .m extension)
- The effect is identical to typing the commands (i.e. all new variables remain, all old variables are accessible)
- Convenient if the same set of commands need to be executed with minor changes
- Commonly used for 'driver' programs on assignments

Script Example

```
clear all;
close all;

% Initial data
x = [ 9 8 7 3 1 1 2 5 8 7 5 ];
y = [ 4 2 1 2 5 7 9 11 9 8 7 ];
n = length(x);

% Initialize t
t = zeros(size(x));

% Choose t to be arclength
for i = 2:n
    dt = sqrt((x(i)-x(i-1))^2 + (y(i)-y(i-1))^2);
    t(i) = t(i-1) +dt;
end
```

Function Files

- Defined in text files with .m extensions
- Called by typing the filename (no .m)
- Functions do not have access to existing variables (separate scope)
- Functions can accept/return zero or more values
- Control is lost when the end of the file is reached, or the command return is encountered

Function Example

```
function [newmarks] = bell(oldmarks, method)
% Whatever appears here is displayed when the user
% types ‘help bell’

% This line will not appear in the help text
if method == 1
    newmarks = 10*oldmarks.^(1/2);
elseif method == 2
    newmarks = oldmarks + 10*ones(1, length(oldmarks));
else
    newmarks = oldmarks;
end
return
```

Function Example

```
>> help bell

  Whatever appears here is displayed when the user
  types ‘help bell’

>> m = [23 67 43 49 75 55];
>> bell(m,1)
ans =
   47.9583   81.8535   65.5744   70.0000   86.6025   74.1620
>> m_new = bell(m,2)
m_new =
    33    77    53    59    85    65
```

Debugging

- See `help debug`
- Set a breakpoint with `dbstop`
- Trace through the execution with `dbstep`
- Show the execution stack with `dbstack`
- Continue execution with `dbcont`
- Quit debugging with `dbquit`

Text Strings

- Use single quotes to define text: 'string'
- Use `disp` to display text without the associated variable name (also works for variables)
- Can have an array of strings if each string has the same length
- Can convert from numbers to strings using the `num2str` command

```
>> a = 1;
>> b = 5;
>> t = ['Plot ' num2str(a) ' of ' num2str(b)];
>> disp(t)
Plot 1 of 5
```

Graphics

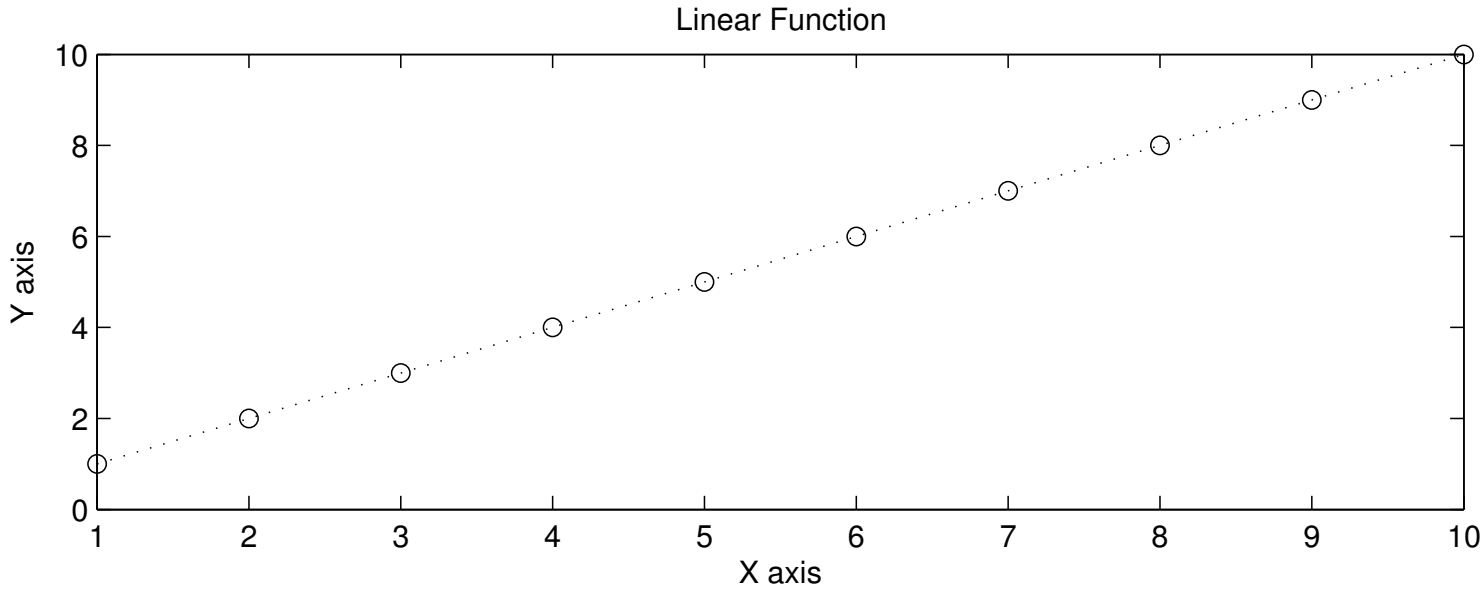
- Matlab has excellent graphics support for experimenting with data
- Since the data is 'live', you can quickly and easily change plots and figures
- Figure windows can easily be saved and printed (as eps or pdf for assignments)
- Figures can be edited by clicking on edit in Figure Window

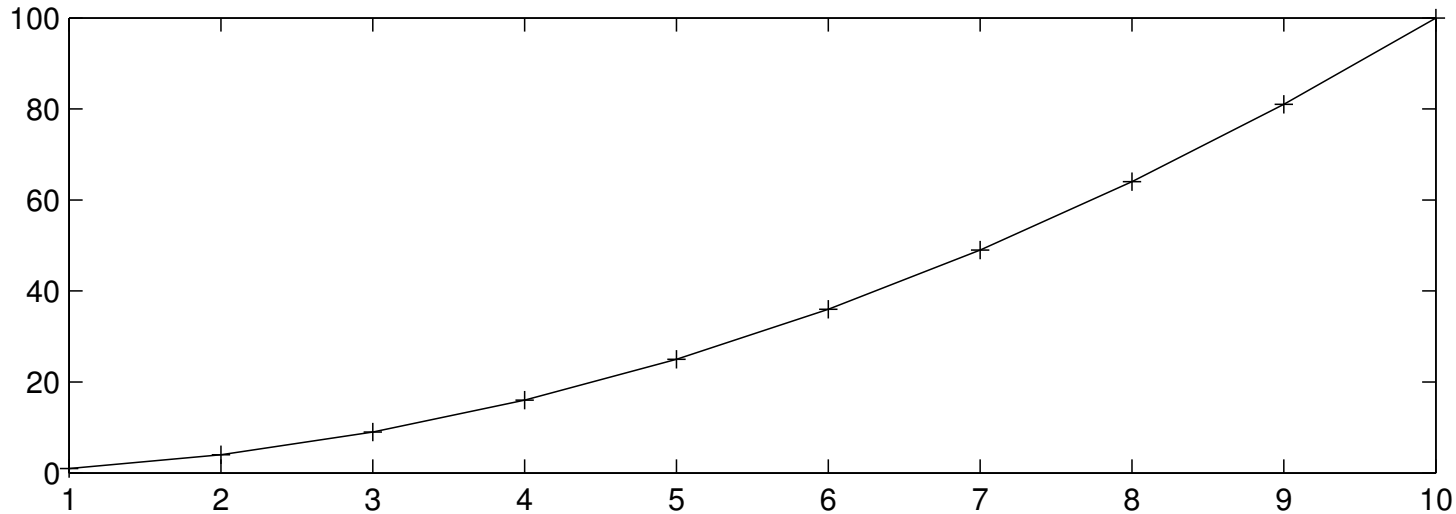
Plots

- `plot(x,y)` - Basic plotting command
- `plot(x,y,'opts')`- `opts` specifies characteristics of the curve (color, style and data markers)
- `help plot` - Details on options available
- Can plot multiple curves on a single figure:
  `plot(x1,y1,'opt1',x2,y2,'opt2')`
  or use `hold on`
- Can add title, axis labels and legend with appropriate commands

2D plots

```
>> x = [1:1:10];
>> y_lin = x;
>> y_quad = x.^2;
>> subplot(2,1,1), plot(x,y_lin,'bo:')
>> title('Linear Function')
>> xlabel('X axis')
>> ylabel('Y axis')
>> subplot(2,1,2), plot(x,y_quad,'r+-')
>> print -deps fig1.eps
>> close
```

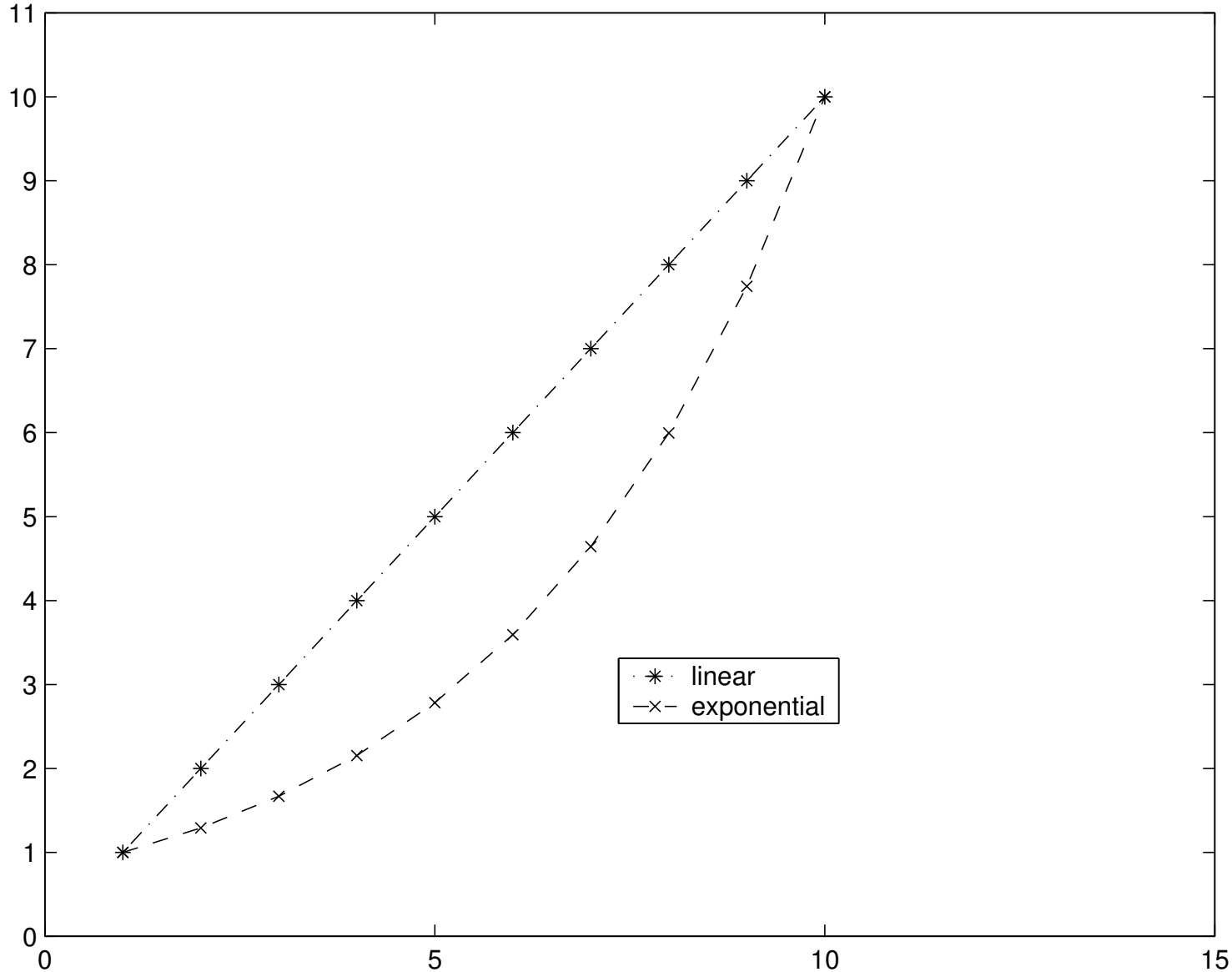

Linear Function
Y axis
X axis
0
2
4
6
8
10
1
2
3
4
5
6
7
8
9
10


0
20
40
60
80
100
1
2
3
4
5
6
7
8
9
10

2D plots (cont.)

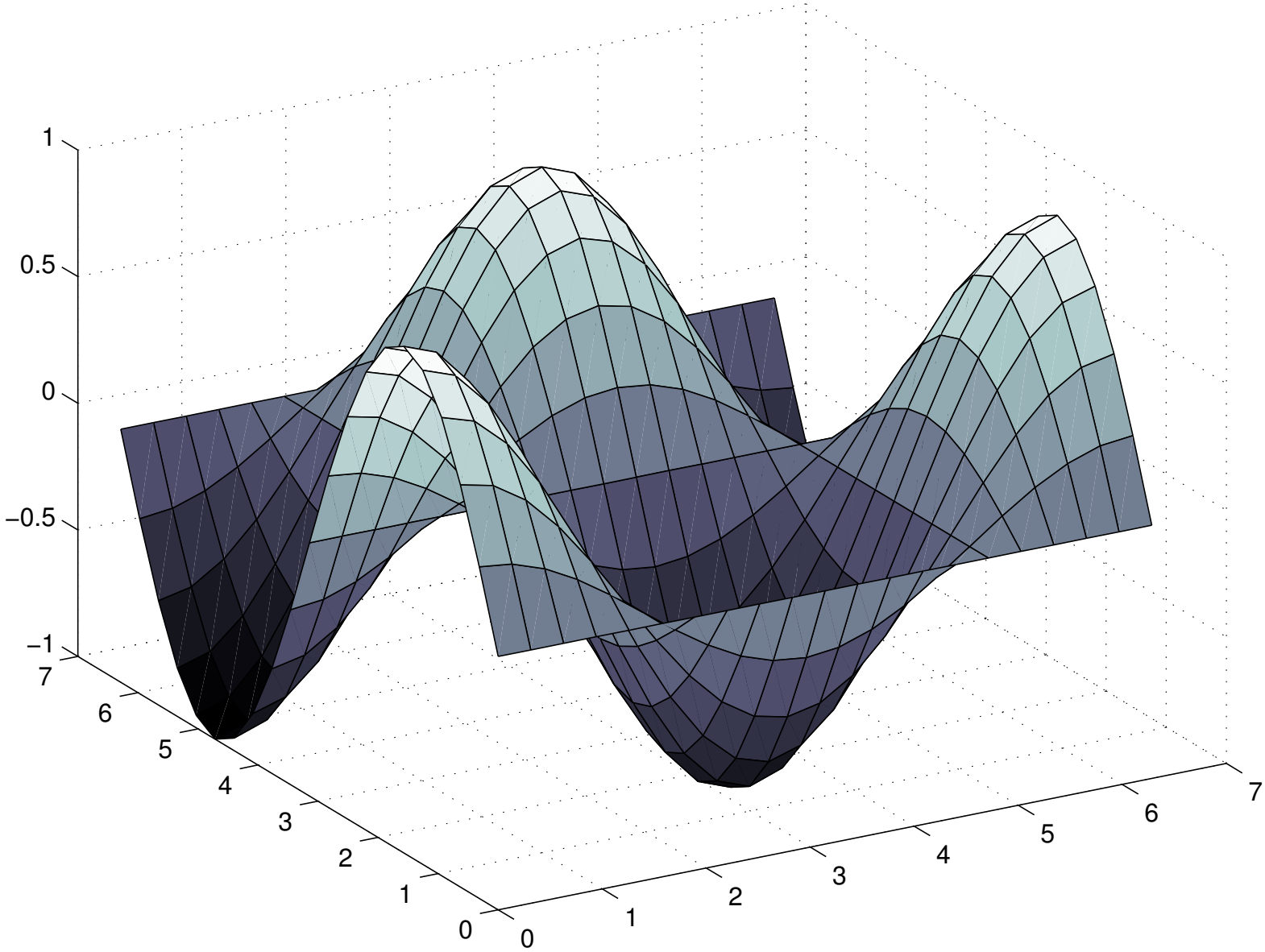
```
>> x=linspace(1,10,10);
>> y_lin = x
y_lin =
     1     2     3     4     5     6     7     8     9    10
>> y_log = logspace(0,1,10) % 10^[ equally spaced 0..1 ]
y_log =
  Columns 1 through 6
    1.0000    1.2915    1.6681    2.1544    2.7826    3.5938
  Columns 7 through 10
    4.6416    5.9948    7.7426   10.0000

>> plot(x,y_lin,'*-.')
>> hold on
>> plot(x,y_log,'x--')
>> axis([0 15 0 11])
>> legend('linear', 'exponential')
```


11
10
9
8
7
6
5
4
3
2
1
0
0
5
10
15
linear
exponential

3D plots

```
>> figure
>> x=[0:2*pi/20:2*pi];
>> y=x;
>> z=sin(x)'*cos(y);
>> surf(x,y,z)
>> colormap('bone')
>> view(-30,30)
>> print -deps mesh3d.eps
```


1
0.5
0
−0.5
−1
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7

Efficiency Issues

- Vectorize loops whenever possible
- Pre-allocate arrays whenever possible
- We will be checking for efficient code on assignments if we mention this specifically
- Otherwise, don't worry too much about this (but your code may take a long time (:)

Vectorization Example: Monte Carlo Simulation

Slow code:

```
 ...
  S_new = zeros(N_sim,1);

for m=1:N_sim % simulation loop
 S = S_init;

%
%   one path
%
 for i=1:N % timestep loop
    S = S + S*( drift + sigma_sqrt_delt*randn(1,1) );
    S = max(0.0, S );
           % check to make sure that S_new cannot be < 0
 end % timestep loop

 S_new(m,1) = S;

end % simulation loop
```

Vectorization Example: Monte Carlo Simulation

Fast code:

```
 ...
   S_new = zeros(N_sim,1);
   S_old(1:N_sim,1) = S_init;

for i=1:N % timestep loop
     % now, for each timestep, generate info for
     % all simulations
     % now, only one explicit loop, second loop
     % replaced by vector commands

   S_new(:,1) = S_old(:,1) +...
       S_old(:,1).*( drift + sigma_sqrt_delt*randn(N_sim,1) );

   S_new(:,1) = max(0.0, S_new(:,1) );
        % check to make sure that S_new cannot be < 0

    S_old(:,1) = S_new(:,1);
end % timestep loop
```

Once Again: Matlab is Matrix Oriented

Most common source of errors

- All entities in Matlab are matrices by default
- A common cause of errors: size mismatch

```
>> a = 1;
>> size(a)
ans =
     1     1
```

This sometimes causes unexpected results when multiplying objects

- There is a difference between a row vector and a column vector!
- Usual rules for matrix multiplication must be followed

Examples:

```
>>  a = [1 2 3]; b = [ 4 5 6];

>>  a'*b
ans =
     4     5     6
     8    10    12
    12    15    18

>>  a*b'

ans =
    32


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

Matrix Condition Numbers

- The **matrix condition number**, $\kappa(A) = \|A\|\|A^{-1}\|$ (where $\|A\| = \max \frac{\|Ax\|}{\|x\|}$), provides a measure for the stability of solutions to the system $Ax = b$, under small changes to A.
- We will use condition numbers later on.
- Note that κ
  - depends on the choice of norm, $\|\cdot\|$, and
  - is non-negative.
- MATLAB has 2 built-in functions for computing the condition number of a matrix, A:
  - `cond(A)`, which uses the 2-norm, and
  - `cond(A,P)`, which uses the P-norm.

Summary

- Use help and lookfor on a regular basis
- Use more on and semi-colons to maintain an intelligible display
- When interpreting error messages, remember that all variables are matrices
- Use script files and functions to automate repetitive tasks (anything over 5 lines should probably be in an M-file)

  $\rightarrow$ On assignments, you should hand in hard copy of all M-files used
- Try to use operations on vectors/matrices, instead of loop constructs