




Matlab toolbox, User's Guide *

François Cuvelier[†]

April 20, 2018

Abstract

The  Matlab toolbox allows to benchmark functions and much more

*Compiled with Matlab 2017a, with toolboxes `fc-bench`['dev'] and `fc-tools`['dev']

[†]Université Paris 13, Sorbonne Paris Cité, LAGA, CNRS UMR 7539, 99 Avenue J-B Clément, F-93430 Villetaneuse, France, cuvelier@math.univ-paris13.fr

This work was partially supported by the ANR project DEDALES under grant ANR-14-CE23-0005.

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1 Introduction

The `fc_bench` Matlab toolbox aims to perform simultaneous benchmarks of several functions performing the same tasks but implemented in different ways.

We are going on an example to illustrate its possibilities. This one will focus on different ways of coding the Lagrange interpolation polynomial. We first recall some generalities about this polynomial.

Let \mathbf{X} and \mathbf{Y} be 1-by- $(n+1)$ arrays where no two $\mathbf{X}(j)$ are the same. The Lagrange interpolating polynomial is the polynomial $P(t)$ of degree $\leq n$ that passes through the $(n+1)$ points $(\mathbf{X}(j), \mathbf{Y}(j))$ and is given by

$$P(t) = \sum_{j=1}^{n+1} Y(j) \prod_{k=1, k \neq j}^{n+1} \frac{t - X(k)}{X(j) - X(k)}.$$

Three different functions have been implemented to compute this polynomial. They all have the same header given by

$$\mathbf{y} = \text{fun}(\mathbf{X}, \mathbf{Y}, \mathbf{x})$$

where \mathbf{x} is a 1-by- m array and \mathbf{y} is a 1-by- m so that

$$\mathbf{y}(i) = P(\mathbf{x}(i)).$$

These functions are

- `fc_bench.demos.Lagrange`, a simplistic writing;
- `fc_bench.demos.lagint`, an optimized writing ;
- `fc_bench.demos.polyLagrange`, using `polyfit` and `polyval` Matlab functions.

Their source codes is in directory `+fc_bench\+demos` of the toolbox.

To run benchmarks, the main tool is `fc_bench.bench` function described in section 3. To use it, you must first write a function to initialize the Lagrange function input datas: it is given in Listing 1. Then this function is used as second argument of the `fc_bench.bench` function while the first one contains the three handle functions to benchmark. A complete script is given in Listing 2 with its displayed output.

```
function [Inputs, bDs]=setLagrange00(N, verbose, varargin)
    n=N(1); % degree of the interpolating polynomial
    m=N(2); % number of interpolate values
    a=0; b=2*pi;
    X=a:(b-a)/n:b;
    Y=cos(X);
    x=a+(b-a)*rand(1,m);

    bDs(1)=fc_bench.bdata('m',m,'%d',5); % first column in bench output
    bDs(2)=fc_bench.bdata('n',n,'%d',5); % second column in bench output
    Inputs={X,Y,x}; % is the inputs of the matricial product functions
end
```

Listing 1: `fc_bench.demos.setLagrange00` function

Listing 2: `fc_bench.demos.bench_Lagrange00` script

```

Lfun={@(X,Y,x) fc_bench.demos.Lagrange(X,Y,x), ...
      @(X,Y,x) fc_bench.demos.lagint(X,Y,x), ...
      @(X,Y,x) fc_bench.demos.polyLagrange(X,Y,x) };

setfun=@(varargin) fc_bench.demos.setLagrange00(varargin{:});
n=[5,9,15]; m=[100,500,1000];
[N,M]=meshgrid(n,m);
LN=[N(:),M(:)];
fc_bench.bench(Lfun, setfun, 'LN',LN, 'labelsinfo',true);

```

Output

```

#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
# Benchmarking functions:
# fun[0], Lagrange: @(X,Y,x)fc_bench.demos.Lagrange(X,Y,x)
# fun[1], lagint: @(X,Y,x)fc_bench.demos.lagint(X,Y,x)
# fun[2], polyLagrange: @(X,Y,x)fc_bench.demos.polyLagrange(X,Y,x)
#-----
#date:2018/04/20 16:58:47
#nbruns:5
#numpy: i4 i4 f4 f4 f4
#format: %d %d %.3f %.3f %.3f
#labels: m n Lagrange(s) lagint(s) polyLagrange(s)
100 5 0.002 0.004 0.002
500 5 0.008 0.016 0.008
1000 5 0.015 0.030 0.015
100 9 0.003 0.005 0.003
500 9 0.013 0.025 0.013
1000 9 0.026 0.049 0.025
100 15 0.004 0.008 0.004
500 15 0.022 0.041 0.022
1000 15 0.043 0.082 0.043

```

We now propose a slightly more elaborate version of the initialization function that allows to display some informations and to choose certain parameters when generating inputs datas. This new version named `fc_bench.demos.setLagrange` is given in Listing 3. A complete script is given in Listing 4 with its displayed output. In this script some options of the `fc_bench.bench` function are used `'error'`, `'info'`, `'labelsinfo'`, jointly with those of the `fc_bench.demos.setLagrange`: `'a'`, `'b'` and `'fun'`. One must be careful not to take as an option name for the initialization function one of those used in `fc_bench.bench` function. More details are given in section 3.

```

function [Inputs, bDs]=setLagrange(N, verbose, varargin)
    p = inputParser;
    p.addParamValue('fprintf', @(varargin) fprintf(varargin{:}));
    p.addParamValue('a', 0, @isscalar);
    p.addParamValue('b', 2*pi, @isscalar);
    p.addParamValue('fun', @cos);
    p.parse(varargin{:});
    R=p.Results;
    Fprintf=R.fprintf; a=R.a; b=R.b;
    n=N(1); % degree of the interpolating polynomial
    m=N(2); % number of interpolate values
    X=a:(b-a)/n:b; Y=R.fun(X);
    x=a+(b-a)*rand(1,m);
    if verbose
        Fprintf('# Setting inputs of Lagrange polynomial functions: ...
                y=LAGRANGE(X,Y,x)\n');
        Fprintf('# where X is a: (b-a)/n:b, Y=fun(X) and x is random values on ...
                [a,b]\n');
        Fprintf('# n is the order of the Lagrange polynomial\n');
        Fprintf('# fun function is: %s\n', func2str(R.fun));
        Fprintf('# [a,b]=[%g,%g]\n', a,b);

        Fprintf('# X: 1-by-(n+1) array\n');
        Fprintf('# Y: 1-by-(n+1) array\n');
        Fprintf('# x: 1-by-m array\n');
    end

    bDs(1)=fc_bench.bdata('m',m,'%d',5); % first column in bench output
    bDs(2)=fc_bench.bdata('n',n,'%d',5); % second column in bench output
    Inputs={X,Y,x}; % is the inputs of the matricial product functions
end

```

Listing 3: fc_bench.demos.setLagrange function

Listing 4: : `fc_bench.demos.bench_Lagrange` script

```

Lfun=@(X,Y,x) fc_bench.demos.Lagrange(X,Y,x), ...
    @(X,Y,x) fc_bench.demos.lagint(X,Y,x), ...
    @(X,Y,x) fc_bench.demos.polyLagrange(X,Y,x) };

error=@(o1,o2) norm(o1-o2,Inf);
setfun=@(varargin) fc_bench.demos.setLagrange(varargin{:});
n=[5,9,15]; m=[100,500,1000];
[N,M]=meshgrid(n,m);
LN=[N(:),M(:)];
fc_bench.bench(Lfun, setfun,'LN',LN, 'error',error, 'info',false, ...
    'labelsinfo',true, 'a',-pi,'b',pi,'fun',@sin);

```

Output

```

#-----
# Benchmarking functions:
# fun[0], Lagrange: @(X,Y,x)fc_bench.demos.Lagrange(X,Y,x)
# fun[1], lagint: @(X,Y,x)fc_bench.demos.lagint(X,Y,x)
# fun[2], polyLagrange: @(X,Y,x)fc_bench.demos.polyLagrange(X,Y,x)
# cmpErr[1], error between fun[0] and fun[i] outputs computed with function
# @(o1,o2)norm(o1-o2,Inf)
# where
# - 1st input parameter is the output of fun[0]
# - 2nd input parameter is the output of fun[i]
#-----
# Setting inputs of Lagrange polynomial functions: y=LAGRANGE(X,Y,x)
# where X is a:(b-a)/n:b, Y=fun(X) and x is random values on [a,b]
# n is the order of the Lagrange polynomial
# fun function is: sin
# [a,b]=[-3.14159,3.14159]
# X: 1-by-(n+1) array
# Y: 1-by-(n+1) array
# x: 1-by-m array
#-----
#date:2018/04/20 16:59:22
#nbruns:5
#numpy: i4 i4 f4 f4 f4 f4 f4
#format: %d %d %.3f %.3f %.3e %.3f %.3e
#labels: m n Lagrange(s) lagint(s) cmpErr[1] polyLagrange(s) cmpErr[2]

```

| m | n | Lagrange(s) | lagint(s) | cmpErr[1] | polyLagrange(s) | cmpErr[2] |
|------|----|-------------|-----------|-----------|-----------------|-----------|
| 100 | 5 | 0.002 | 0.004 | 6.661e-16 | 0.002 | 0.000e+00 |
| 500 | 5 | 0.008 | 0.017 | 7.772e-16 | 0.008 | 0.000e+00 |
| 1000 | 5 | 0.016 | 0.032 | 9.992e-16 | 0.016 | 0.000e+00 |
| 100 | 9 | 0.003 | 0.006 | 2.442e-15 | 0.003 | 0.000e+00 |
| 500 | 9 | 0.015 | 0.028 | 2.554e-15 | 0.014 | 0.000e+00 |
| 1000 | 9 | 0.028 | 0.055 | 2.887e-15 | 0.027 | 0.000e+00 |
| 100 | 15 | 0.005 | 0.009 | 7.316e-14 | 0.004 | 0.000e+00 |
| 500 | 15 | 0.023 | 0.043 | 5.518e-14 | 0.022 | 0.000e+00 |
| 1000 | 15 | 0.045 | 0.088 | 5.837e-14 | 0.045 | 0.000e+00 |

2 Installation

2.1 Automatic installation, all in one (recommended)

For this method, one just has to get/download the install file

```
mfc_bench_install.m
```

or get it on the dedicated web page. Thereafter, one runs it under Matlab. This script downloads, extracts and configures the *fc-bench* and the required toolbox (*fc-tools*) in the current directory.

For example, to install this toolbox in `~/Matlab/toolboxes` directory, one has to copy the file `mfc_bench_install.m` in the `~/Matlab/toolboxes` directory. Then in a Matlab terminal run the following commands

```
>> cd ~/Matlab/toolboxes
>> mfc_bench_install
```

This is the output of the `mfc_bench_install` command on a Linux computer:

```
Parts of the <fc-bench> Matlab toolbox.
Copyright (C) 2018 F. Cuvelier <cuvelier@math.univ-paris13.fr>

1- Downloading and extracting the toolboxes
2- Setting the <fc-bench> toolbox
Write in ...
   ~/Matlab/toolboxes/fc-bench-full/fc_bench-0.0.2/configure_loc.m ...
3- Using toolboxes :
   ->          fc-tools : 0.0.21
   ->          fc-bench : 0.0.2
*** Using instructions
To use the <fc-bench> toolbox:
addpath('~/Matlab/toolboxes/fc-bench-full/fc_bench-0.0.2')
fc_bench.init()

See ~/Matlab/toolboxes/mfc_bench_set.m
```

The complete toolbox (i.e. with all the other needed toolboxes) is stored in the directory `~/Matlab/toolboxes/fc-bench-full` and, for each Matlab session, one have to set the toolbox by:

```
>> addpath('~/Matlab/toolboxes/fc-bench-full/fc_bench-0.0.2')
>> fc_bench.init()
```

For **uninstalling**, one just has to delete directory

```
~/Matlab/toolboxes/fc-bench-full
```

3 `fc_bench.bench` function

The `fc_bench.bench` function run benchmark

Syntaxe

```
fc_bench.bench(Lfun, setfun)
fc_bench.bench(Lfun, setfun, key, value, ...)
R=fc_bench.bench(Lfun, setfun)
R=fc_bench.bench(Lfun, setfun, key, value, ...
...)
```

Description

```
fc_bench.bench(Lfun, setfun)
```

Runs benchmark for each function given in the cell array `Lfun`. The function handle `setfun` is used to set input datas to these functions.

There is the imposed syntax:

```
function [Inputs,Bdatas]=setfun(N,verbose,varargin)
...
end
```

By default, for all `N` in `5:5:20`, computational time in second of each function in `Lfun` is evaluated by `tic-toc` command:

```
t=tic(); out=Lfun{i}( Inputs{:} ); tcpu=toc(t);
```

where `Inputs` is given by

```
[Inputs,Bdatas]=setfun(N,verbose,varargin{:})
```

```
fc_bench.bench(Lfun, setfun, key, value, ...)
```

Some optional `key/value` pairs arguments are available with `key`:

- `'LN'`, to set values of the first input of the `setfun` function of the `n` benchmark to be run. For `i`-th benchmark, the `setfun` function is used with the `i`-th `value` as follows
 - if `value` is an `n`-by-1 or 1-by-`n` array, `value(i)` is used,
 - if `value` is an `n`-by-`m` array, `value(i,:)` is used,
 - if `value` is an `n`-by-`m` cell array, `value{i,:}` is used,

By default, `value` is `5:5:20`.

- `'names'`, set the names that will be displayed during the benchmarks to name each of the functions of `Lfun`. By default `value` is the empty cell and all the names are guessed from the handle functions of `Lfun`. Otherwise, `value` is a cell array with same length as `Lfun` such that `value{i}` is the string name associated with `Lfun{i}` function. If `value{i}` is the empty string, then the name is guessed from the handle function `Lfun{i}`.
- `'nbruns'`, to set number of benchmark runs for each case and the mean of computational times is taken. Default `value` is `5`. In fact, `value+2` benchmarks are executed and the two worst are forgotten (see `fc_bench.mean_run` function)
- `'comment'`, string or cell of strings displayed before running the benchmarks. If `value` is a cell of strings, after printing the `value{i}`, a line break is performed.
- `'info'`, if `value` is `true`(default), some informations on the computer and the system are displayed.
- `'labelsinfo'`, if `value` is `true`, some informations on the labels of the columns are displayed. Default is `false`.
- `'savefile'`, if `value` is a not empty string, then displayed results are saved in directory `benchs` with `value` as filename. One can use `'savedir'` option to change the directory.
- `'savedir'`, if `value` is a not empty string, then when using `'savefile'`, the directory `value` is where file is saved.

- `'error'`, to use when comparative errors between the various functions are desired when displaying. In this case an handle function must be given which returns error (as scalar) between the output of the first function `Lfun{1}` and one of the others.

3.1 Matricial product examples

Let X be a m -by- n matrix and Y be a n -by- p matrix We want to measure efficiency of the matricial product `mtimes(X,Y)` (function version) or `X*Y` (operator function) with various values of m , n and p .

3.1.1 Square matrices: `fc_bench.demos.bench_MatProd00` script

Let $m = n = p$.

```
function [Inputs,bDs]=setMatProd00(m,verbose,varargin)
    X=randn(m,m); Y=randn(m,m);
    bDs(1)=fc_bench.bdata('m',m,'%d',5); % first column in bench output
    Inputs={X,Y}; % is the inputs of the matricial product functions
end
```

Listing 5: `fc_bench.demos.setMatProd00` function

The `fc_bench.demos.setMatProd00` function given in Listing 5 is used in `fc_bench.demos.bench_MatProd00` script (file `+fc_bench/+demos/bench_MatProd00.m` of the toolbox directory)

Listing 6: : `fc_bench.demos.bench_MatProd00` script

```
Lfun={@(X,Y) mtimes(X,Y)};
setfun=@(varargin) fc_bench.demos.setMatProd00(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',500:500:4000);
```

Output

```
#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
#-----
#date:2018/04/20 16:59:57
#nbruns:5
#numpy: i4 f4
#format: %d %.3f
#labels: m mtimes(s)
500 0.002
1000 0.007
1500 0.021
2000 0.044
2500 0.059
3000 0.090
3500 0.138
4000 0.189
```

3.1.2 Square matrices: `fc_bench.demos.bench_MatProd01` script

Let $m = n = p$.

```

function [Inputs, bDs]=setMatProd01(m, verbose, varargin)
X=randn(m,m); Y=randn(m,m);
if verbose
    fprintf('# 1st input parameter: m-by-m matrix\n')
    fprintf('# 2nd input parameter: m-by-m matrix\n')
end
bDs(1)=fc_bench.bdata('m',m,'%d',5); % first column in bench output
Inputs={X,Y}; % is the inputs of the matricial product functions
end

```

Listing 7: `fc_bench.demos.setMatProd01` function

The `fc_bench.demos.setMatProd01` function given in Listing 7 is used in `fc_bench.demos.bench_MatProd01` script (file `+fc_bench/+demos/bench_MatProd01.m` of the toolbox directory)

Listing 8: `fc_bench.demos.bench_MatProd01` script

```

Lfun=@(X,Y) mtimes(X,Y);
Comment={'# benchmarking function @(X,Y) mtimes(X,Y)', ...
        '# where X and Y are m-by-m matrices'};
setfun=@(varargin) fc_bench.demos.setMatProd01(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN', 500:500:4000, 'comment', Comment, ...
    'savefile', 'MadProd01.out');

```

Output

```

#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
# benchmarking function @(X,Y) mtimes(X,Y)
# where X and Y are m-by-m matrices
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#benchfile: benches/MadProd01.out
#date:2018/04/20 17:00:32
#nbruns:5
#numpy: i4      f4
#format: %d      %.3f
#labels: m      mtimes(s)
500      0.002
1000     0.008
1500     0.022
2000     0.037
2500     0.073
3000     0.090
3500     0.138
4000     0.190

```

```

-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
-----
# benchmarking function t(X,Y) mtimes(X,Y)
# where X and Y are m-by-m matrices
#-----
#benchfile: benches/MatProd01.out
#date:2018/04/20 17:00:32
#nbruns:5
#numpy: 14 f4
#format: %d %3f
#labels: m mtimes(s)
500 0.002
1000 0.008
1500 0.022
2000 0.037
2500 0.073
3000 0.090
3500 0.138
4000 0.190
-----

```

Listing 9: Output file benches/MatProd01.out

As we can see the information print in `fc_bench.demos.setMatProd01` function are missing in output file `benches/MatProd01.out`. In the next section we will see how to print them also in output file.

3.1.3 Square matrices: `fc_bench.demos.bench_MatProd02` script

Let $m = n = p$.

```

function [Inputs, bDs]=setMatProd02(m, verbose, varargin)
    p = inputParser;
    p.addParamValue('fprintf', @(varargin) fprintf(varargin{:}));
    p.parse(varargin{:});
    fprintf=p.Results.fprintf;
    X=randn(m,m); Y=randn(m,m);
    if verbose
        fprintf('#_1st_input_parameter: %m-by-m_matrix\n');
        fprintf('#_2nd_input_parameter: %m-by-m_matrix\n');
    end
    bDs(1)=fc_bench.bdata('m',m,'%d',5); % first column in bench output
    Inputs={X,Y}; % is the inputs of the matricial product functions
end

```

Listing 10: `fc_bench.demos.setMatProd02` function

The `fc_bench.demos.setMatProd02` function given in Listing 10 is used in `fc_bench.demos.bench_MatProd02` script (file `bench_MatProd02.m` of the `+fc_bench/+demos` toolbox directory)

Listing 11: : fc_bench.demos.bench_MatProd02 script

```
Lfun=@(X,Y) mtimes(X,Y);
Comment={'# benchmarking function @(X,Y) mtimes(X,Y)', ...
         '# where X and Y are m-by-m matrices'};
setfun=@(varargin) fc_bench.demos.setMatProd02(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',500:500:4000, 'comment',Comment, ...
              'savefile','MadProd02.out');
```

Output

```
#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
# benchmarking function @(X,Y) mtimes(X,Y)
# where X and Y are m-by-m matrices
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#benchfile: benches/MadProd02.out
#date:2018/04/20 17:01:10
#nbruns:5
#numpy: i4 f4
#format: %d %3f
#labels: m mtimes(s)
500 0.002
1000 0.005
1500 0.026
2000 0.035
2500 0.059
3000 0.094
3500 0.138
4000 0.190
```

```
#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
# benchmarking function @(X,Y) mtimes(X,Y)
# where X and Y are m-by-m matrices
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#benchfile: benches/MadProd02.out
#date:2018/04/20 17:01:10
#nbruns:5
#numpy: i4 f4
#format: %d %3f
#labels: m mtimes(s)
500 0.002
1000 0.005
1500 0.026
2000 0.035
2500 0.059
3000 0.094
3500 0.138
4000 0.190
```

Listing 12: Output file benches/MadProd02.out

3.1.4 Square matrices: `fc_bench.demos.bench_MatProd03` and `04` scripts

Let $m = n = p$. We want to compare computational times between the `mtimes(X,Y)` function, the `X*Y` command and the `fc_bench.demos.matprod01` function given in Listing 13.

```
function C=matprod01(A,B)
    [n,m]=size(A);[p,q]=size(B);
    assert( m==p )
    C=zeros(n,q);
    for i=1:n
        for j=1:q
            S=0;
            for k=1:m
                S=S+A(i,k)*B(k,j);
            end
            C(i,j)=S;
        end
    end
end
```

Listing 13: `fc_bench.demos.matprod01` function

The `fc_bench.demos.setMatProd02` function given in Listing 10 is used in `fc_bench.demos.bench_MatProd03` script (file `bench_MatProd03.m` of the `+fc_bench/+demos` toolbox directory)

Listing 14: `fc_bench.demos.bench_MatProd03` script

```
Lfun={@(X,Y) mtimes(X,Y), @(X,Y) X*Y, @(X,Y) ...
    fc_bench.demos.matprod02(X,Y)};
Comment='#_benchmarking_matricial_product_functions';
setfun=@(varargin) fc_bench.demos.setMatProd02(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'comment',Comment);
```

Output

```
#-----
# computer: cosmos
# system: Ubuntu 17.10 (x86_64)
# processor: Intel(R) Core(TM) i9-7940X CPU @ 3.10GHz
# (1 procs/14 cores by proc/2 threads by core)
# RAM: 62.6 Go
# software: Matlab
# release: 2017a
# MaxThreads: 14
#-----
# benchmarking matricial product functions
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#date:2018/04/20 17:01:46
#nbruns:5
#numpy: i4      f4      f4      f4
#format: %d      %.3f   %.3f   %.3f
#labels: m      mtimes(s) @ (s) matprod02(s)
100      0.001  0.000      0.048
200      0.000  0.000      0.207
300      0.001  0.001      0.488
400      0.001  0.001      0.893
```

As the second handle function in `Lfun` has no name, the guess name is `@`. One can set a more convenient name by using the `'names'` option: this is the object of Listing 15. When empty value is set in `'names'` cell then a guessed name is used.

Listing 15: `fc_bench.demos.bench_MatProd04` script

```

Lfun=@(X,Y) mtimes(X,Y), @(X,Y) X*Y, @(X,Y) ...
    fc_bench.demos.matprod02(X,Y) };
names={'mtimes(X,Y)', 'X*Y', ''};
Comment={'# benchmarking functions @(X,Y) mtimes(X,Y) and @(X,Y) ...
    X*Y', ...
    '# where X and Y are m-by-m matrices'};
error=@(o1,o2) norm(o1-o2,Inf);
setfun=@(varargin) fc_bench.demos.setMatProd02(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'comment',Comment, ...
    'names',names, 'info',false);

```

Output

```

#-----
# benchmarking functions @(X,Y) mtimes(X,Y) and @(X,Y) X*Y
# where X and Y are m-by-m matrices
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#date:2018/04/20 17:02:29
#nbruns:5
#numpy: i4          f4          f4          f4
#format: %d          %.3f         %.3f         %.3f
#labels: m  mtimes(X,Y) (s) X*Y(s) matprod02(s)
100          0.001         0.000         0.050
200          0.000         0.000         0.212
300          0.001         0.000         0.507
400          0.001         0.001         0.928

```

3.1.5 Square matrices: `fc_bench.demos.bench_MatProd05` script

As previous section, we want to compare computational times between the `mtimes(X,Y)` function, the `X*Y` command and the `fc_bench.demos.matprod01` function given in Listing 13. In addition, we also want to display errors between the outputs of the functions. The first function is the reference one and errors are always computed by using output of this reference function and output of the functions.

Two examples, using the `fc_bench.bench` function with `'error'` option to display comparative errors, are proposed. They both use the `fc_bench.demos.setMatProd02` function given in Listing 10. The first one given in Listing 16 uses the `'comment'` option and manual writing to print some informations on labels columns. The second one given in Listing 17 uses the `'labelsinfo'` option to automatically print some informations on labels columns.

Listing 16: : fc_bench.demos.bench_MatProd05 script

```

Lfun=@(X,Y) mtimes(X,Y), @(X,Y) X*Y, @(X,Y) ...
    fc_bench.demos.matprod02(X,Y) };
names={'mtimes(X,Y)', 'X*Y', ''};
Comment={'# Benchmarking functions: ' ...
    '# A1=mtimes(X,Y) (reference)', ...
    '# A2=X*Y', ...
    '# A3=fc_bench.demos.matprod02(X,Y)', ...
    '# where X and Y are m-by-m matrices', ...
    '# cmpErr[1] is the norm(A1-A2,Inf)', ...
    '# cmpErr[2] is the norm(A1-A3,Inf)'};
error=@(o1,o2) norm(o1-o2,Inf);
setfun=@(varargin) fc_bench.demos.setMatProd02(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'comment',Comment, ...
    'names',names, 'error',error, 'info',false);

```

Output

```

#-----
# Benchmarking functions:
#   A1=mtimes(X,Y) (reference)
#   A2= X*Y
#   A3= fc_bench.demos.matprod02(X,Y)
# where X and Y are m-by-m matrices
# cmpErr[1] is the norm(A1-A2,Inf)
# cmpErr[2] is the norm(A1-A3,Inf)
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#date:2018/04/20 17:03:13
#nbruns:5
#numpy:  i4          f4      f4          f4          f4          f4
#format: %d          %.3f   %.3f          %.3e          %.3f          %.3e
#labels: m  mtimes(X,Y) (s) X*Y(s)  cmpErr[1]  matprod02(s)  cmpErr[2]
100      0.001  0.000  0.000e+00  0.048  3.260e-13
200      0.000  0.000  0.000e+00  0.212  6.667e-13
300      0.001  0.000  0.000e+00  0.503  2.680e-12
400      0.001  0.001  0.000e+00  0.896  4.558e-12

```

Listing 17: : fc_bench.demos.bench_MatProd05bis script

```

Lfun=@(X,Y) mtimes(X,Y), @(X,Y) X*Y, @(X,Y) ...
    fc_bench.demos.matprod02(X,Y) };
names={'mtimes(X,Y)', 'X*Y', ''};

error=@(o1,o2) norm(o1-o2,Inf);
setfun=@(varargin) fc_bench.demos.setMatProd02(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'names',names, ...
    'error',error, 'info',false, 'labelsinfo',true);

```

Output

```

#-----
# Benchmarking functions:
# fun[0], mtimes(X,Y): @(X,Y)mtimes(X,Y)
# fun[1],   X*Y: @(X,Y)X*Y
# fun[2], matprod02: @(X,Y)fc_bench.demos.matprod02(X,Y)
# cmpErr[i], error between fun[0] and fun[i] outputs computed with function
#   @(o1,o2)norm(o1-o2,Inf)
# where
# - 1st input parameter is the output of fun[0]
# - 2nd input parameter is the output of fun[i]
#-----
# 1st input parameter: m-by-m matrix
# 2nd input parameter: m-by-m matrix
#-----
#date:2018/04/20 17:03:54
#nbruns:5
#numpy:  i4          f4      f4          f4          f4          f4
#format: %d          %.3f   %.3f          %.3e          %.3f          %.3e
#labels: m  mtimes(X,Y) (s) X*Y(s)  cmpErr[1]  matprod02(s)  cmpErr[2]
100      0.001  0.000  0.000e+00  0.050  3.260e-13
200      0.000  0.000  0.000e+00  0.219  6.667e-13
300      0.001  0.001  0.000e+00  0.521  2.680e-12
400      0.001  0.001  0.000e+00  0.944  4.558e-12

```

3.1.6 Non-square matrices: `fc_bench.demos.bench_MatProd06` script

As previous section, we want to compare computational times between the `mtimes(X,Y)` function, the `X*Y` command and the `fc_bench.demos.matprod01` function given in Listing 13 but this time with non-square matrices. In addition, we also want to display errors between the outputs of the functions. The first function is the reference one and errors are always computed by using output of this reference function and output of the functions.

```
function [Out,bDs]=setMatProd03(N,verbose,varargin)
    assert( ismember(length(N), [1,3]) )
    p = inputParser;
    %p. KeepUnmatched=true;
    p.addParamValue('fprintf',@(varargin) fprintf(varargin{:}));
    p.addParamValue('lclass','double');
    p.addParamValue('rclass','double');
    p.addParamValue('lcomplex',false,@islogical);
    p.addParamValue('rcomplex',false,@islogical);
    p.parse(varargin{:});
    R=p.Results;
    R.lclass=lower(R.lclass);R.rclass=lower(R.rclass);
    Fprintf=R.fprintf;
    if length(N)==1
        m=N;n=N;p=N; % square matrices
    else
        m=N(1);n=N(2);p=N(3);
    end

    X=genMat(m,n,R.lclass,R.lcomplex);
    Y=genMat(n,p,R.rclass,R.rcomplex);

    if verbose
        if isreal(X), name=class(X); else, name=['complex_',class(X)]; end
        Fprintf('#1st input parameter: %m-by-n matrix [%s]\n',name)
        if isreal(Y), name=class(Y); else, name=['complex_',class(Y)]; end
        Fprintf('#2nd input parameter: %n-by-p matrix [%s]\n',name)
    end

    bDs(1)=fc_bench.bdata('m',m,'%d',7);
    bDs(2)=fc_bench.bdata('n',n,'%d',7);
    bDs(3)=fc_bench.bdata('p',p,'%d',7);
    Out={X,Y};
end

function V=genMat(m,n,classname,iscomplex)
    V=randn(m,n,classname);
    if iscomplex, V=complex(V,randn(m,n,classname));end
end
```

Listing 18: `fc_bench.demos.setMatProd03` function

The `fc_bench.demos.setMatProd03` function given in Listing 18 is used in `fc_bench.demos.bench_MatProd06` script (file `bench_MatProd06.m` of the `+fc_bench/+demos` toolbox directory)

Listing 19: : `fc_bench.demos.bench_MatProd06` script

```

Lfun=@(X,Y) mtimes(X,Y), @(X,Y) X*Y, @(X,Y) ...
    fc_bench.demos.matprod01(X,Y) );
names={'mtimes(X,Y)', 'X*Y', ''};
Comment={'# benchmarking functions:' ...
    '# A1=mtimes(X,Y) (reference)', ...
    '# A2=X*Y', ...
    '# A3=fc_bench.demos.matprod02(X,Y)', ...
    '# where X and Y are m-by-m matrices', ...
    '# Error[1] is the norm(A1-A2,Inf)', ...
    '# Error[2] is the norm(A1-A3,Inf)'};
error=@(o1,o2) norm(o1-o2,Inf);
setfun=@(varargin) fc_bench.demos.setMatProd03(varargin{:});
LN=[ 100,50,100; 150,50,100; 200,50,100; 150,100,300 ];
fc_bench.bench(Lfun, setfun, 'LN',LN, 'lcomplex',true, ...
    'rclass','single', ...
    'comment',Comment, 'names',names, 'error',error, 'info',false);

```

Output

```

#-----
# benchmarking functions:
#   A1=mtimes(X,Y) (reference)
#   A2= X*Y
#   A3= fc_bench.demos.matprod02(X,Y)
# where X and Y are m-by-m matrices
# Error[1] is the norm(A1-A2,Inf)
# Error[2] is the norm(A1-A3,Inf)
#-----
# 1st input parameter: m-by-n matrix [complex double]
# 2nd input parameter: n-by-p matrix [single]
#-----
#date:2018/04/20 17:04:36
#nbruns:5
#numpy:   i4   i4   i4           f4   f4           f4           f4           f4
#format:  %d   %d   %d           %.3f  %.3f           %.3e           %.3f           %.3e
#labels:  m    n    p   mtimes(X,Y) (s) X*Y (s)   cmpErr[1]   matprod01 (s)   cmpErr[2]
100      50   100           0.001  0.000       0.000e+00   0.027          1.365e-04
150      50   100           0.000  0.000       0.000e+00   0.040          1.625e-04
200      50   100           0.000  0.000       0.000e+00   0.053          1.565e-04
150      100  300           0.000  0.000       0.000e+00   0.200          7.885e-04

```

3.2 LU factorization examples

Let A be a m -by- m matrix. The function `fc_bench.demos.permLU` computes the permuted LU factorization of A and returns the three m -by- m matrices L , U and P which are respectively a lower triangular matrix with unit diagonal, an upper triangular matrix and a permutation matrix so that

$$P * A = L * U$$

Its header is given in Listing 20.

```

function [L,U,P]=permLU(A)
% FUNCTION fc_bench.demos.permLU
% -- [L,U,P]=permLU(A)
%   Computes permuted LU factorization of A.
%   L, U and P are respectively the lower triangular matrix with unit
%   diagonal, the upper triangular matrix and the permutation matrix
%   so that
%       P*A = L*U.

```

Listing 20: Header of the `fc_bench.demos.permLU` function

3.2.1 `fc_bench.demos.bench_LU00`

We present a very simple benchmark, using the `fc_bench` toolbox, of the `fc_bench.demos.permLU` function. The `fc_bench.demos.setLU00` function given in Listing 21 is used in the script `fc_bench.demos.bench_LU00` (file `bench_LU00.m` of the `+fc_bench/+demos` toolbox directory). The source code and the printed output are given in Listing 22.

```
function [Out, bDs]=setLU00(N, verbose, varargin)
    p = inputParser;
    p.addParamValue('fprintf', @(varargin) fprintf(varargin{:}));
    p.parse(varargin{:});
    R=p.Results;
    Ffprintf=R.ffprintf;
    m=N;
    A=randn(m,m);
    if verbose
        Ffprintf('#input parameter: m-by-n matrix [%s]\n', class(A))
    end
    bDs(1)=fc_bench.bdata('m', m, '%d', 7);
    Out={A};
end
```

Listing 21: `fc_bench.demos.setLU00` function

Listing 22 : `fc_bench.demos.bench_LU00` script

```
Lfun=@(A) fc_bench.demos.permLU(A);
Comment='#benchmarking fc_bench.demos.permLU function (LU...
factorization)';
setfun=@(varargin) fc_bench.demos.setLU00(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN', 100:100:400, 'comment', Comment, ...
'info', false);
```

Output

```
#-----
# benchmarking fc_bench.demos.permLU function (LU factorization)
#-----
# input parameter: m-by-n matrix [double]
#-----
#date:2018/04/20 17:05:09
#nbruns:5
#numpy:   i4      f4
#format:  %d      %.3f
#labels:  m      permLU(s)
          100    0.012
          200    0.048
          300    0.123
          400    0.248
```

3.2.2 `fc_bench.demos.bench_LU01`

We return to the previous benchmark example to which we want to add for each `m` value the error committed:

$$\text{norm}(P*A-L*U, \text{Inf}).$$

The syntax of the `fc_bench.demos.permLU` function is

$$[L, U, P]=\text{fc_bench.demos.permLU}(A).$$

So we can defined, for each input matrix `A`, an `Error` function which only depends on the outputs (with same order)

$$\text{Error}=@(L, U, P) \text{norm}(L*U-P*A, \text{Inf});$$

This command is written in the initialization function (after initialization of returned input datas) and the handle function `Error` is appended at the end of the `Inputs` cell array. The initialization function named `fc_bench.demos.setLU01` is provided in Listing 23.

```
function [Inputs,Bdatas]=setLU01(N,verbose,varargin)
    p = inputParser;
    p.addParamValue('fprintf',@(varargin) fprintf(varargin{:}));
    p.parse(varargin{:});
    R=p.Results;
    Fprintf=R.fprintf;
    m=N;
    A=randn(m,m); % A is the input of the LU functions
    Error=@(L,U,P) norm(L*U-P*A,Inf); % A is known
    if verbose
        Fprintf('#_Prototype_ functions _without_ wrapper:_...
                [L,U,P]=fun(A)\n',class(A))
        Fprintf('#_Input_parameter_A:_m-by-n_matrix_[%s]\n',class(A))
        Fprintf('#_Outputs_are_[L,U,P]_such_that_P*A=L*U\n')
        Fprintf('#_Error[i]_computed_with_fun[i]_outputs:_\n#...
                %s\n',func2str(Error))
    end
    Bdatas(1)=fc_bench.bdata('m',m,'%d',7);
    Inputs={A,Error}; % Adding Error function handle
end
```

Listing 23: `fc_bench.demos.setLU01` function

The `fc_bench.demos.permLU` function returns multiple outputs, so we need to write a wrapper function for using it as input function in `fc_bench.bench` function. This wrapper function is very simple: it converts the three outputs `[L,U,P]` of the `fc_bench.demos.permLU` in a 1-by-3 cell array `{L,U,P}`. We give in Listing 24 an example of a such function for a generic LU factorization function given by a function handle named `fun`.

```
function R=wrapperLU(fun,A)
% wrapper of LU factorization functions (needed by fc_bench.bench function)
    [L,U,P]=fun(A);
    R={L,U,P};
end
```

Listing 24: `fc_bench.demos.wrapperLU` function

Listing 25 : `fc_bench.demos.bench_LU01` script

```
Lfun={ @(A) fc_bench.demos.wrapperLU(@(X) fc_bench.demos.permLU(X),A) };
names={'permLU'}; % Cannot guess name of the function , so one give it
Comment='#_benchmarking_LU_factorization_functions';
setfun=@(varargin) fc_bench.demos.setLU01(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'comment',Comment, ...
              'names',names,'info',false);
```

Output

```
#-----
# benchmarking LU factorization functions
#-----
# Prototype functions without wrapper: [L,U,P]=fun(A)
# Input parameter A: m-by-n matrix [double]
# Outputs are [L,U,P] such that P*A=L*U
# Error[i] computed with fun[i] outputs :
#   @(L,U,P)norm(L*U-P*A,Inf)
#-----
#date:2018/04/20 17:05:42
#nbruns:5
#numpy:   i4         f4         f4
#format:  %d         %.3f        %.3e
#labels:  m   permLU(s)   Error[0]
          100      0.012   1.019e-13
          200      0.050   3.483e-13
          300      0.129   7.411e-13
          400      0.262   1.258e-12
```

3.2.3 `fc_bench.demos.bench_LU02`

We now want to add to previous example the computational times of the `lu` Matlab function. This function accepts various number of inputs and outputs but the command

$$[L,U,P]=lu(A)$$

must give the same results as the `fc_bench.demos.permLU` function. So we can use the same initialization and wrapper functions

Listing 26 : fc_bench.demos.bench_LU02 script

```

Lfun=@(A) fc_bench.demos.wrapperLU(@lu,A), ...
      @(A) fc_bench.demos.wrapperLU(@(X) fc_bench.demos.permLU(X),A) };
names={'lu','permLU'};
Comment='#_benchmarking_LU_factorization_functions';
error=@(o1,o2) ...
      norm(o1{o1}-o2{o1},Inf)+norm(o1{o2}-o2{o2},Inf)+norm(o1{o3}-o2{o3},Inf);
setfun=@(varargin) fc_bench.demos.setLU01(varargin{:});
fc_bench.bench(Lfun, setfun, 'LN',100:100:400, 'comment',Comment, ...
              'names',names, 'error',error, 'info',false, 'labelsinfo',true);

```

Output

```

#-----
# benchmarking LU factorization functions
#-----
# Benchmarking functions:
# fun[0],      lu: @(A)fc_bench.demos.wrapperLU(@lu,A)
# fun[1],  permLU: @(A)fc_bench.demos.wrapperLU(@(X)fc_bench.demos.permLU(X),A)
# cmpErr[i], error between fun[0] and fun[i] outputs computed with function
#   @(o1,o2)norm(o1{o1}-o2{o1},Inf)+norm(o1{o2}-o2{o2},Inf)+norm(o1{o3}-o2{o3},Inf)
# where
#   - 1st input parameter is the output of fun[0]
#   - 2nd input parameter is the output of fun[i]
#-----
# Prototype functions without wrapper: [L,U,P]=fun(A)
# Input parameter A: m-by-n matrix [double]
# Outputs are [L,U,P] such that P*A=L*U
# Error[i] computed with fun[i] outputs :
#   @(L,U,P)norm(L*U-P*A,Inf)
#-----
#date:2018/04/20 17:06:16
#nbruns:5
#numpy:  i4      f4      f4      f4      f4      f4
#format: %d    %.3f    %.3e    %.3f    %.3e    %.3e
#labels:  m    lu(s)    Error[0]  permLU(s)  Error[1]  cmpErr[1]
100  0.003  8.005e-14  0.012  1.019e-13  7.296e-13
200  0.001  2.796e-13  0.049  3.483e-13  4.350e-12
300  0.002  6.575e-13  0.126  7.411e-13  1.181e-11
400  0.002  1.184e-12  0.257  1.258e-12  2.884e-11

```