# Performance Analysis of Matlab Code

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```
tic;
nsize = 10000;
for k = 1:nsize
    B(k) = sum( A(:,k) );
end
toc;
```

## Overview

- Why should we optimize the **Matlab** code?
- When should we optimize **Matlab** code?
- What can we do with the optimization of the **Matlab** code?
- **Profiling** and **benchmark** Matlab applications
- **General** techniques for performance tuning
- Some **Matlab-specific** optimization techniques
- Remarks on using Matlab on **LSU HPC** and **LONI** clusters
- Further reading

# Why should we optimize the Matlab code?

- Matlab has broad applications in a variety of disciplines: engineering, science, applied maths, and economics;
- Matlab makes programming **easier** compared to others;
- It supports plenty of **builtin** functions (math functions, matrix operations, FFT, etc);
- Matlab is both a **scripting** and **programming** language;
- Newer version focuses on **Just-In-Time** (**JIT**) engine for **compilation**;
- Interfacing with other languages: Fortran, C, Perl, Java, etc;
- In some case, Matlab code may suffer more performance **penalties** than other languages;
- Optimization means **(1)** increase **FLOPs** per second. **(2)** make those that are impossible possible;

## When should we optimize Matlab code?

- The first thing is to make your code work to some extent;
- Debug and test your code to produce **correct** results, even it runs slowly;
- While the correct results are **maintained**, if necessary, try to optimize it and improve the performance;
- **Optimization** includes **(1)** adopting a better algorithm, **(2)** to implement the algorithm, data and loop structures, array operations, function calls, etc, **(3)** how to parallelize it;
- Write the code in an **optimized** way at the beginning;
- Optimization may or may not be a **post-processing** procedure;
- In some cases, we won't be able to get anywhere if we don't do it right: make impossible **possible**;

# What to do with optimization of Matlab code?

- Most **general** optimization techniques applied;
- In addition, there are some techniques that are **unique** to Matlab code;
- Identify where the **bottlenecks** are (**hot spots**);
    - Data structure;
    - CPU usage;
    - Memory and cache efficiency;
    - Input/Output (I/O);
    - Builtin functions;
- Though we cannot directly control the performance of **builtin** functions, we have different options to choose a better one;
- Let Matlab use **JIT** engine as much as possible;

## Profiling and benchmark Matlab applications

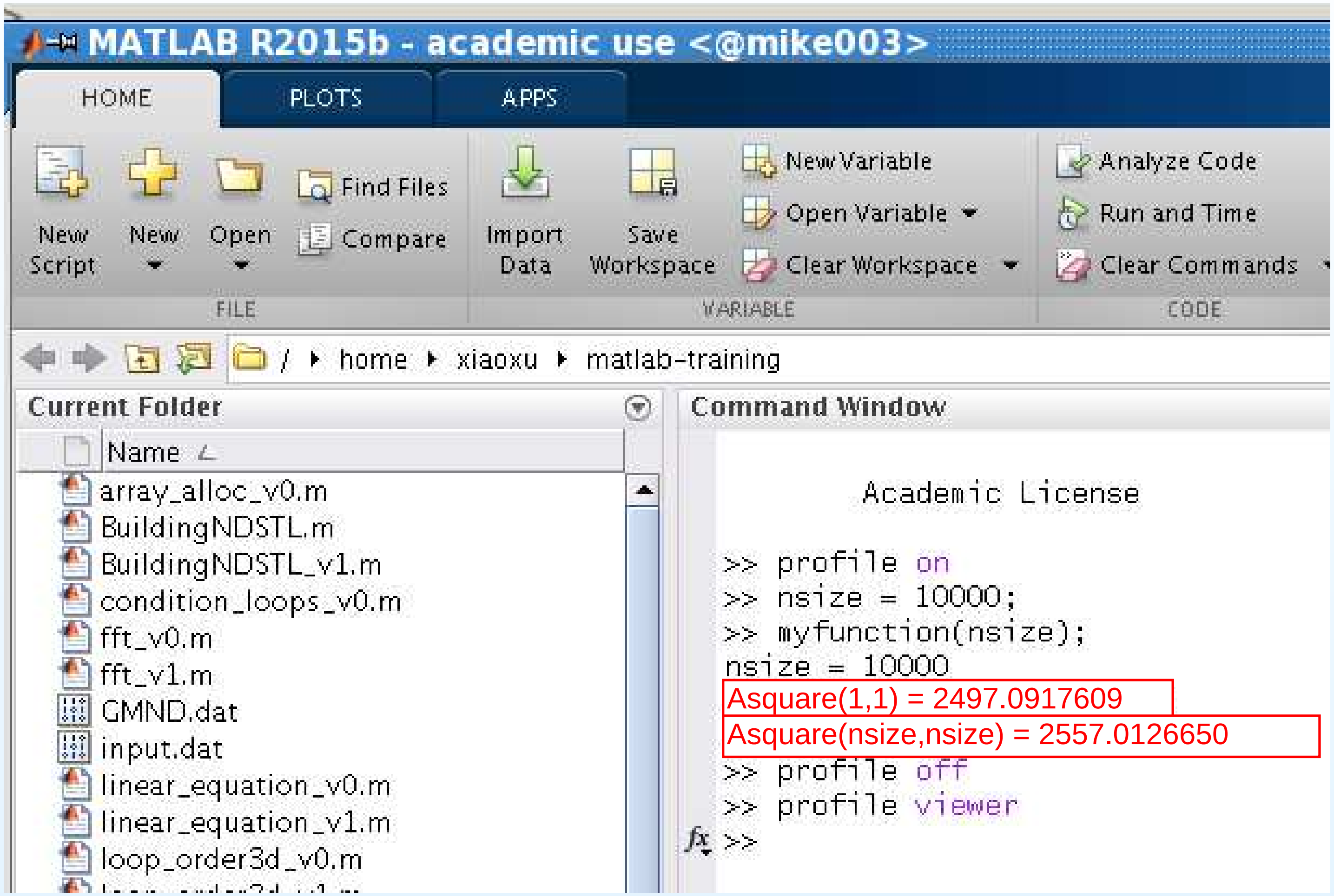
- Overall **wall-clock** time can be obtained from the job log, but this might not be what we want;
- Matlab 5.2 (R10) or higher versions provide a builtin **profiler**:

```
$ matlab
$ matlab -nosplash % don't display logo
$ matlab -nodesktop -nosplash    % turn desktop off
$ matlab -nodesktop -nosplash -nojvm  % java engine off
```

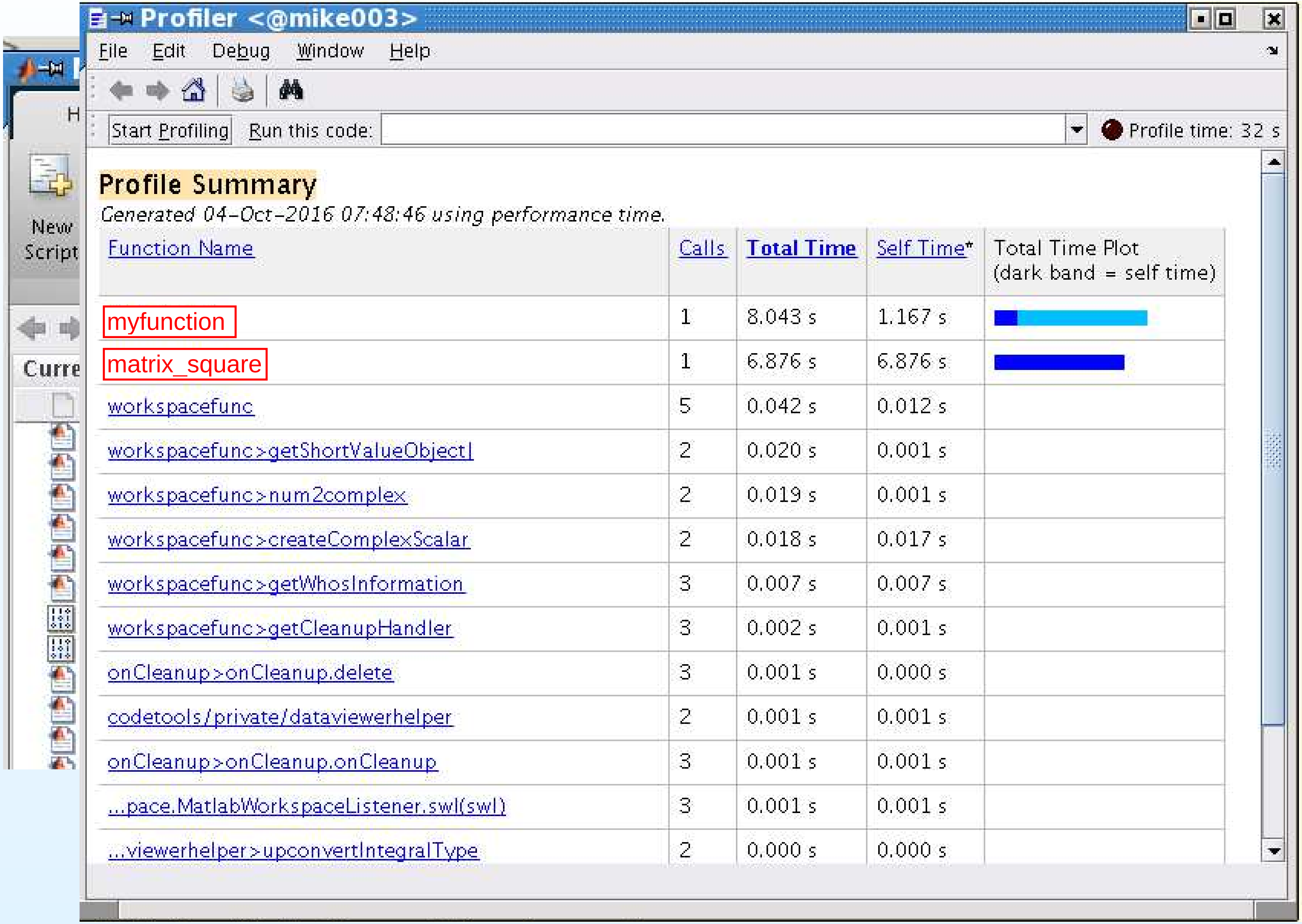
- On a matlab terminal, let's run

```
>> profile on              # turn the profiler on
>> nsize = 10000;
>> myfunction(nsize);      # call a function
>> profile off             # turn the profiler off
>> profile viewer          # A GUI report
```

# Profiling and benchmark Matlab applications

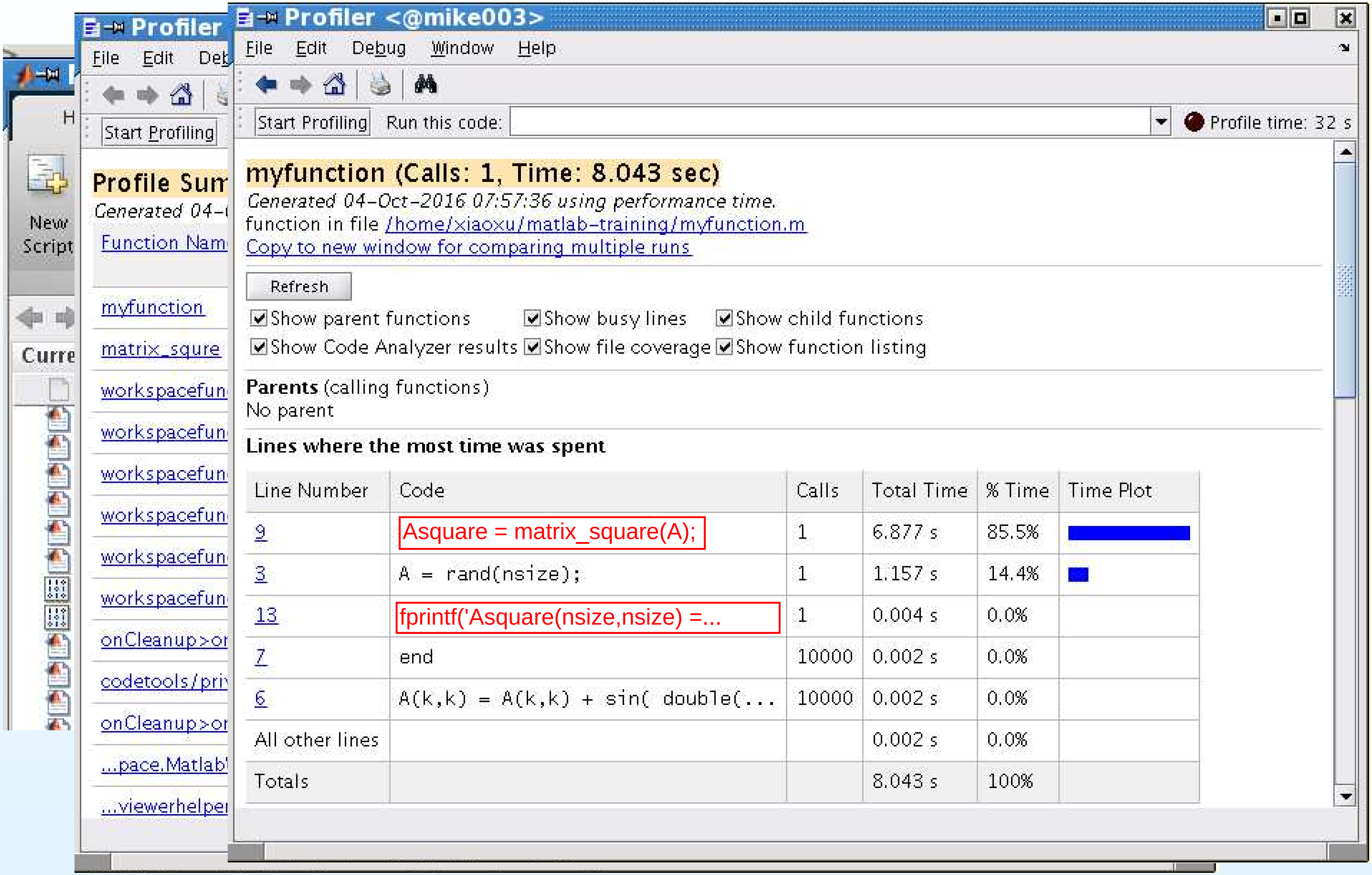


# Profiling and benchmark Matlab applications




| Function Name | Calls | Total Time | Self Time* | Total Time Plot (dark band = self time) |
|---|---|---|---|---|
| myfunction | 1 | 8.043 s | 1.167 s | |
| matrix_square | 1 | 6.876 s | 6.876 s | |
| workspacefunc | 5 | 0.042 s | 0.012 s | |
| workspacefunc>getShortValueObjectJ | 2 | 0.020 s | 0.001 s | |
| workspacefunc>num2complex | 2 | 0.019 s | 0.001 s | |
| workspacefunc>createComplexScalar | 2 | 0.018 s | 0.017 s | |
| workspacefunc>getWhosInformation | 3 | 0.007 s | 0.007 s | |
| workspacefunc>getCleanupHandler | 3 | 0.002 s | 0.001 s | |
| onCleanup>onCleanup.delete | 3 | 0.001 s | 0.000 s | |
| codetools/private/dataviewerhelper | 2 | 0.001 s | 0.001 s | |
| onCleanup>onCleanup.onCleanup | 3 | 0.001 s | 0.001 s | |
| ...pace.MatlabWorkspaceListener.swl(swl) | 3 | 0.001 s | 0.001 s | |
| ...viewerhelper>upconvertIntegralType | 2 | 0.000 s | 0.000 s | |

# Profiling and benchmark Matlab applications



# Profiling and benchmark Matlab applications

- The profiler sorts **time elapsed** for all functions, and reports the number of calls, the **time-consuming** lines and block;
- Time is reported in both percentage and absolute value;
- It is not required to modify your code;
- A simple and efficient way to use the builtin functions: **tic** and **toc** (elapsed time in **seconds**);

```
...... ;      % initialize the array
tic;          % start timer at 0
nsize = ......;
for k = 1:nsize
    vectora(k,1) = matrix_b(k,5) + matrix_c(k,3);
end
toc;     % stop timer
Elapsed time is 18.309452 seconds.
```

## Profiling and benchmark Matlab applications

- **tic/toc** can be used to measure elapsed time in a more complicated way;
- Let's consider two nested loops: how to measure the **outer** and **inner** loops separately:

```
nsize = 3235;
A=rand(nsize); b=rand(nsize,1); c=zeros(nsize,1);
tic;
for i = 1:nsize    % outer loop
    A(i,i) = A(i,i) - sum(sum(A));
for j = 1:nsize    % inner loop
    c(i,1) = c(i,1) + A(i,j)*b(j,1);
end
end
toc;
```

tictoc_loops_v0.m

# Profiling and benchmark Matlab applications

- **tic/toc** can be used to measure elapsed time in a more complicated way:

```
timer_inner = 0; timer_outer = 0;
for i = 1:nsize    % outer loop
    tic;
    A(i,i) = A(i,i) - sum(sum(A));
    timer_outer = timer_outer + toc;
    tic;
for j = 1:nsize    % inner loop
    c(i,1) = c(i,1) + A(i,j)*b(j,1);
end
    timer_inner = timer_inner + toc;
end
fprintf('Inner loop %f seconds\n', timer_inner);
fprintf('Outer loop %f seconds\n', timer_outer);
```

tictoc_loops_v1.m

# General techniques for performance tuning

- We discuss some **general** aspects of optimization techniques that are applied to **Matlab** and **other** codes;
- It is mostly about loop-level optimization:
  - Hoist **index-invariant** code segments outside of loops.
  - Avoid unnecessary computation.
  - Nested loops and change loop **orders**.
  - Optimize the **data structure** if necessary.
  - Loop merging/split (unrolling).
  - Optimize **branches** in loops.
  - Use **inline** functions.
  - Spatial and temporal **data locality**.

## General techniques for performance tuning

- Hoist **index-invariant** code segments outside of loops;
- Consider the same code tictoc_loops_v1.m and then _v2.m:

```
timer_inner = 0; timer_outer = 0;
for i = 1:nsize    % outer loop
    tic;
    A(i,i) = A(i,i) - sum(sum(A));
    timer_outer = timer_outer + toc;
    tic;
for j = 1:nsize    % inner loop
    c(i,1) = c(i,1) + A(i,j)*b(j,1);
end
    timer_inner = timer_inner + toc;
end
fprintf('Inner loop %f seconds\n', timer_inner);
fprintf('Outer loop %f seconds\n', timer_outer);
```

tictoc_loops_v1.m

## General techniques for performance tuning

- Hoist **index-invariant** code segments outside of loops;
- Consider the same code tictoc_loops_v1.m and then _v2.m:

```
timer_inner = 0; timer_outer = 0;
for i = 1:nsize    % outer loop
    tic;
    A(i,i) = A(i,i) - sum(sum(A));    % out of the loop
    timer_outer = timer_outer + toc;
    tic;                              tictoc_loops_v2.m
for j = 1:nsize    % inner loop
    c(i,1) = c(i,1) + A(i,j)*b(j,1);
end
    timer_inner = timer_inner + toc;
end
fprintf('Inner loop %f seconds\n', timer_inner);
fprintf('Outer loop %f seconds\n', timer_outer);
```

## General techniques for performance tuning

- Hoist **index-invariant** code segments outside of loops;
- Consider the same code tictoc_loops_v1.m and then _v2.m:
- tictoc_loops_v1.m:

```
>> The time elapsed for inner loop is 0.926248 s.
>> The time elapsed for outer loop is 5.810867 s.
>> The total time is 6.769521 s.
```

- tictoc_loops_v2.m:

```
>> The time elapsed for inner loop is 0.488543 s.
>> The time elapsed for outer loop is 0.002263 s.
>> The total time is 0.521508 s.
```

- The overall speedup is $13\times$: we only touched the **outer** loop;
- Why does it affect the **inner** loop in a **positive** way?
- How can we optimize the inner loop?

## Avoid unnecessary computation

- This might be attributed to reengineering your algorithms:
- Let's consider a vector operation: $\boldsymbol{v}_{\text{out}} = \exp\left(i\boldsymbol{z}_1\right)\exp\left(i\boldsymbol{z}_2\right)$

```
nsize = 8e+6;
......;
cvector_inp_1 = complex(vector_zero,vector_inp_1);
cvector_inp_2 = complex(vector_zero,vector_inp_2);
for i = 1:nsize
  cvector_out_1(i,1) = exp( cvector_inp_1(i,1) ) ;
end
for i = 1:nsize
  cvector_out_2(i,1) = exp( cvector_inp_2(i,1) ) ;
end
 cvectort_out_3 = cvector_out_1 .* cvector_out_2 ;
```

avoid_unness_v0.m

```
>> Elapsed time is 2.303156 s.
```

## Avoid unnecessary computation

- This might be attributed to reengineering your algorithms:
- Let's consider a vector operation: $v_{\text{out}} = \exp(iz_1)\exp(iz_2)$

avoid_unness_v1.m

```
nsize = 8e+6;
...;
vector_out_real = zeros(nsize,1);
vector_out_imag = zeros(nsize,1);
vector_inp_3 = zeros(nsize,1);
vector_inp_3 = vector_inp_1 + vector_inp_2;
for i = 1:nsize
  vector_out_real(i,1) = cos( vector_inp_3(i,1) );
  vector_out_imag(i,1) = sin( vector_inp_3(i,1) );
end
```

```
>> Elapsed time is 0.835313 s.
```

$\mathbf{2.8}\times$

## Nested loops and change loop orders

- Consider a very simple case: sum over all matrix elements:

loop_order_v0.m

```
a = rand(4000,6000);
n = size(a,1);
m = size(a,2);
tic;
total = 0.0;
for inrow = 1:n
for incol = 1:m
    total = total + a(inrow,incol); % row-wise sum
end
end
```

```
>> Elapsed time is 0.700789 s.
```

# Nested loops and change loop orders

- Consider a very simple case: sum over all matrix elements:

loop_order_v1.m

```
a = rand(4000,6000);
n = size(a,1);
m = size(a,2);
tic;
total = 0.0;
for incol = 1:m
for inrow = 1:n          % two loops were swapped
 total = total + a(inrow,incol); % column-wise sum
end
end
```

```
>> Elapsed time is 0.317501 s.
```

$2.2\times$

- In matlab, multi-dimensional arrays are stored in **column wise** (same as **Fotran**); What happens to `sum(sum(a))`?

## Nested loops and change loop orders

- Let's consider the problem of string vibration with the fixed ends: $\partial^2 u/\partial t^2 = c^2\, \partial^2 u/\partial x^2$, $x \in [0, a]$ and $t \in [0, T]$;
- Initial conditions: $u(x, 0) = \sin(\pi x)$, $\partial u(x, 0)/\partial t = 0$;
- Boundary conditions: $u(0, t) = u(a, t) = 0$.
- Finite differences in both spatial and temporal coordinates;
- $x_i = i\Delta x$ and $t_k = k\Delta t$ lead to $u(x_i, t_k) = u_{ik}$;

$$\frac{\partial^2 u(x_i, t_k)}{\partial x^2} \simeq \frac{1}{\Delta x^2}[u_{i+1,k} - 2u_{i,k} + u_{i-1,k}], \quad (1)$$

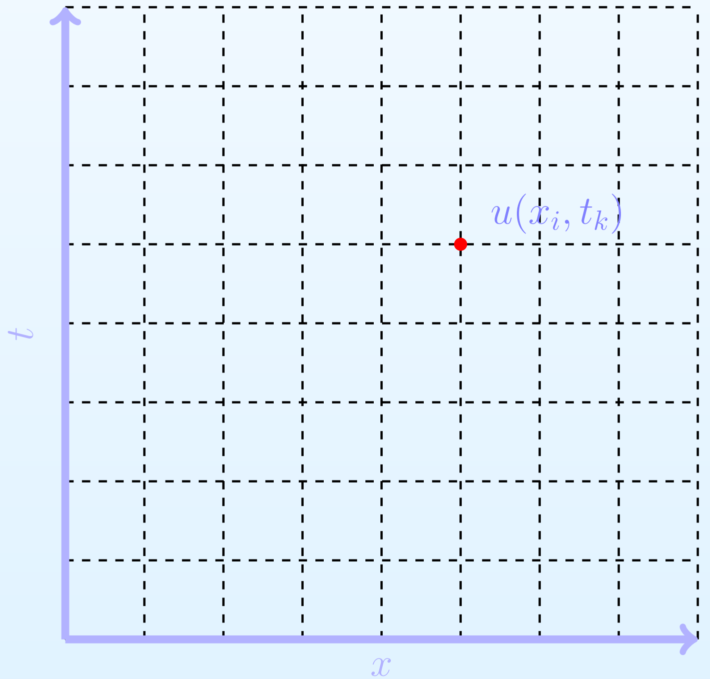
$$\frac{\partial^2 u(x_i, t_k)}{\partial t^2} \simeq \frac{1}{\Delta t^2}[u_{i,k+1} - 2u_{i,k} + u_{i,k-1}], \quad (2)$$

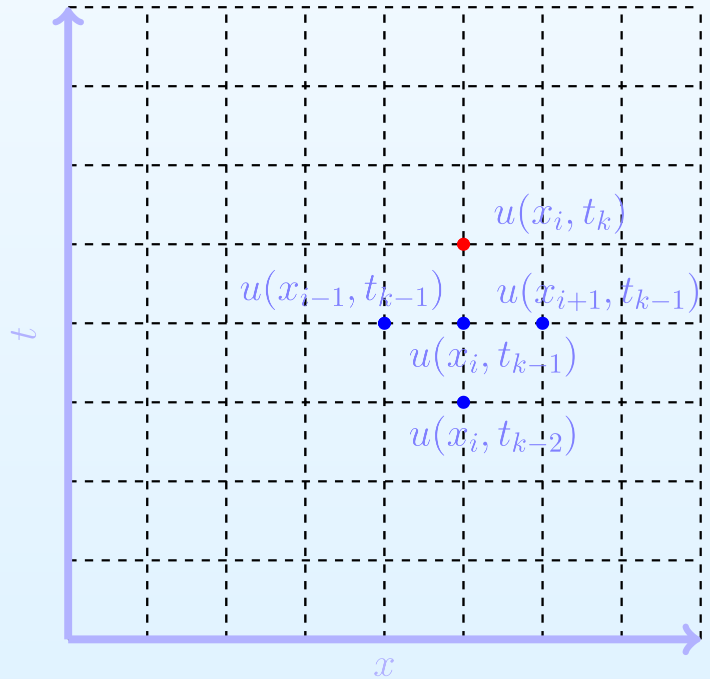
$$u_{i,k+1} = f u_{i+1,k} + 2(1 - f)u_{i,k} + f u_{i-1,k} - u_{i,k-1}, \quad (3)$$

and $f = (c\Delta t/\Delta x)^2$.

# Nested loops and change loop orders

- Let's consider the problem of string vibration with the fixed ends: $\partial^2 u/\partial t^2 = c^2\ \partial^2 u/\partial x^2$, $x \in [0, a]$ and $t \in [0, T]$;
- Initial conditions: $u(x, 0) = \sin(\pi x)$, $\partial u(x, 0)/\partial t = 0$;
- Boundary conditions: $u(0, t) = u(a, t) = 0$.
- Finite differences in both spatial and temporal coordinates;
- $x_i = i\Delta x$ and $t_k = k\Delta t$ lead to $u(x_i, t_k) = u_{ik}$;



# Nested loops and change loop orders

string_vib_v0.m

```
for jt = 1:Ntime;
u(jt,1) = 0.0; u(jt,Nx) = 0.0;
end
for ix = 2:Nx-1
u(1,ix) = sin(pi*x_step);
u(2,ix) = 0.5*const*( u(1,ix+1) + u(1,ix-1) ) ...
        + (1.0-const)*u(1,ix);
end
for jt = 2:Ntime-1
for ix = 2:Nx-1
u(jt+1,ix) = 2.0*(1.0-const)*u(jt,ix) ...
  + const*(u(jt,ix+1) + u(jt,ix-1)) - u(jt-1,ix);
end
end
```

How can we optimize it?

```
>> Elapsed time is 19.222726 s.
```

# Nested loops and change loop orders

string_vib_v1.m

```
for jt = 1:Ntime;
u(1,jt) = 0.0; u(Nx,jt) = 0.0;
end
for ix = 2:Nx-1
u(ix,1) = sin(pi*x_step);
u(ix,2) = 0.5*const*( u(ix+1,1) + u(ix-1,1) ) ...
        + (1.0-const)*u(ix,1);
end
for jt = 2:Ntime-1
for ix = 2:Nx-1
u(ix,jt+1) = 2.0*(1.0-const)*u(ix,jt) ...
  + const*(u(ix+1,jt) + u(ix-1,jt)) - u(ix,jt-1);
end
end
```

```
>> Elapsed time is 0.291292 s.
```

$66\times$

## Optimize branches in loops

- Loop merging/split (unrolling). Optimize **branches** in loops;
- Consider a summation: $\pi = 4(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \ldots)$.

pi_v0.m

```
n = 500000;
total = 0.0; k= 0;
for id =1:2:n
     k = k + 1;
     if mod(k,2)==0 tmp = -1.0/double(id);
     else tmp = 1.0/double(id);
     end
     total = total + tmp;
end
total = 4.0 * total;
fprintf('%15.12f', total);
```

```
>> Elapsed time is 0.043757 s.
```

# Optimize branches in loops

- Loop merging/split (unrolling). Optimize **branches** in loops;
- Consider a summation: $\pi = 4(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \ldots)$.

pi_v1.m

```
n = 500000;
total = 0.0;
for id =1:4:n
    tmp = 1.0/double(id);
    total = total + tmp;
end
for id =3:4:n
    tmp = -1.0/double(id);
    total = total + tmp;
end
total = 4.0 * total;
fprintf('%15.12f', total);
```

loop split

```
>> Elapsed time is 0.023158 s.
```

$\mathbf{1.9}\times$

## Optimize branches in loops

- Loop merging/split (unrolling). Optimize **branches** in loops;
- Consider a summation: $\pi = 4(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \ldots)$.

pi_v2.m

```
n = 500000;
total = 0.0;
fac = 1.0;
for id =1:2:n
    tmp = fac/double(id);
    total = total + tmp;
    fac = -fac;
end
total = 4.0 * total;
fprintf('%15.12f', total);
```

```
>> Elapsed time is 0.020947 s.
```

$\mathbf{2.0}\times$

- In the last two versions, the branches were removed from the loops.

# Use inline functions

- Consider the computation of distances between any two points $\boldsymbol{a}(3, \mathrm{ncol})$ and $\boldsymbol{b}(3, \mathrm{ncol})$ in 3D space:

norm_v0.m

```
ncol = 2000;
a = rand(3,ncol);
b = rand(3,ncol);

tic;
for i = 1:ncol
for j = 1:ncol
    c(i,j) = norm( a(:,j)-b(:,i) );
end
end
toc;
```

```
>> Elapsed time is 15.803001 s.
```

## Use inline functions

- Consider the computation of distances between any two points $\boldsymbol{a}(3, \mathrm{ncol})$ and $\boldsymbol{b}(3, \mathrm{ncol})$ in 3D space:

norm_v1.m

```
ncol = 2000;
a = rand(3,ncol);
b = rand(3,ncol);
tic;
c = zeros(ncol,ncol);                    % allocate c array first
for i = 1:ncol
for j = 1:ncol
     c(i,j) = norm( a(:,j)-b(:,i) );
end
end
toc;
```

```
>> Elapsed time is 13.185580 s.
```

$1.2\times$

## Use inline functions

- Consider the computation of distances between any two points $\boldsymbol{a}(3, \mathrm{ncol})$ and $\boldsymbol{b}(3, \mathrm{ncol})$ in 3D space:

norm_v2.m

```
ncol = 2000;
a = rand(3,ncol);
b = rand(3,ncol);
tic;
c = zeros(ncol,ncol);              % allocate c array first
for j = 1:ncol
for i = 1:ncol
    c(i,j) = norm( a(:,j)-b(:,i) );
end
end
toc;
```

```
>> Elapsed time is 13.153847 s.
```

$\mathbf{1.2}\times$

## Use inline functions

- Consider the computation of distances between any two points $\boldsymbol{a}(3, \mathrm{ncol})$ and $\boldsymbol{b}(3, \mathrm{ncol})$ in 3D space:

norm_v3.m

```
tic;
c = zeros(ncol,ncol);          % allocate c array first
for j = 1:ncol
for i = 1:ncol
    x = a(1,j) - b(1,i);
    y = a(2,j) - b(2,i);
    z = a(3,j) - b(3,i);
    c(i,j) = sqrt(x*x + y*y + z*z);  % replace norm
end
end
toc;
```

```
>> Elapsed time is 0.472565 s.
```

$\mathbf{33}\times$

## Exercise: solving a set of linear equations

- Let's consider using the iterative **Gauss-Seidel** method to solve a linear system $\boldsymbol{A}x = \boldsymbol{b}$ (assume that $a_{ii} \neq 0$, $i = 1, 2, \ldots, n$);

$$x_i^{(k+1)} = \frac{1}{a_{ii}}\Big(b_i - \sum_{j<i} a_{ij} x_j^{(k+1)} - \sum_{j>i} a_{ij} x_j^{(k)}\Big). \tag{4}$$

## Exercise: solving a set of linear equations

- Let's consider using iterative **Gauss-Seidel** method to solve a linear system $\boldsymbol{A}x = \boldsymbol{b}$ (assume that $a_{ii} \neq 0$, $i = 1, 2, \ldots, n$);

```
function x = GaussSeidel(A,b,es,maxit)
......
while (1)
xold = x;
    for i = 1:n;
    x(i) = d(i) - C(i,:)*x;
    if x(i) ~= 0;
    ea(i) = abs((x(i) -xold(i))/x(i)) * 100;
    end
    end
iter = iter + 1;
if max(ea) <= es | iter >= maxit, break, end
end
```

GaussSeidel_v0.m

adapted from Chapra's Appliced Numerical Methods with MATLAB (2nd ed. p.269)

How can we optimize it?

## Exercise: solving a set of linear equations

- Let's consider using iterative **Gauss-Seidel** method to solve a linear system $\boldsymbol{A}x = \boldsymbol{b}$ (assume that $a_{ii} \neq 0$, $i = 1, 2, \ldots, n$);

driver_GaussSeidel.m

```
nsize = 6000;
A = zeros(nsize); b = zeros(nsize,1);
es = 0.00001; maxit = 100;
for i = 1:nsize
    b(i) = 3.0 - 2.0*sin(double(i)*15.0);
    for j = 1:nsize
    A(j,i) = cos(double(i-j)*123.0);
    end
end
tic;
xsolution = GaussSeidel_v0(A,b,es,maxit);
toc;
```

```
>> Elapsed time is 18.823522 s (..._v0.m).
```

# Optimization techniques specific to Matlab

- In addition to understanding general tuning techniques, there are techniques unique to Matlab programming;
- There are always multiple ways to solve the same problem;
    - Fast Fourier transform (FFT).
    - Convert numbers to strings.
    - Dynamic allocation of arrays.
    - Construct a sparse matrix.
    - . . .

# FFT

- Let's consider the FFT of a series signal:

fft_v0.m

```
tic;
nsize = 3e6; nsizet = nsize + 202;
a = rand(1,nsize);
b = fft(a,nsizet);
toc;
```

```
>> Elapsed time is 0.650933 s.
```

fft_v1.m

```
tic;
nsize = 3e6;
n = nextpow2(nsize); nsizet = 2^n;
a = rand(1,nsize);
b = fft(a,nsizet);
toc;
```

```
>> Elapsed time is 0.293406 s.
```

$2.2\times$

## Preallocation of arrays

- Matlab supports **dynamical allocation** of arrays;
- It is both good and bad in terms of **easy coding** and **performance**:

array_alloc_v0.m

```
My_data=importdata('input.dat');
tic;
Sortx=zeros(1,1);
k=0; s=1;
while k<=My_data(1,1)
      Sortx(s,1)=My_data(s,4);
      s=s+1;
      k=My_data(s,1);
end
toc;
```

```
>> Elapsed time is 0.056778 s.
```

## Preallocation of arrays

- It is always a good idea to **preallocate** arrays:

array_alloc_v1.m

```
tic;
k=0; s=1;
while k<=My_data(1,1)
      s=s+1; k=My_data(s,1);
end
Sortx=zeros(s-1,1);
k=0; s=1;
while k<=My_data(1,1)
      Sortx(s,1)=My_data(s,4);
      s=s+1;
      k=My_data(s,1);
end
toc;
```

```
>> Elapsed time is 0.027005 s.
```

$\mathbf{2.1}\times$

# Convert numbers to strings

- Matlab provides a builtin function `num2str`:

num2str_v0.m

```
tic;
i = 12345.6;
A = num2str(sin(i+i),'%f');
toc;
```

```
>> Elapsed time is 0.019238 s.
```

num2str_v1.m

```
tic;
i = 12345.6;
A = sprintf('%f',sin(i+i));
toc;
```

```
>> Elapsed time is 0.005372 s.
```

**3.6**×

- In this case, `sprintf` is much better than `num2str`;

# What we haven't covered

- There are other Matlab techniques that are **not** covered here:
  - Parallel programming in Matlab.
  - Matlab vectorization.
  - File I/O.
  - Matlab indexing techniques.
  - Object oriented programming in Matlab.
  - Binary MEX code.
  - Matlab programming on GPUs.
  - Graphics.
  - . . .

## Remarks on LSU HPC and LONI clusters

- All LSU HPC and LONI clusters **don't** have parallel toolboxes;
- Therefore, we can only run Matlab code on a `single` node;
- You can run Matlab jobs on **multiple** cores but without **multi-threading** programming. Choose queue properly;
- On LSU HPC and LONI clusters we don't support **explicitly** parallel programming in Matlab at least at this point;
- However, it is possible that Matlab automatically spawns several threads;
- If you use `single` queue on **Mike-II** or **QB-2**, please always add `-singleCompThread` in your matlab command line;
- For LONI users on **QB-2**, for instance, you have to provide your own license file;
- **Matlab on LSU HPC website**

## Further reading

- **Matlab bloggers:** `http://blogs.mathworks.com`
- **Accelerating MATLAB Performance**
  (Y. Altman, CRC Press, 2015)
- Matlab Central (File Exchange)

# `Questions?`

`sys-help@loni.org`