Tutorial Overview

- General advice about optimization
- A typical workflow for performance optimization
- MATLAB's performance measurement tools
- Common performance issues in MATLAB and how to solve them

General Advice on Performance Optimization

- "The First Rule of Program Optimization: **Don't do it.** The Second Rule of Program Optimization (for experts only!): **Don't do it yet.**" –- *Micheal A. Jackson, 1988*

- "We should forget about small efficiencies, say about 97% of the time: **premature optimization is the root of all evil.** Yet we should not pass up our opportunities in that critical 3%. A good programmer will not be lulled into complacency by such reasoning, he will be wise to look carefully at the critical code; but only after that code has been identified" --- Donald Knuth, 1974

- ...learn to trust your instruments. If you want to know how a program behaves, **your best bet is to run it and see what happens**" --- Carlos Bueno, 2013

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Design and write the program
- Test to make sure that it works as designed / required
- Don't pay “undue” attention to performance at this stage.

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Run and time the program
- Be sure to try a typical workload, or a range of workloads if needed.
- Compare your results with you goals/requirements. If it is “fast enough”, you are done!

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Detailed measurement of execution time, typically line-by-line
- Use these data to identify “hotspots” that you should focus on

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Focus on just one "hotspot"
- Diagnose and fix the problem, if you can

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- You just made some changes to a working program, make sure you did not break it!

A typical optimization workflow

```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Run and time the program, as before.

A typical optimization workflow

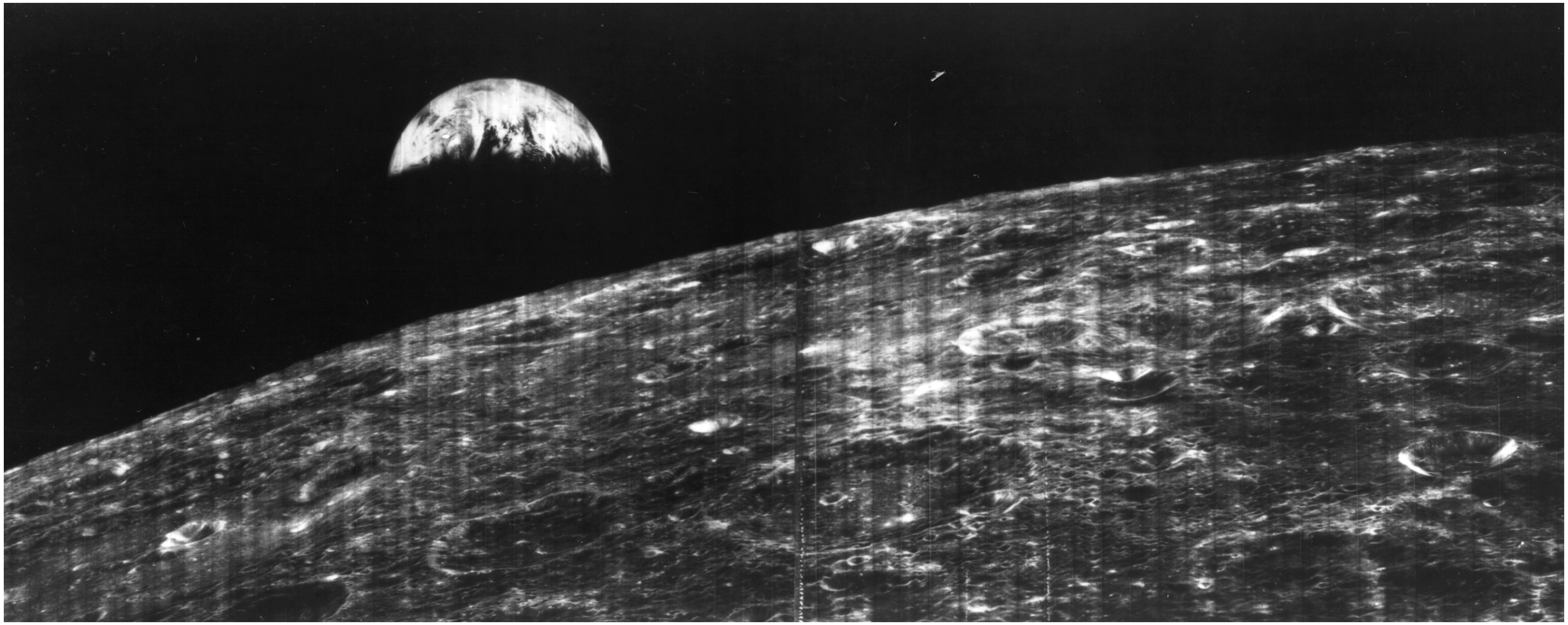
```
create
measure
while goals not met
    profile
    modify
    test
    measure
end while
```

- Repeat until your performance goals are met

Tools to measure performance

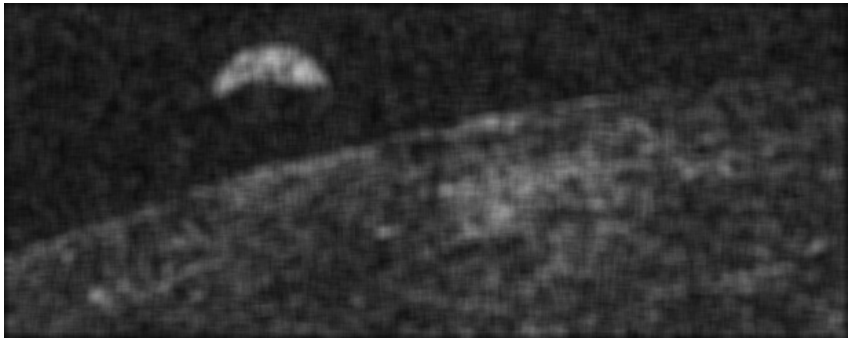
- `tic` and `toc`
  - Simple timer functions (CPU time)
- `timeit`
  - Runs/times repeatedly, better estimate of the mean run time, for functions only
- `profile`
  - Detailed analysis of program execution time
  - Measures time (CPU or wall) and much more
- MATLAB Editor
  - Code Analyzer (Mlint) warns of many common issues

Example: sliding window image smoothing



Original: first view of the earth from the moon, NASA Lunar Orbiter 1, 1966

Input: downsampled, with gaussian noise



Output: smoothed with 9x9 window

Where to Find Performance Gains ?

- Serial Performance
  - Eliminate unnecessary work
  - Improve memory use
  - Vectorize (eliminate loops)
  - Compile (MEX)
- Parallel Performance
  - "For-free" in many built-in MATLAB functions
  - Explicit parallel programming using the Parallel computing toolbox

Unnecessary work (1): redundant operations*

Avoid redundant operations in loops:

bad

```
for i=1:N
   x = 10;
     .
     .
end
```

good

```
x = 10;
for i=1:N
     .
     .
end
```

Unnecessary work (2): reduce overhead

..from function calls

bad

```
function myfunc(i)
  % do stuff
end

for i=1:N
   myfunc(i);
end
```

good

```
function myfunc2(N)
   for i=1:N
      % do stuff
   end
end


myfunc2(N);
```

..from loops

bad

```
for i=1:N
    x(i) = i;
end
for i=1:N
    y(i) = rand();
end
```

good

```
for i=1:N
    x(i) = i;
    y(i) = rand();
end
```

Unnecessary work (3): logical tests

Avoid unnecessary logical tests...

...by using short-circuit logical operators

bad

```
if (i == 1 | j == 2) & k == 5
   % do something
end
```

good

```
if (i == 1 || j == 2) && k == 5
   % do something
end
```

...by moving known cases out of loops

bad

```
for i=1:N
   if i == 1
      % i=1 case
   else
      % i>1 case
   end
end
```

good

```
% i=1 case
for i=2:N
      % i>1 case
end
```

Unnecessary work (4): reorganize equations*

Reorganize equations to use fewer or more efficient operators

Basic operators have different speeds:

```
Add          3- 6 cycles
Multiply     4- 8 cycles
Divide       32-45 cycles
Power, etc  (worse)
```

bad

```
c = 4;
for i=1:N
   x(i)=y(i)/c;
   v(i) = x(i) + x(i)^2 + x(i)^3;
   z(i) = log(x(i)) * log(y(i));
end
```

good

```
s = 1/4;
for i=1:N
   x(i) = y(i)*s;
   v(i) = x(i)*(1+x(i)*(1+x(i)));
   z(i) = log(x(i) + y(i));
end
```

Unnecessary work (5): avoid re-interpreting code

MATLAB improves performance by interpreting a program only once, unless you tell it to forget that work by running “clear all”

Value of ItemType	Items Cleared							
	Variables in scope	Scripts and functions	Class definitions	Persistent variables	MEX functions	Global variables	Import list	Java classes on the dynamic path
all	✓	✓		✓	✓	✓	From command prompt only	
variables	✓							

MATLAB a run faster the 2nd time

Functions are typically faster than scripts (not to mention better in all other ways

Vectorize*

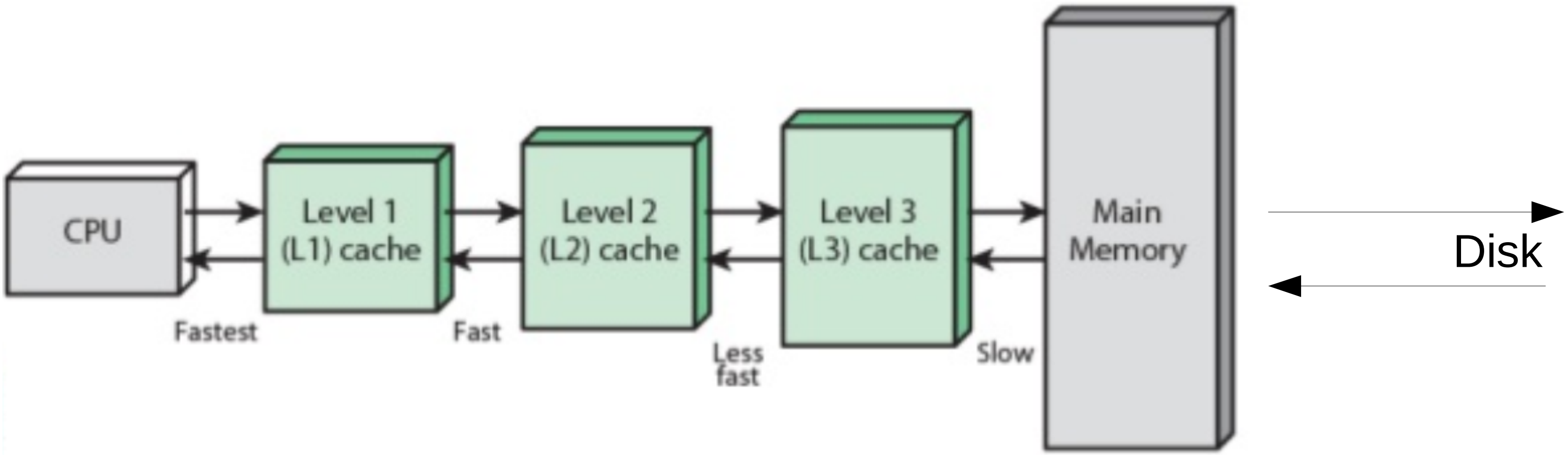
Vectorization is the process of making your code work on array-structured data in parallel, rather than using for-loops.

This can make your code much faster since vectorized operations take advantage of low level optimized routines such as LAPACK or BLAS, and can often utilize multiple system cores.

There are many tools and tricks to vectorize your code, a few important options are:

- Using built-in operators and functions
- Working on subsets of variables by slicing and indexing
- Expanding variable dimensions to match matrix sizes

Memory (1): the memory hierarchy



To use memory efficiently:

- Minimize disk I/O
- Avoid unnecessary memory access
- Make good use of the cache

Memory (2): preallocate arrays

- Arrays are always allocated in **contiguous** address space
- If an array changes size, and runs out of contiguous space, it must be moved.

```
x = 1;
for i = 2:4
   x(i) = i;
end
```

- This can be very very bad for performance when variables become large

Memory Address	Array Element
1	x(1)
…	…
2000	x(1)
2001	x(2)
2002	x(1)
2003	x(2)
2004	x(3)
…	…
10004	x(1)
10005	x(2)
10006	x(3)
10007	x(4)

Memory (3): preallocate arrays, cont.*

- Preallocating array to its maximum size prevents intermediate array movement and copying

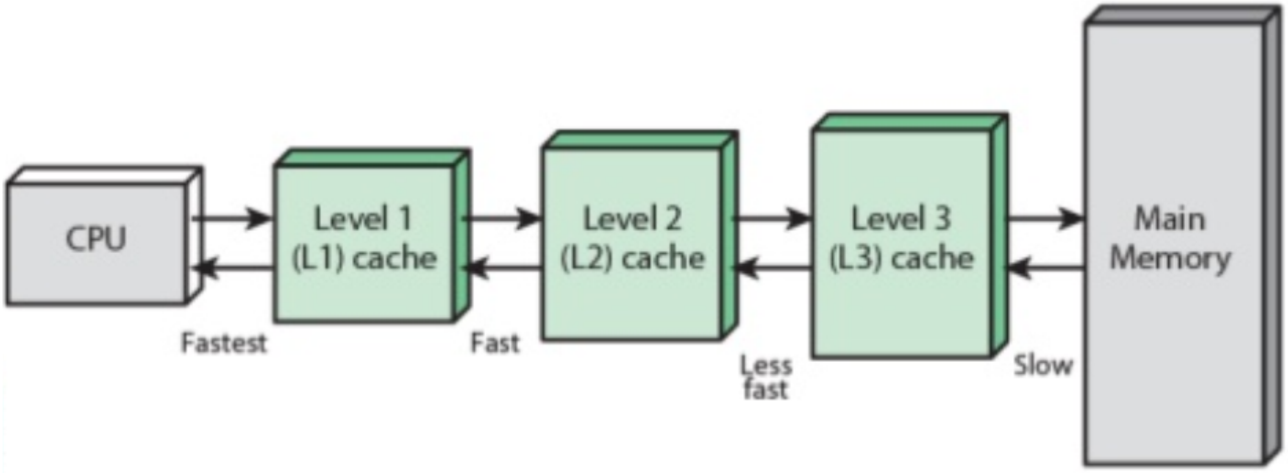
```
A = zeros(n,m); % initialize A to 0
A(n,m) = 0;     % or touch largest element
```

- If maximum size is not known apriori, estimate with upperbound. Remove unused memory after.

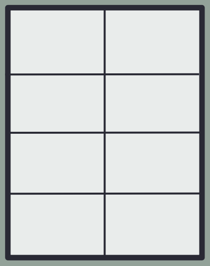
```
A=rand(100,100);
% . . .
% if final size is 60x40, remove unused portion
A(61:end,:)=[]; A(:,41:end)=[];  % delete
```

Memory (4): cache and data locality

- Cache is much faster than main memory (RAM)
- Cache hit: required variable is in cache, fast
- Cache miss: required variable not in cache, slower
- Long story short: **faster to access contiguous data**



Memory (5): cache and data locality, cont.



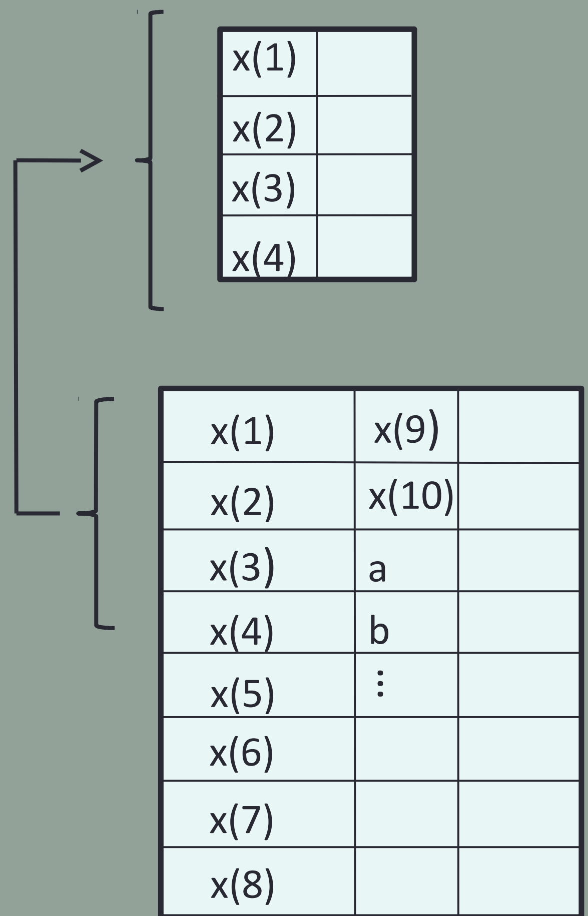
"mini" cache
holds 2 lines, 4 words each

```
for i = 1:10
      x(i) = i;
end
```

x(1)	x(9)	
x(2)	x(10)	
x(3)	a	
x(4)	b	
x(5)	⋮	
x(6)		
x(7)		
x(8)		

Main memory

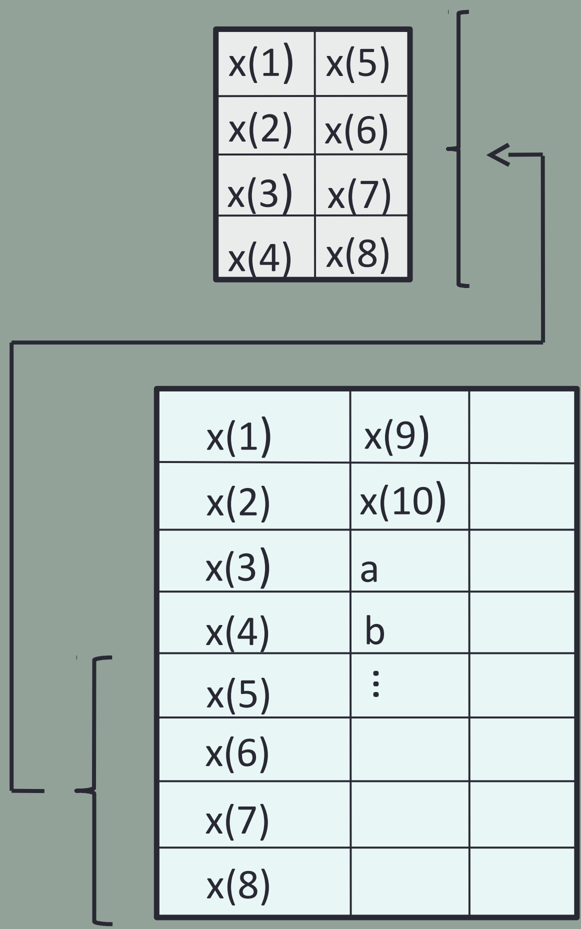
Memory (6): cache and data locality, cont.



- **ignore i for simplicity**
- **need x(1), not in cache, cache miss**
- **load line from memory into cache**
- **next 3 loop indices result in cache hits**

```
for i=1:10
    x(i) = i;
end
```

Memory (7): cache and data locality, cont.

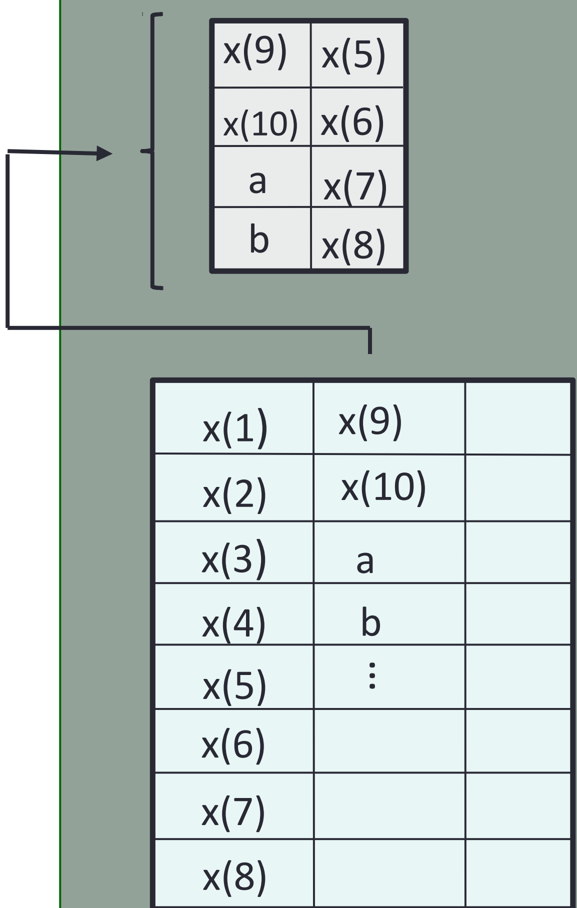


need x(5), not in cache, cache miss

- **load line from memory into cache**
- **free ride next 3 loop indices, cache hits**

```
for i = 1:10
    x(i) = i;
end
```

Memory (8): cache and data locality, cont.



- need x(9), not in cache --> cache miss
- load line from memory into cache
- no room in cache, replace old line

```
for i=1:10
    x(i) = i;
end
```

Memory (9): for-loop order*

- Multidimensional arrays are stored in memory along columns (column-major)
- Best if inner-most loop is for array left-most index, etc.

bad

```
n=5000; x = zeros(n);
for i = 1:n          % rows
   for j = 1:n       % columns
     x(i,j) = i+(j-1)*n;
   end
end
```

good

```
n=5000; x = zeros(n);
for j = 1:n          % columns
   for i = 1:n       % rows
     x(i,j) = i+(j-1)*n;
   end
end
```

Memory (10): avoid creating unnecessary variables

Avoid time needed to allocate and write data to main memory.

Compute and save array in-place improves performance and reduces memory usage

bad

```
x = rand(5000);
y = x.^2;
```

good

```
x = rand(5000);
x = x.^2;
```

Caveat: May not be work if the data type or size changes – these changes can force reallocation or disable JIT acceleration