Lecture 1
MATLAB Fundamentals: Features, Syntaxes, Concepts

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Introduction

- High-level language for technical computing
  - Integrates computation, visualization, and programming
  - Sophisticated data structures, editing and debugging tools, object-oriented programming
- MATrix LABoratory (MATLAB)
  - Highly optimized for matrix operations
  - Originally written to provide easy access to matrix software: LINPACK (linear system package) and EISPACK (eigen system package)
  - Basic element is array that does not require dimensioning
- Highly interactive, interpreted programming language
  - Development time usually significantly reduced compared to compiled languages
- ***Very*** useful graphical debugger

Outline

Overview

- Numeric Data Types
  - `single`, `double`, `int8`, `int16`, `int32`, `int64`, `uint8`, `uint16`, `uint32`, `uint64`, `NaN`, `Inf`
- Characters and strings
- Tables
- Structures
- Cell Arrays
- Function Handles
- Map Containers

Overview

- One-based indexing
- Fortran ordering (column-wise) contrary to C/C++ (row-wise)
- Array creation
  - `blkdiag`, `diag`, `eye`, `true/false`, `linspace/logspace`, `ones`, `rand`, `zeros`
- Array concatenation
  - `vertcat` ([· ; ·]), `horzcat` ([· , ·])
- Indexing/Slicing
  - Linear indexing
  - Indexing with arrays
  - Logical indexing
  - Colon operator, `end` keyword
- Reshaping/sorting
  - `fliplr`, `flipud`, `repmat`, `reshape`, `squeeze`, `sort`, `sortrows`
- Matrix vs. Elementwise Operations

Fortran Ordering

- MATLAB uses Fortran (column-wise) ordering of data
  - First dimension is fastest varying dimension

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```
>> M = reshape(linspace(11,18,8),[2,2,2])

M(:,:,1) =
     11     13
     12     14

M(:,:,2) =
     15     17
     16     18
```

11
12
13
14
15
16
17
18

Linear Indexing

- Linear storage and Fortran ordering can be used to index into array with *single* index

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```
>> M(1)
ans =
    11
>> M(8)
ans =
    18
>> M(5:8)
ans =
    15    16    17    18
>> M([1,3,4,8])
ans =
    11    13    14    18
```

Indexing with Arrays

- Arrays can be used to index/slice into arrays
  - Result is an array of the same size as the index array
  - Works with linear indexing or component-wise indexing
  - Component-wise indexing with matrices is equivalent to component-wise indexing with vectorization of matrix

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```
>> M([1,3,4,8]) % Linear indexing (array)
ans =
    11    13    14    18

>> M([1,5,2;8,3,2;7,4,6]) % Linear indexing (matrix)
ans =
    11    15    12
    18    13    12
    17    14    16
```

Indexing with Arrays (continued)

```
>> M([1,2],[2,1],[2,1]) % Component indexing (array)

ans(:,:,1) =
    17    15
    18    16
ans(:,:,2) =
    13    11
    14    12

% Component-wise matrix indexing equivalent to
% component-wise indexing with vectorized matrix
>> isequal(M([2,2;2,1],[2,1],1),...
                        M(vec([2,2;2,1]),[2,1],1))
ans =
     1
```

Logical Indexing

- Index into array based on some *boolean* array
  - Match element in boolean array with those in original array one-to-one
  - If ith entry of boolean array `true`, ith entry of original array extracted
  - Useful in extracting information from an array conditional on the content of the array
- "Linear" and component-wise available
- Much quicker than using `find` and then vector indexing

```
>> P = rand(5000);
>> tic; for i = 1:10, P(P<0.5); end; toc
Elapsed time is 6.071476 seconds.
>> tic; for i = 1:10, P(find(P<0.5)); end; toc
Elapsed time is 9.003642 seconds.
```

Logical Indexing (continued)

- Example

```
>> R = rand(5)
R =
    0.8147    0.0975    0.1576    0.1419    0.6557
    0.9058    0.2785    0.9706    0.4218    0.0357
    0.1270    0.5469    0.9572    0.9157    0.8491
    0.9134    0.9575    0.4854    0.7922    0.9340
    0.6324    0.9649    0.8003    0.9595    0.6787

>> R(R < 0.15)'
ans =
    0.1270    0.0975    0.1419    0.0357

>> isequal(R(R < 0.15),R(find(R<0.15)))
ans =
     1
```

Logical Indexing (Exercise)

```
% logical array assignment
x = linspace(0,2*pi,1000);
y = sin(2*x);

plot(x,y,'k--','linew',2); hold on;
```

- Run the above code in your MATLAB command window (or use `logarray_assign.m`)
- Plot only the values of `y = sin(2*x)` in the interval $[0, \pi/2]$ in 1 additional line of code
  - Use `plot( . , ., 'r--','linew',2);`
- Plot only the values of `sin(2*x)` in the set $\{x \in [0, 2\pi] | -0.5 < \sin(2x) < 0.5\}$ in 1 additional line of code
  - Use `plot( . , ., 'b:','linew',2);`

Reshaping Arrays

Command	Description
`reshape(X,[m n p ..])`	Returns N-D matrix, size $m \times n \times p \times \cdots$
`repmat(X,[m n p ..])`	Tiles X along N dimensional specified number of times
`fliplr(X)`	Flip matrix in left/right direction
`flipud(X)`	Flip matrix in up/down direction
`squeeze(X)`	Remove singleton dimensions

- `squeeze_ex.m`

Reshaping Arrays (continued)

- Example: `reshape`, `repmat`

```
>> N = rand(100,1);
>> size(reshape(N,...
                    [50,2]))
ans =
    50     2

>> size(reshape(N,...
                  [25,2,2]))
ans =
    25     2     2
```

```
>> size(repmat(N,[4,1]))
ans =
   400     1

>> size(repmat(N,[4,3]))
ans =
   400     3

>> size(repmat(N,...
                   [4,3,2]))
ans =
   400     3     2
```

Reshaping Arrays (continued)

- Example: `fliplr`, `flipud`, `squeeze`

```
>> A = [1,2;3,4];
>> fliplr(A)
ans =
     2     1
     4     3

>> flipud(A)
ans =
     3     4
     1     2
```

```
>> A = [1,2;3,4];
>> A(:,:,2) = [5,6;7,8];
>> size(A(1,:,:))
ans =
     1     2     2

>> size(...
        squeeze(A(1,:,:)))
ans =
     2     2
```

Matrix Operations

- MATLAB operations on numeric arrays are *matrix* operations
  - $+$, $-$, $*$, $\backslash$, $/$, $\hat{}$, etc
- Prepend . for element-wise operations
  - $.*$, $./$, $.\hat{}$, etc
- Expansion of singleton dimension not automatic
  - `bsxfun(func, A, B)`

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```
>> A = rand(2); b = rand(2,1);
>> A-b
??? Error using ==> minus
Matrix dimensions must agree.
>> bsxfun(@minus,A,b)
ans =
    0.0990   -0.2978
    0.0013    0.1894
```

Create Cell Array and Access Data

- Collection of data of *any* MATLAB type
- Additional flexibility over numeric array
  - Price of generality is storage efficiency
- Constructed with {} or `cell`
- Cell arrays are MATLAB arrays of *cell*
- Indexing
  - Cell *containers* indexed using ()
    - `c(i)` returns *i*th cell of cell array `c`
  - Cell *contents* indexed using {}
    - `c{i}` returns contents of *i*th cell of cell array `c`

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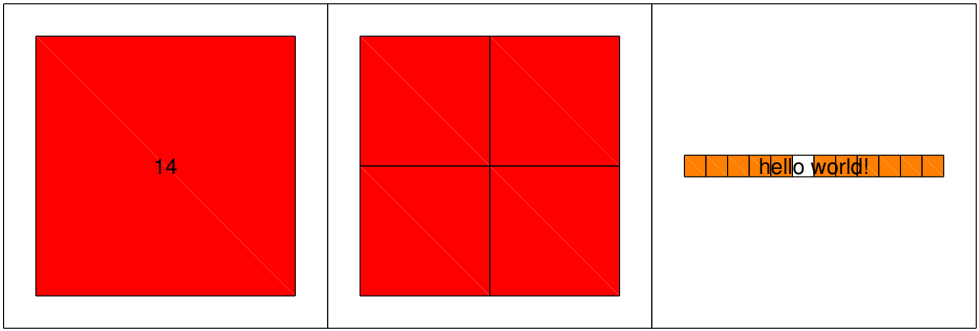
```
>> c = {14, [1,2;5,10], 'hello world!'};
>> class(c(2))
ans =
cell
>> class(c{2})
double
```

Cellplot

```
>> c = {14, [1,2;5,10], 'hello world!'}
c =
    [14]    [2x2 double]    'hello world!'
>> cellplot(c)
```



Cell Array in For Loop

- Distinction between cell *container* and cell *contents* is important
- Previous example
  - Matrix operations on `c(2)` $\Longrightarrow$ Error
  - Matrix operations on `c{2}` are valid
- Another example: using cell array in for loop

```
>> for i = c, class(i), end
```

- What is displayed?
  - `cell`

Add and Delete Data

- Adding data to cell array
  - Create/access entry with {}
  - Assign contents of container with =
- Deleting data from cell array
  - Grab cell containers with ()
  - Delete containers by assigning the value []

```
>> A = {};
>> A{1,1} = '() vs {}'; A{2,2} = 'is important'
A =
    '() vs {}'                []
              []    'is important'
>> A{1,1} = [] %Doesn't delete cell entries
A =
    []                  []
    []    'is important'
>> A(1,:) = [] % Deletes cell entries
A =
    []    'is important'
```

Combine Cell Arrays

- Like numerical arrays, cell array can be combined into a single cell array
  - `horzcat`, $[\cdot, \cdot]$
  - `vertcat`, $[\cdot; \cdot]$

```
>> A = {'cell combin','works just like'};
>> B = {'numeric array combin','yes!'};
>> [A,B]
ans =
    'cell combin'    'works just like'    [1x20 char]    'yes!'
>> [A;B]
ans =
    'cell combin'              'works just like'
    'numeric array combin'     'yes!'
```

Comma-Separated Lists via Cell Arrays

- Comma-Separated List
  - List of MATLAB objects separated by commas
  - Each item displayed individually when printed
  - Useful in passing arguments to functions and assigning output variables
  - Can be generated using {:} operator in cell array

```
>> pstr={'bo-','linewidth',2,'markerfacecolor','r'};
>> plot(1:10,pstr{:}) % Pass comma-sep list to func
```

```
>> A={[1,2;5,4],[0,3,6;1,2,6]};
>> [A{:}] % Pass comma-sep list to func
ans =
     1     2     0     3     6
     5     4     1     2     6
```

Memory Requirements

- Cell arrays require additional memory to store information describing each cell
  - Information is stored in a *header*
  - Memory required for header of single cell

```
>> c = {[]}; s=whos('c'); s.bytes
ans =
     60
```

  - Memory required for cell array
    - `(head_size x number_of_cells)+ data`
- Contents of a single cell stored contiguously
- Storage not necessarily contiguous between cells in array

Functions

Command	Description
`cell2mat`	Convert cell array to numeric array
`cell2struct`	Convert cell array to structure array
`cellfun`	Apply function to each cell in cell array
`cellstr`	Create cell array of strings from character array
`iscell`	Determine whether input is cell array
`iscellstr`	Determine whether input is cell array of strings
`mat2cell`	Convert array to cell array
`num2cell`	Convert array to cell array
`struct2cell`	Convert structure to cell array

Structures

- Like cell arrays, can hold arbitrary MATLAB data types
- Unlike cell arrays, each entry associated with a *field*
  - Field-Value relationship
- Structures can be arranged in N-D arrays: *structure arrays*
- Create structure arrays
  - `struct`
  - `<var-name>.<field-name> = <field-value>`
- Access data from structure array
  - () to access structure from array, . to access field

```
>> classes=struct('name',{'CME192','CME292'},...
                  'units',{1,1},'grade',{'P','P'});
>> classes(2)
     name: 'CME292'
    units: 1
    grade: 'P'
```

Structures (continued)

- Concatenation of structures to form structure arrays
  - `horzcat`, $[\cdot, \cdot]$
  - `vertcat`, $[\cdot; \cdot]$
- Nested structures
  - Create and access nested structure array with multiple () and . syntax

```
>> s(2).name(4).first='Your First Name';
>> s(2).name(4).last='Your Last Name'
s =
1x2 struct array with fields:
    name
```

Dynamic Field Names

- Field names not necessarily known in advance
  - Generate field names during computation

```
>> s = struct();
>> for i=1:3, s.(['P',num2str(i)]) = i; end
>> s
s =
     P1: 1
     P2: 2
     P3: 3
```

Memory Requirements

- Structs require additional memory to store information
  - Information is stored in a *header*
  - Header for entire structure array
- Each field of a structure requires contiguous memory
- Storage not necessarily contiguous between fields in structure or structures in array
- Structure of arrays faster/cheaper than array of structures
  - Contiguous memory, Memory overhead

Functions

Command	Description
`fieldnames`	Field names of structure
`getfield`	Field of structure array
`isfield`	Determine whether input is structure field
`isstruct`	Determine whether input is structure array
`orderfields`	Order fields of structure array
`rmfield`	Remove fields from structure
`setfield`	Assign values to structure array field
`arrayfun`	Apply function to each element of array
`structfun`	Apply function to each field of scalar structure

Function Handles (@)

- Callable association to MATLAB function stored in variable
  - Enables invocation of function outside its normal scope
  - Invoke function indirectly
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  - Solution of ODEs
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  - Solution of ODEs
  - Numerical Integration
- Function handles must be scalars, i.e. can't be indexed with ()

Example

- Trapezoidal rule for integration

$$\int_a^b f(x)dx \approx \sum_{i=1}^{n_{el}} \frac{b-a}{2n_{el}} \left[f(x_{i+1/2}) + f(x_{i-1/2}) \right]$$

```
function int_f = trap_rule(f,a,b,nel)

x=linspace(a,b,nel+1)';
int_f=0.5*((b-a)/nel)*sum(f(x(1:end-1))+f(x(2:end)));

end
```

```
>> a = exp(1);
>> f = @(x) a*x.^2;
>> trap_rule(f,-1,1,1000) % (2/3)*exp(1) = 1.8122
ans =
    1.8122
```

Outline

Scripts vs. Functions

- *Scripts*
  - Execute a series of MATLAB statements
  - Uses *base* workspace (does not have own workspace)
  - Parsed and loaded into memory every execution

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  - Execute a series of MATLAB statements
  - Uses *base* workspace (does not have own workspace)
  - Parsed and loaded into memory every execution
- *Functions*
  - Accept inputs, execute a series of MATLAB statements, and return outputs
  - *Local* workspace defined only during execution of function
    - `global`, `persistent` variables
    - `evalin`, `assignin` commands
  - Local, nested, private, anonymous, class methods
  - Parsed and loaded into memory during *first* execution

Anonymous Functions

- Functions without a file
  - Stored directly in function handle
  - Store expression and required variables
  - Zero or more arguments allowed
  - Nested anonymous functions permitted
- Array of function handle not allowed; function handle may return array

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```
>> f1 = @(x,y) [sin(pi*x), cos(pi*y), tan(pi*x*y)];
>> f1(0.5,0.25)
ans =
    1.0000    0.7071    0.4142
>> quad(@(x) exp(1)*x.^2,-1,1)
ans =
    1.8122
```

Local Functions

- A given MATLAB file can contain multiple functions
  - The first function is the *main* function
    - Callable from anywhere, provided it is in the search path
  - Other functions in file are *local* functions
    - Only callable from main function or other local functions in *same* file
    - Enables modularity (large number of small functions) without creating a large number of files
    - Unfavorable from code reusability standpoint

Local Function Example

Contents of `loc_func_ex.m`

```
function main_out = loc_func_ex()
main_out = ['I can call the ',loc_func()];
end

function loc_out = loc_func()
loc_out = 'local function';
end
```

Command-line

```
>> loc_func_ex()
ans =
I can call the local function

>> ['I can''t call the ',loc_func()]
??? Undefined function or variable 'loc_func'.
```

Nested Functions

- A *nested function* is a function *completely* contained within some parent function.
- Useful as an alternative to *anonymous* function that can't be confined to a single line
- Can't be defined within MATLAB control statements
  - `if`/`elseif`/`else`, `switch`/`case`, `for`, `while`, or `try`/`catch`
- Variables *sharable* between parent and nested functions
- If variable in nested function not used in parent function, it remains local to the nested function
- Multiple levels of nesting permitted
  - Nested function available from
    - Level immediately above
    - Function nested at same level with same parent
    - Function at any lower level

Nested Functions: Example

- Parent and nested function can share variables

```
function nested_ex1
x = 5;
nestfun1;
   function nestfun1
     x = x + 1;
   end
   function nestfun2
     y = 4;
   end
disp(x)   % x = 6
nestfun2
disp(y+1) % y = 5
end
```

Private Functions

- Private functions useful for limiting scope of a function
- Designate a function as `private` by storing it in a subfolder named *private*
- Only available to functions/scripts in the folder immediately above the private subfolder

Evaluate/Assign in Another Workspace

- Eval expression in other workspace (`'caller'`, `'base'`)
  - `evalin`(ws,*expression*)
  - Useful for evaluating expression in caller's workspace *without* passing name variables as function arguments
- Assign variable in other workspace (`'caller'`, `'base'`)
  - `assignin`(ws, `'var'`, val)
  - Useful for circumventing local scope restrictions of functions

Variable Number of Inputs/Outputs

- Query number of inputs passed to a function
  - `nargin`
  - Don't try to pass more than in function declaration
- Determine number of outputs requested from function
  - `nargout`
  - Don't request more than in function declaration

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```
function  [o1,o2,o3] = narginout_ex(i1,i2,i3)
fprintf('Number inputs = %i;\t',nargin);
fprintf('Number outputs = %i;\n',nargout);
o1 = i1; o2=i2; o3=i3;
end
```

```
>> narginout_ex(1,2,3);
Number inputs = 3;  Number outputs = 0;
>> [a,b]=narginout_ex(1,2,3);
Number inputs = 3;  Number outputs = 2;
```

Variable-Length Input/Output Argument List

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  - Think of `plot, get, set` and the various Name-Property pairs that can be specified in a given function call

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- All arguments prior to `varargin`/`varargout` will be matched one-to-one with calling expression

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- Remaining input/outputs will be stored in a cell array named `varargin`/`varargout`

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  - Think of `plot, get, set` and the various Name-Property pairs that can be specified in a given function call
- Use `varargin` as last function input and `varargout` as last function output for input/output argument lists to be of variable length
- All arguments prior to `varargin/varargout` will be matched one-to-one with calling expression
- Remaining input/outputs will be stored in a cell array named `varargin/varargout`
- `help varargin`, `help varargout` for more information

varargin, varargout Example

```
1 function [b,varargout] = vararg_ex(a,varargin)
2
3 b = a^2;
4 class(varargin)
5 varargout = cell(length(varargin)-a,1);
6 [varargout{:}] = varargin{1:end-a};
7
8 end
```

```
>> [b,vo1,vo2] = ...
    vararg_ex(2,'varargin','varargout','example','!');
ans =
cell
vo1 =
varargin
vo2 =
varargout
```

Publishing Scripts and Functions

- Generate view of MATLAB file in specified format
  - `publish(file,format)`
- Generate view of MATLAB file, fine-grained control
  - `publish(file,Name,Value)`, `publish(file,options)`
- By default, publishing MATLAB file runs associated code
  - Problematic when publishing functions
  - Set `'evalCode'` to `false`
  - File → Publish Configuration for <filename>

Outline

Debugger

- Breakpoint
- Step, Step In, Step Out
- Continue
- Tips/Tricks
  - Very useful!
  - Error occurs only on 10031 iteration. *How to debug?*

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  - Very useful!
  - Error occurs only on 10031 iteration. *How to debug?*
    - Conditional breakpoints
    - Try/catch
    - If statements

Profiler

- Debug and optimize MATLAB code by tracking execution time
  - Itemized timing of individual functions
  - Itemized timing of individual lines within each function
  - Records information about execution time, number of function calls, function dependencies
  - Debugging tool, understand unfamiliar file
- `profile` (`on`, `off`, `viewer`, `clear`, `-timer`)
- `profsave`
  - Save profile report to HTML format
- **Demo**: `profiler_ex.m`
- Other performance assessment functions
  - `tic`, `toc`, `timeit`, `bench`, `cputime`
  - `memory`

Outline

Performance Optimization

- Optimize the algorithm itself
- Be careful with matrices!
  - Sparse vs. full
  - Parentheses
    - `A*B*C*v`
    - `A*(B*(C*v))`
- Order of arrays matters
  - Fortran ordering: Operators with equal precedence evaluated left to right
- Vectorization
  - MATLAB highly optimized for array operations
  - Whenever possible, loops should be re-written using arrays
- Memory management
  - Preallocation of arrays
  - Delayed copy
  - Contiguous memory

Order of Arrays

- Due to Fortran ordering, indexing column-wise is much faster than indexing row-wise
  - Contiguous memory

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```
mat = ones(1000, 1000); n = 1e6;

tic();
for i=1:n, vec = mat(1,:); end
toc()

tic();
for i=1:n, vec = mat(:,1); end
toc()
```

Vectorization

Toy Example

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for t = 0:.01:10
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    y(i) = sin(t);
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Slightly less toy example

```
n = 100;
M = magic(n);
v = M(:,1);
for i = 1:n
    M(:,i) = ...
        M(:,i) - v
end
```

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n = 100;
M = magic(n);
v = M(:,1);
for i = 1:n
    M(:,i) = ...
        M(:,i) - v
end
```

Vectorized

```
n = 100;
M = magic(n);
v = M(:,1);
M=bsxfun(@minus,M,v);
```

Memory Management Functions

Command	Description
`clear`	Remove items from workspace
`pack`	Consolidate workspace memory
`save`	Save workspace variables to file
`load`	Load variables from file into workspace
`inmem`	Names of funcs, MEX-files, classes in memory
`memory`	Display memory information
`whos`	List variables in workspace, sizes and types

pack

`pack` frees up needed space by reorganizing information so that it only uses the minimum memory required. All variables from your base and global workspaces are preserved. Any persistent variables that are defined at the time are set to their default value (the empty matrix, []).

- Useful if you have a large numeric array that you *know* you have enough memory to store, but can't find enough *contiguous* memory
- Not useful if your array is too large to fit in memory

Delayed Copy

- When MATLAB arrays passed to a function, only copied to local workspace when it is *modified*
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```
1 function  b = delayed_copy_ex1(A)
2 b = 10*A(1,1);
3 end
```

```
1 function  b = delayed_copy_ex2(A)
2 A(1,1) = 5; b = 10*A(1,1);
3 end
```

```
>> A = rand(10000);
>> tic; b=delayed_copy_ex1(A); toc
Elapsed time is 0.000083 seconds.
>> tic; b=delayed_copy_ex2(A); toc
Elapsed time is 0.794531 seconds.
```

Delayed Copy

```
1 function  b = delayed_copy_ex3(A)
2 b = 10*A(1,1); disp(A); A(1,1) = 5; disp(A);
3 end
```

```
>> format debug
>> A = rand(2);
>> disp(A) % Output pruned for brevity

pr = 39cd3220

>> delayed_copy_ex3(A);  % Output pruned for brevity

pr = 39cd3220

pr = 3af96320
```

Contiguous Memory and Preallocation

- Contiguous memory
  - Numeric arrays are *always* stored in a contiguous block of memory
  - Cell arrays and structure arrays are not necessarily stored contiguously
    - The contents of a given cell or structure *are* stored contiguously

Contiguous Memory and Preallocation

- Contiguous memory
  - Numeric arrays are *always* stored in a contiguous block of memory
  - Cell arrays and structure arrays are not necessarily stored contiguously
    - The contents of a given cell or structure *are* stored contiguously
- Preallocation of contiguous data structures
  - Data structures stored as contiguous blocks of data should be preallocated instead of incrementally grown (i.e. in a loop)
  - Each size increment of such a data type requires:
    - Location of *new* contiguous block of memory able to store new object
    - Copying original object to new memory location
    - Writing new data to new memory location