6.094 Introduction to MATLAB®
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6.094

Introduction to Programming in MATLAB®

Lecture 1: Variables, Operations, and Plotting

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Course Layout

- Lectures (7pm-9pm)
  - 1: Variables, Operations and Plotting
  - 2: Visualization & Programming
  - 3: Solving Equations, Fitting
  - 4: Advanced Methods

Course Layout

- Problem Sets / Office Hours
  - One per day, should take about 3 hours to do
  - Submit doc or pdf (include pertinent code)
- Requirements for passing
  - Attend all lectures
  - Complete all problem sets (FAIL, Check or +)
- Prerequisites
  - Basic familiarity with programming
  - Basic linear algebra, differential equations, and probability

Outline

(1) Getting Started

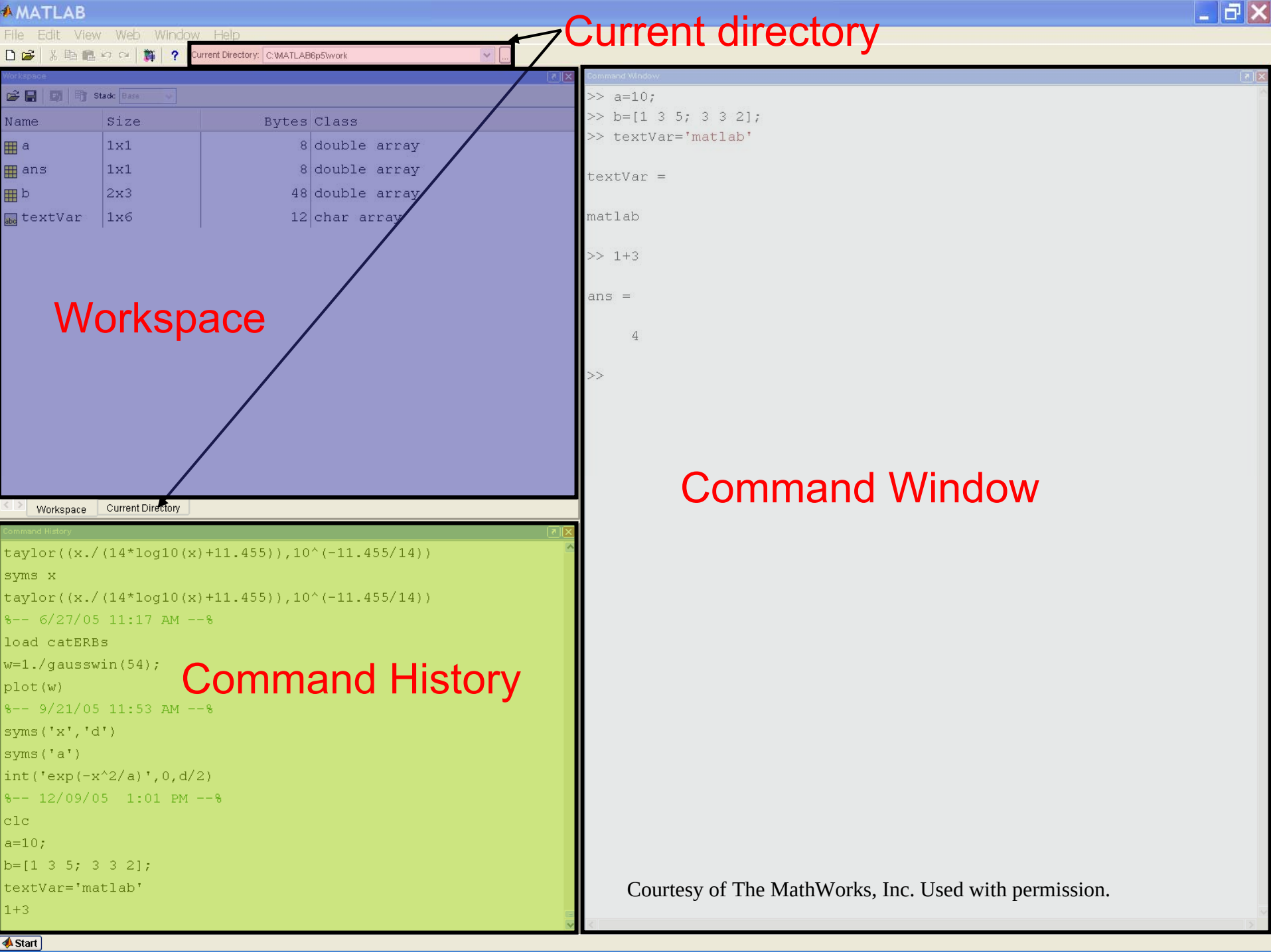
(2) Making Variables

(3) Manipulating Variables

(4) Basic Plotting

Getting Started

- To get MATLAB Student Version for yourself
  - » **https://msca.mit.edu/cgi-bin/matlab**
    - ➢ Use VPN client to enable off-campus access
    - ➢ Note: MIT certificates are required
- Open up MATLAB for Windows
    - ➢ Through the START Menu
- On Athena
  - » **add matlab**
  - » **matlab &**



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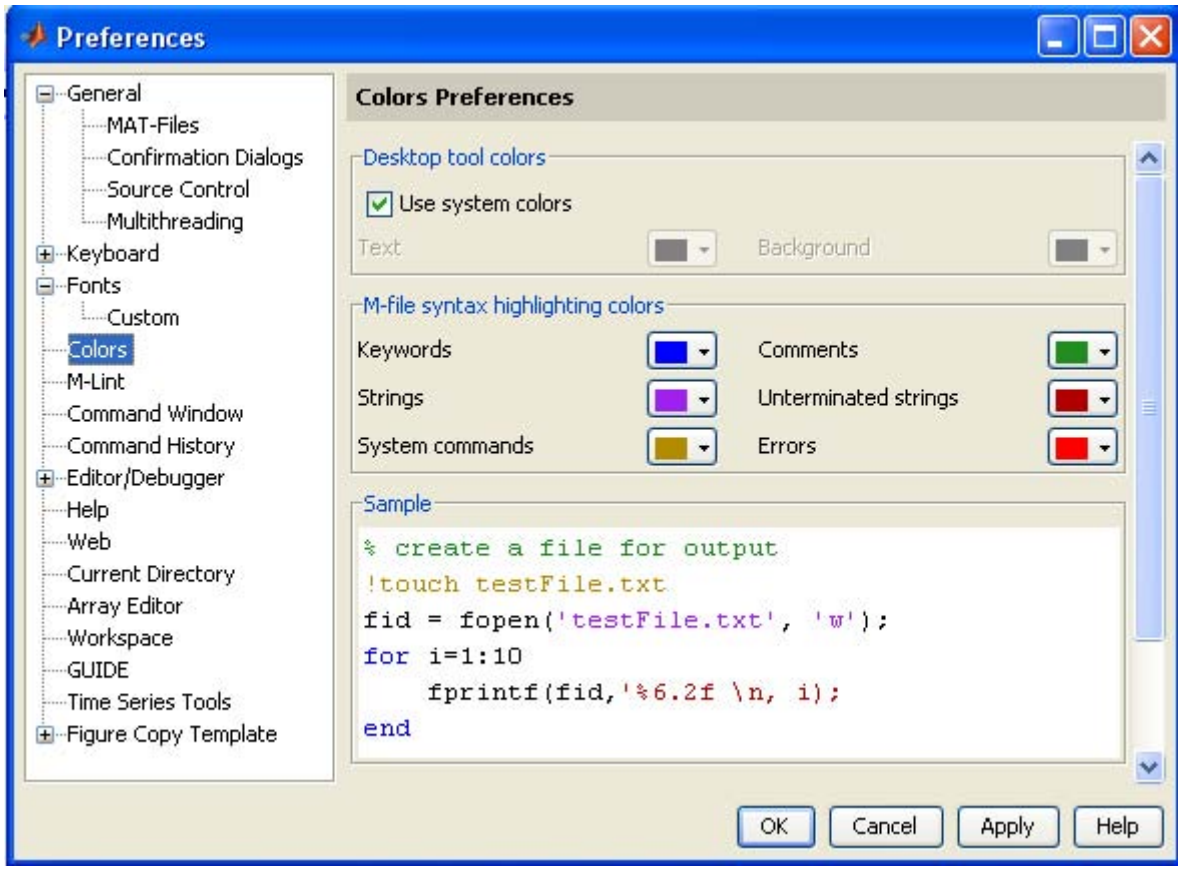
Customization

- File → Preferences
  - Allows you personalize your MATLAB experience



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MATLAB Basics

- MATLAB can be thought of as a super-powerful graphing calculator
  - Remember the TI-83 from calculus?
  - With many more buttons (built-in functions)
- In addition it is a programming language
  - MATLAB is an interpreted language, like Scheme
  - Commands executed line by line

Conversing with MATLAB

- **`who`**
  - MATLAB replies with the variables in your workspace
- **`what`**
  - MATLAB replies with the current directory and MATLAB files in the directory
- **`why`**
- **`help`**
  - **The most** important function for learning MATLAB on your own
  - More on help later

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Variable Types

- MATLAB is a weakly typed language
  - No need to initialize variables!
- MATLAB supports various types, the most often used are
  - `» 3.84`
    - 64-bit double (default)
  - `» 'a'`
    - 16-bit char
- Most variables you'll deal with will be arrays or matrices of doubles or chars
- Other types are also supported: complex, symbolic, 16-bit and 8 bit integers, etc.

Naming variables

- To create a variable, simply assign a value to a name:
  - » **`var1=3.14`**
  - » **`myString='hello world'`**

- Variable names
  - ➢ first character must be a LETTER
  - ➢ after that, any combination of letters, numbers and _
  - ➢ CASE SENSITIVE! (**`var1`** is different from **`Var1`**)

- Built-in variables
  - ➢ **`i`** and **`j`** can be used to indicate complex numbers
  - ➢ **`pi`** has the value 3.1415926…
  - ➢ **`ans`** stores the last unassigned value (like on a calculator)
  - ➢ **`Inf`** and **`-Inf`** are positive and negative infinity
  - ➢ **`NaN`** represents 'Not a Number'

Hello World

- Here are several flavors of Hello World to introduce MATLAB
- MATLAB will display strings automatically
  - » **‘Hello 6.094’**
- To remove “ans =“, use **disp()**
  - » **disp('Hello 6.094')**
- **sprintf()** allows you to mix strings with variables
  - » **class=6.094;**
  - » **disp(sprintf('Hello %g', class))**
    - ➢ The format is C-syntax

Scalars

- A variable can be given a value explicitly
  - » `a = 10`
    - ➢ shows up in workspace!
- Or as a function of explicit values and existing variables
  - » `c = 1.3*45-2*a`
- To suppress output, end the line with a semicolon
  - » `cooldude = 13/3;`

Arrays

- Like other programming languages, arrays are an important part of MATLAB
- Two types of arrays

(1) matrix of numbers (either double or complex)

(2) cell array of objects (more advanced data structure)

MATLAB makes vectors easy!
That's its power!

Row Vectors

- Row vector: comma or space separated values between brackets
  - `» row = [1 2 5.4 -6.6];`
  - `» row = [1, 2, 5.4, -6.6];`

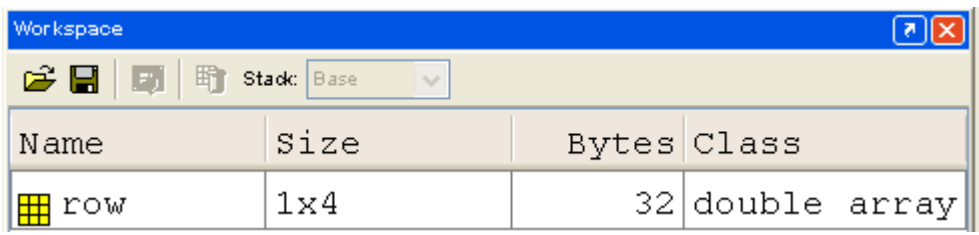
- Command window:

```
>> row=[1 2 5.4 -6.6]

row =

    1.0000    2.0000    5.4000   -6.6000
```

- Workspace:



Column Vectors

- Column vector: semicolon separated values between brackets
  - » **column = [4;2;7;4];**

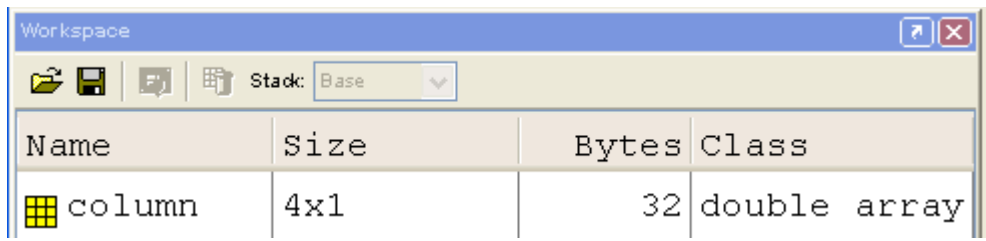
- Command window:

```
>> column=[4;2;7;4]

column =

     4
     2
     7
     4
```

- Workspace:

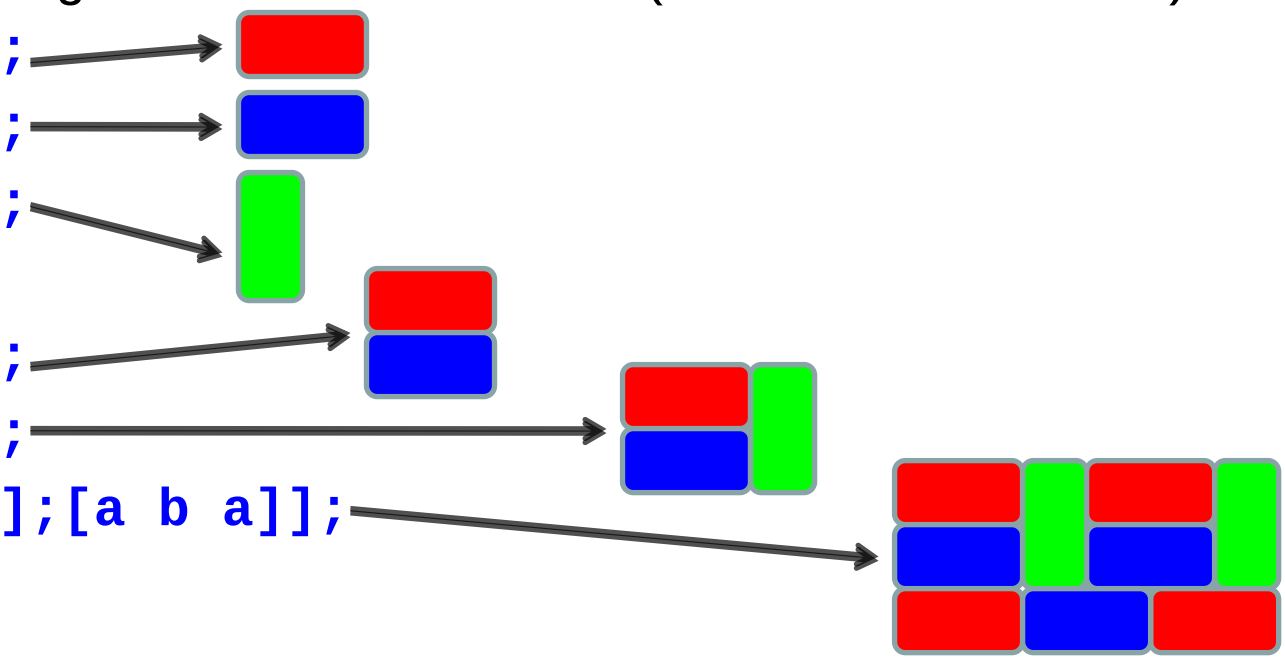


Matrices

- Make matrices like vectors
- Element by element
  - » `a= [1 2;3 4];`

$$a = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}$$

- By concatenating vectors or matrices (dimension matters)
  - » `a = [1 2];`
  - » `b = [3 4];`
  - » `c = [5;6];`
  - » `d = [a;b];`
  - » `e = [d c];`
  - » `f = [[e e];[a b a]];`



save / clear / load

- Use **save** to save variables to a file
  - » `save myfile a b`
    - ➢ saves variables a and b to the file myfile.mat
    - ➢ myfile.mat file in the current directory
    - ➢ Default working directory is
  - » `\MATLAB\work`
    - ➢ Create own folder and change working directory to it
  - » `MyDocuments\6.094\day1`

- Use **clear** to remove variables from environment
  - » `clear a b`
    - ➢ look at workspace, the variables a and b are gone

- Use **load** to load variable bindings into the environment
  - » `load myfile`
    - ➢ look at workspace, the variables a and b are back

- Can do the same for entire environment
  - » `save myenv; clear all; load myenv;`

Exercise: Variables

- Do the following 5 things:
  - Create the variable **r** as a row vector with values 1 4 7 10 13
  - Create the variable **c** as a column vector with values 13 10 7 4 1
  - Save these two variables to file **varEx**
  - clear the workspace
  - load the two variables you just created

```
» r=[1 4 7 10 13];
» c=[13; 10; 7; 4; 1];
» save varEx r c
» clear r c
» load varEx
```

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Basic Scalar Operations

- Arithmetic operations (+,-,*,/)
  - » `7/45`
  - » `(1+i)*(2+i)`
  - » `1 / 0`
  - » `0 / 0`
- Exponentiation (^)
  - » `4^2`
  - » `(3+4*j)^2`
- Complicated expressions, use parentheses
  - » `((2+3)*3)^0.1`
- Multiplication is NOT implicit given parentheses
  - » `3(1+0.7) gives an error`
- To clear cluttered command window
  - » `Clc`

Built-in Functions

- MATLAB has an **enormous** library of built-in functions

- Call using parentheses – passing parameter to function

```
» sqrt(2)
» log(2), log10(0.23)
» cos(1.2), atan(-.8)
» exp(2+4*i)
» round(1.4), floor(3.3), ceil(4.23)
» angle(i); abs(1+i);
```

Help / Docs

- To get info on how to use a function:
  - » **`help sin`**
    - ➢ Help contains related functions
- To get a nicer version of help with examples and easy-to-read descriptions:
  - » **`doc sin`**

- To search for a function by specifying keywords:
  - » **`doc`** + Search tab
  - » **`lookfor hyperbolic`**

One-word description of what you're looking for

Exercise: Scalars

- Verify that e^(i*x) = cos(x) + i*sin(x) for a few values of x.

```
» x = pi/3;
» a = exp(i*x)
» b = cos(x)+ i*sin(x)
» a-b
```

size & length

- You can tell the difference between a row and a column vector by:
  - Looking in the workspace
  - Displaying the variable in the command window
  - Using the size function

```
>> size(row)

ans =

     1     4
```

```
>> size(column)

ans =

     4     1
```

- To get a vector's length, use the length function

```
>> length(row)

ans =

     4
```

```
>> length(column)

ans =

     4
```

transpose

- The transpose operators turns a column vector into a row vector and vice versa
  - `» a = [1 2 3 4]`
  - `» transpose(a)`
- Can use dot-apostrophe as short-cut
  - `» a.'`
- The apostrophe gives the Hermitian-transpose, i.e. transposes and conjugates all complex numbers
  - `» a = [1+j 2+3*j]`
  - `» a'`
  - `» a.'`
- For vectors of real numbers `.'` and `'` give same result

Addition and Subtraction

- Addition and subtraction are element-wise; sizes must match (unless one is a scalar):

$$\begin{array}{r} \begin{bmatrix} 12 & 3 & 32 & -11 \end{bmatrix} \\ +\begin{bmatrix} 2 & 11 & -30 & 32 \end{bmatrix} \\ \hline =\begin{bmatrix} 14 & 14 & 2 & 21 \end{bmatrix} \end{array}$$

$$\begin{bmatrix} 12 \\ 1 \\ -10 \\ 0 \end{bmatrix} - \begin{bmatrix} 3 \\ -1 \\ 13 \\ 33 \end{bmatrix} = \begin{bmatrix} 9 \\ 2 \\ -23 \\ -33 \end{bmatrix}$$

- The following would give an error
  - `» c = row + column`
- Use the transpose to make sizes compatible
  - `» c = row' + column`
  - `» c = row + column'`
- Can sum up or multiply elements of vector
  - `» s=sum(row);`
  - `» p=prod(row);`

Element-Wise Functions

- All the functions that work on scalars also work on vectors
  - » `t = [1 2 3];`
  - » `f = exp(t);`
    - ➢ is the same as
  - » `f = [exp(1) exp(2) exp(3)];`

- If in doubt, check a function's help file to see if it handles vectors elementwise

- Operators (`* / ^`) have two modes of operation
  - ➢ element-wise
  - ➢ standard

Operators: element-wise

- To do element-wise operations, use the dot. BOTH dimensions must match (unless one is scalar)!
  - » **a=[1 2 3];b=[4;2;1];**
  - » **a.*b, a./b, a.^b → all errors**
  - » **a.*b', a./b', a.^(b') → all valid**

$$\begin{bmatrix}1 & 2 & 3\end{bmatrix}.*\begin{bmatrix}4\\2\\1\end{bmatrix} = ERROR$$

$$\begin{bmatrix}1\\2\\3\end{bmatrix}.*\begin{bmatrix}4\\2\\1\end{bmatrix} = \begin{bmatrix}4\\4\\3\end{bmatrix}$$

$$3\times 1 .* 3\times 1 = 3\times 1$$

$$\begin{bmatrix}1 & 1 & 1\\2 & 2 & 2\\3 & 3 & 3\end{bmatrix}.*\begin{bmatrix}1 & 2 & 3\\1 & 2 & 3\\1 & 2 & 3\end{bmatrix} = \begin{bmatrix}1 & 2 & 3\\2 & 4 & 6\\3 & 6 & 9\end{bmatrix}$$

$$3\times 3 .* 3\times 3 = 3\times 3$$

$$\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}.\wedge 2 = \begin{bmatrix}1^2 & 2^2\\3^2 & 4^2\end{bmatrix}$$

Can be any dimension

Operators: standard

- Multiplication can be done in a standard way or element-wise
- Standard multiplication (*) is either a dot-product or an outer-product
  - Remember from linear algebra: inner dimensions must MATCH!!
- Standard exponentiation (^) implicitly uses *
  - Can only be done on square matrices or scalars
- Left and right division (/ \) is same as multiplying by inverse
  - Our recommendation: just multiply by inverse (more on this later)

$$\begin{bmatrix}1 & 2 & 3\end{bmatrix} * \begin{bmatrix}4\\2\\1\end{bmatrix} = 11$$

$$1\times 3 * 3\times 1 = 1\times 1$$

$$\begin{bmatrix}1 & 2\\3 & 4\end{bmatrix} \wedge 2 = \begin{bmatrix}1 & 2\\3 & 4\end{bmatrix} * \begin{bmatrix}1 & 2\\3 & 4\end{bmatrix}$$

Must be square to do powers

$$\begin{bmatrix}1 & 1 & 1\\2 & 2 & 2\\3 & 3 & 3\end{bmatrix} * \begin{bmatrix}1 & 2 & 3\\1 & 2 & 3\\1 & 2 & 3\end{bmatrix} = \begin{bmatrix}3 & 6 & 9\\6 & 12 & 18\\9 & 18 & 27\end{bmatrix}$$

$$3\times 3 * 3\times 3 = 3\times 3$$

Exercise: Vector Operations

- Find the inner product between [1 2 3] and [3 5 4]
  - » `a=[1 2 3]*[3 5 4]'`
- Multiply the same two vectors element-wise
  - » `b=[1 2 3].*[3 5 4]`
- Calculate the natural log of each element of the resulting vector
  - » `c=log(b)`

Automatic Initialization

- Initialize a vector of **ones**, **zeros**, or **rand**om numbers
  - » **o=ones(1,10)**
    - ➢ row vector with 10 elements, all 1
  - » **z=zeros(23,1)**
    - ➢ column vector with 23 elements, all 0
  - » **r=rand(1,45)**
    - ➢ row vector with 45 elements (uniform [0,1])
  - » **n=nan(1,69)**
    - ➢ row vector of NaNs (useful for representing uninitialized variables)

The general function call is:

```
var=zeros(M,N);
```

Number of rows

Number of columns

Automatic Initialization

- To initialize a linear vector of values use **linspace**
  - » `a=linspace(0,10,5)`
    - ➢ starts at 0, ends at 10 (inclusive), 5 values
- Can also use colon operator (**:**)
  - » `b=0:2:10`
    - ➢ starts at 0, increments by 2, and ends at or before 10
    - ➢ increment can be decimal or negative
  - » `c=1:5`
    - ➢ if increment isn't specified, default is 1
- To initialize logarithmically spaced values use **logspace**
    - ➢ similar to **linspace**

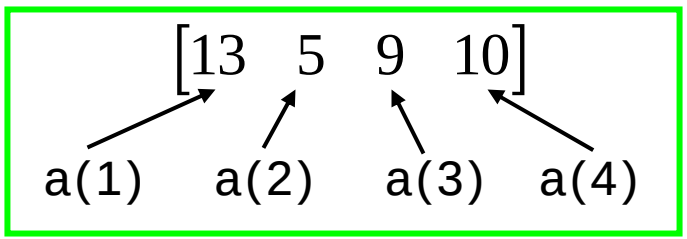
Exercise: Vector Functions

- Make a vector that has 10,000 samples of f(x) = e^{-x}*cos(x), for x between 0 and 10.

```
» x = linspace(0,10,10000);
» f = exp(-x).*cos(x);
```

Vector Indexing

- MATLAB indexing starts with 1, not 0
  - ➢ We will not respond to any emails where this is the problem.
- a(n) returns the n^{th} element

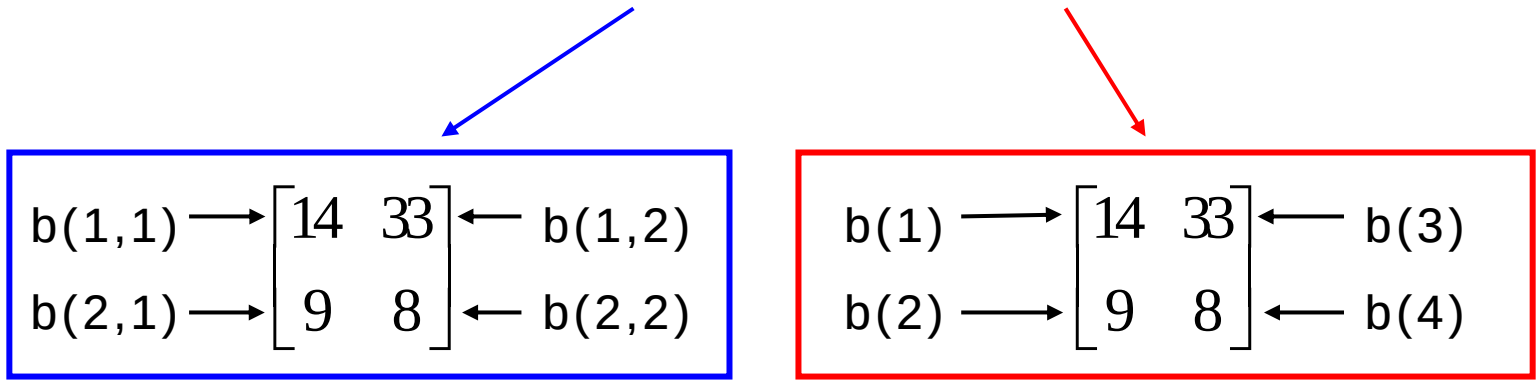


- The index argument can be a vector. In this case, each element is looked up individually, and returned as a vector of the same size as the index vector.

```
» x=[12 13 5 8];
» a=x(2:3);   ⟶  a=[13 5];
» b=x(1:end-1);   ⟶  b=[12 13 5];
```

Matrix Indexing

- Matrices can be indexed in two ways
  - using subscripts (row and column)
  - using linear indices (as if matrix is a vector)
- Matrix indexing: subscripts or linear indices



- Picking submatrices

```
» A = rand(5) % shorthand for 5x5 matrix
» A(1:3,1:2) % specify contiguous submatrix
» A([1 5 3], [1 4]) % specify rows and columns
```

Advanced Indexing 1

- The index argument can be a matrix. In this case, each element is looked up individually, and returned as a matrix of the same size as the index matrix.

```
» a=[-1 10 3 -2];
» b=a([1 2 4;3 4 2]);
```

$$\longrightarrow \quad b = \begin{bmatrix} -1 & 10 & -2 \\ 3 & -2 & 10 \end{bmatrix}$$

- To select rows or columns of a matrix, use the **:**

$$c = \begin{bmatrix} 12 & 5 \\ -2 & 13 \end{bmatrix}$$

```
» d=c(1,:);   ⟶  d=[12 5];
» e=c(:,2);   ⟶  e=[5;13];
» c(2,:)=[3 6];  %replaces second row of c
```

Advanced Indexing 2

- MATLAB contains functions to help you find desired values within a vector or matrix
  - » `vec = [1 5 3 9 7]`
- To get the minimum value and its index:
  - » `[minVal,minInd] = min(vec);`
- To get the maximum value and its index:
  - » `[maxVal,maxInd] = max(vec);`
- To find any the indices of specific values or ranges
  - » `ind = find(vec == 9);`
  - » `ind = find(vec > 2 & vec < 6);`
    - ➢ **find** expressions can be very complex, more on this later
- To convert between subscripts and indices, use **ind2sub**, and **sub2ind**. Look up help to see how to use them.

Exercise: Vector Indexing

- Evaluate a sine wave at 1,000 points between 0 and 2*pi.
- What's the value at
  - Index 55
  - Indices 100 through 110
- Find the index of
  - the minimum value,
  - the maximum value, and
  - values between -0.001 and 0.001

```
» x = linspace(0,2*pi,1000);
» y=sin(x);
» y(55)
» y(100:110)
» [minVal,minInd]=min(y)
» [maxVal,maxInd]=max(y)
» inds=find(y>-0.001 & y<0.001)
```

BONUS Exercise: Matrices

- Make a 3x100 matrix of zeros, and a vector x that has 100 values between 0 and 10
  - `» mat=zeros(3,100);`
  - `» x=linspace(0,10,100);`

- Replace the first row of the matrix with cos(x)
  - `» mat(1,:)=cos(x);`

- Replace the second row of the matrix with log((x+2)^2)
  - `» mat(2,:)=log((x+2).^2);`

- Replace the third row of the matrix with a random vector of the correct size
  - `» mat(3,:)=rand(1,100);`
- Use the sum function to compute row and column sums of mat (see help)
  - `» rs = sum(mat,2);`
  - `» cs = sum(mat); % default dimension is 1`

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Plotting Vectors

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

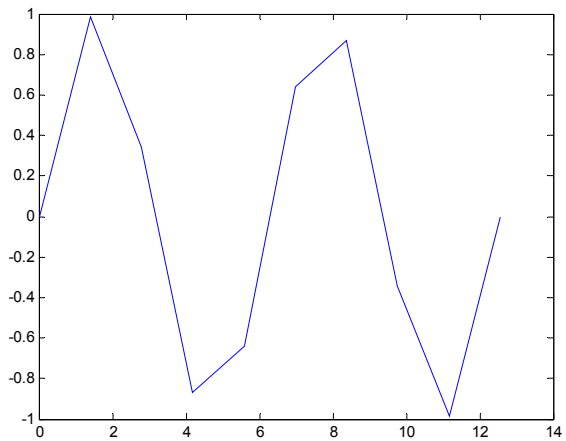
- Plot values against their index
  - » `plot(y);`
- Usually we want to plot y versus x
  - » `plot(x,y);`

MATLAB makes visualizing data fun and easy!

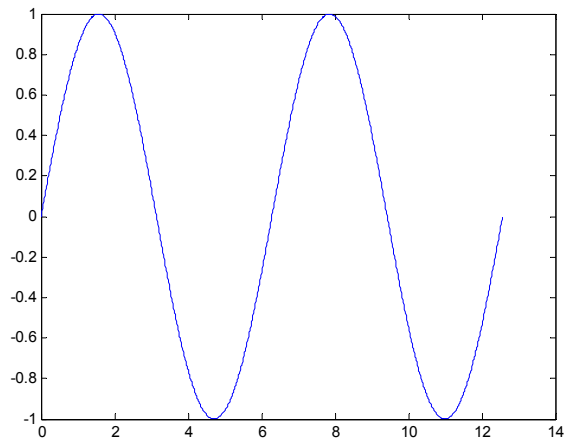
What does plot do?

- **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:



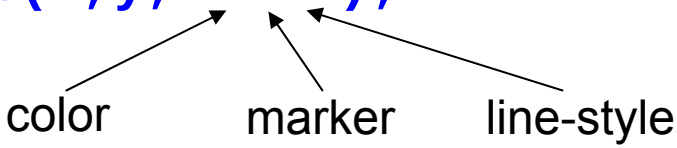
1000 x values:



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 linestyles

Other Useful plot Commands

- Much more on this in Lecture 2, for now some simple commands

- To plot two lines on the same graph
  - » `hold on;`
- To plot on a new figure
  - » `figure;`
  - » `plot(x,y);`

- Play with the figure GUI to learn more
  - add axis labels
  - add a title
  - add a grid
  - zoom in/zoom out

Exercise: Plotting

- Plot f(x) = e^x*cos(x) on the interval x = [0 10]. Use a red solid line with a suitable number of points to get a good resolution.

```
» x=0:.01:10;
» plot(x,exp(x).*cos(x),'r');
```

End of Lecture 1

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Hope that wasn't too much!!