

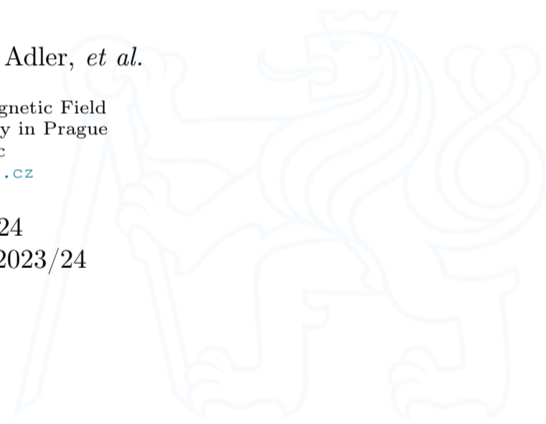
Lecture 4: Loops, Program Branching

B0B17MTB, BE0B17MTB – MATLAB

Miloslav Čapek, Viktor Adler, *et al.*

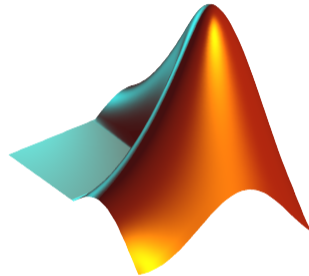
Department of Electromagnetic Field
Czech Technical University in Prague
Czech Republic
matlab@fel.cvut.cz

March 11, 2024
Summer semester 2023/24





1. Loops
2. Program Branching
3. Exercises





Loops I.

- ▶ Repeating certain operation multiple-times, one of the basic programming techniques.
- ▶ There are two types of cycles in MATLAB:
 - ▶ `for`: the most used one, number of repetitions is known in advance,
 - ▶ `while`: condition is known ensuring cycle continuation as long as it remains true.
- ▶ Essential programming principles to be observed:
 - ▶ memory allocation (matrix-related) of sufficient size,
 - ▶ cycles should be properly terminated,
 - ▶ to ensure terminating condition with `while` cycle,
 - ▶ (*more on it later*).
- ▶ Frequently, it is possible to modify array (1D \rightarrow 2D, 2D \rightarrow 3D using function `repmat` or implicit expansion of dimensions, and carry out a matrix-wise operation, vectorized code is faster under certain conditions and more understandable, possibility of utilization of GPU).
- ▶ Always ask the question: **Is the cycle really necessary?**



Loop – for I.

- ▶ `for` loop is applied to **known number of repetitions** of a group of commands:

```
for m = expression
    commands
end
```

- ▶ expression is a vector/matrix.
 - ▶ Columns of this vector/matrix are successively assigned to n/m .

```
for n = 1:4
    n
end
```

```
for m = magic(4)
    m
end
```

- ▶ Frequently, expression is generated using `linspace` or using “:”, with the help of `length`, `size`, `numel`, etc.
- ▶ Instead of m it is possible to use more relevant names as `mPoints`, `mRows`, `nSymbols`, etc.
 - ▶ For clarity, it is suitable to use, *e.g.*, `mXX` for rows and `nXX` for columns.



Loop – for II.

- ▶ Create a script calculating the factorial of N ,
 - ▶ use a cycle, verify your result using MATLAB function `factorial`.

- ▶ Can you come up with other solutions (*e.g.*, using vectorizing)?

- ▶ Compare all possibilities for decimal input N as well.



Memory Allocation

- ▶ Allocation can prevent perpetual increase of the size of a variable.
 - ▶ Code Analyser (M-Lint) will notify you about the possibility of allocation by underlining the matrix's name.
 - ▶ Whenever you know the size of a variable, allocate!
 - ▶ Sometimes, it pays off to allocate even when the final size is not known – then the worst-case scenario size of a matrix is allocated and then it may be reduced.
 - ▶ Allocate the variable of the largest size first, then the smaller ones.
- ▶ Example (try it):

```

%% WITHOUT allocation
tic;
for m = 1:1e7
    A(m) = m + m;
end
toc;
% computed in 0.45s
  
```

```

%% WITH allocation
tic;
A = nan(1,1e7);
for m= 1:1e7
    A(m) = m + m;
end
toc;
% computed in 0.06s
  
```



Loop – while I.

- ▶ Keeps on executing commands contained in the body of the cycle depending on a logical condition.

```
while condition
    commands
end
```

- ▶ Keeps on executing commands as long as **all** elements of the expression (condition can be a multidimensional matrix) are **non-zero**.
 - ▶ The condition is converted to a relational expression, *i.e.*, till all elements are true.
 - ▶ Logical and relational operators are often used for condition testing.
- ▶ If condition is not a scalar, it can be reduced using function any or all.



Typical Application of Loops

```
%% script generates N experiments with M throws with a coin
clear;
mThrows= 1e3;
nTimes= 1e2;
results= nan(mThrows, nTimes);
for iTime= 1:nTimes % however, can be even further vectorized!
    results(:, iTime) = round(rand(mThrows, 1)); % vectorized
end
```

```
%% script finds out the number of lines in a file
clear;
fileName= 'sin.m';
fid = fopen(fileName, 'r');
count = 0;
while ~feof(fid)
    line = fgetl(fid);
    count = count + 1;
end
disp(['lines:' num2str(count)])
fclose(fid);
```




Infinite Loop

- ▶ **Pay attention** to conditions in `while` cycle that are always fulfilled \Rightarrow danger of infinite loop.
 - ▶ Mostly (not always) it is a semantic error.
- ▶ Trivial, but good example of a code:

```
while 1 == 1
    disp('OK');
end
```

```
while true
    disp('OK');
end
```

- ▶ These codes “never” ends. Shortcut to terminate: CTRL+C.



Interchange of an Index and Complex Unit

- ▶ **Be careful** not to confuse complex unit (i , j) with a cycle index.
 - ▶ Try to avoid using i and j as an index.
 - ▶ Overloading can occur (applies generally, *e.g.*, `sum = 2` overloads the `sum` function).
- ▶ Find out the difference in the following pieces of code:

```
A = 0;
for i = 1:10
    A = A + 1i;
end
```

```
A = 0;
for i = 1:10
    A = A + i;
end
```

```
A = 0;
for i = 1:10
    A = A + j;
end
```

- ▶ All the commands can, in principle, be written in one line:

```
A = 0; for i = 1:10, A = A + 1i; end
```

- ▶ Usually less understandable. In general, not as fast as commands written separately line by line.



Nested Loops, Loop Combining

- ▶ Often, there is a need for a nested loops.
 - ▶ Consider vectorizing instead.
 - ▶ Consider proper loop type.
- ▶ Loop nesting usually rapidly increases computational demands.

```
%% script generates N experiments with M throws with a coin
clear;
mThrows = 1e3;
nTimes = 1e2;
results = nan(mThrows, nTimes);
for iThrow = 1:mThrows
    for iExperiment= 1:nTimes % not vectorized (30 times slower!!)
        results(iThrow, iExperiment) = round(rand(1));
    end
end
```



Loops II.

- ▶ Fill in the matrix $\mathbf{A} = [a_{mn}]$ using loops. The matrix entries read

$$a_{mn} = \frac{mn}{4} + \frac{m}{2n}.$$

- ▶ Consider $m \in \{1, \dots, 100\}$, $n \in \{1, \dots, 20\}$, allocate matrix first.
- ▶ To plot the matrix \mathbf{A} use for instance function `pcolor(A)`.



Loops III.

- ▶ In the previous task the loops can be avoided by using vectorizing.
 - ▶ Try to eliminate inner loop.
 - ▶ Try to eliminate both loops using implicitly expansions of vectors with compatible sizes.

```
close all, clear;  
M = 100;  
N = 20;  
m = (1:M) .';  
n = 1:N;  
A = (m.*n)/4 + m./(2*n);  
pcolor(A)
```



Loops IV.

- ▶ Visualize guitar string whose movement is described as

$$\mathbf{I}(x, t) = \mathbf{I}_0(x) e^{-j\omega_0 t},$$
$$\mathbf{I}_0 = \cos x, \quad \omega_0 = 2\pi.$$

- ▶ in the interval $t \in (0, 4\pi)$, $x \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$, choose $N = 101$ samples for both t and x .
- ▶ For visualization inside the loop use following piece of code:

```
figure(1);  
plot(x, real(I));  
axis([x(1) x(end) -1 1]);  
pause(0.1);
```



Commands break and continue

- ▶ Function `break` enables to terminate execution of the loop.

```

% previous code ..
for k = 1:length(v)
    if v(k) > x
        break
    end
    % another code
end

```

if true

- ▶ Function `continue` passes control to the next iteration of the loop.

```

% previous code ..
for k = 1:length(v)
    if v(k) > x
        continue
    end
    % another code
end

```

if true



Loops vs. Vectorizing I.

- ▶ Since MATLAB 6.5 there are two powerful hidden tools available:
 - ▶ *Just-In-Time accelerator* (JIT),
 - ▶ *Run-Time Type Analysis* (RTTA).
- ▶ JIT enables partial compilation of code segments.
 - ▶ Precompiled loops are even faster than vectorizing.
 - ▶ Following rules have to be observed with respect to loops:
 - ▶ Scalar index has to be used with `for` loop.
 - ▶ Only build-in functions are called inside the body of `for` loop.
 - ▶ the loop operates with scalar values only.
- ▶ RTTA assumes the same data types as during the previous course of the code – significant speed up for standardized calculations.
 - ▶ When measuring speed of the code, it is necessary to carry out so called warm-up (first run the code 2 or 3 times).



Loops vs. Vectorizing II.

- ▶ The motivation for introduction of JIT was to catch up with third-generation languages.
 - ▶ When fully utilized, JIT's computation time is comparable to that of C or Fortran.
- ▶ Highest efficiency (the highest speedup) in particular:
 - ▶ when loops operate with scalar data,
 - ▶ when no user-defined functions are called (*i.e.*, only build-in functions are called),
 - ▶ when each line of the loop uses JIT.
- ▶ As the result, some parts of the code don't have to be vectorized (or should not even be!).
- ▶ The whole topic is more complex (and simplified here).

▶ More information



Loops vs. Vectorizing III.

- ▶ Previous statement is verified using a simple code – filling a band matrix.
- ▶ Conditions for using JIT are fulfilled (working with scalars only, calling build-in functions only).
- ▶ HW and MATLAB version dependent!

```
clear; clc;
N = 5e3;
tic
mat = diag(ones(N, 1)) + ...
      2*diag(ones(N-1, 1), 1) + ...
      3*diag(ones(N-1, 1), -1);
toc % computed in 0.2182 s
```

```
mat = toeplitz([1, 3, zeros(1, N-2)], ...
              [1, 2, zeros(1, N-2)]);
% computed in 0.3428 s (2019a, Win10, i5)
```

```
clear; clc;
N = 5e3;
mat = nan(N);
tic
for n1 = 1:N
    for n2 = 1:N
        mat(n1, n2) = 0;
    end
end
for n1 = 1:N
    mat(n1, n1) = 1;
end
for n1 = 1:(N-1)
    mat(n1, n1+1) = 2;
end
for n1 = 2:N
    mat(n1, n1-1) = 3;
end
toc % computed in 0.3407 s
```



Program Branching

- ▶ If it is needed to branch the program (execute certain part of code depending on whether a condition is fulfilled), there are two basic ways:
 - ▶ `if - elseif - else - end`,
 - ▶ `switch - case - otherwise - end`.

```
if condition
    commands
elseif condition
    commands
elseif condition
    commands
else
    commands
end
```

```
switch variable
    case value1
        commands
    case {value2a, value2b}
        commands
    case value3
        commands
    otherwise
        commands
end
```

Cell data type “{ }” will be explained in detail later.



if vs. switch

`if - elseif - else - end`

It is possible to create very complex structure (&& / ||).

Function `strcmp` is used to compare strings of various lengths.

Test equality / inequality.

Great deal of logical expression is needed in the case of testing many options.

`switch - case - otherwise - end`

Simple choice of many options.

Test string directly.

Test equality only.

Enables to easily test many options using cell data type (*more on later*).

Program Branching – `if` – `elseif` – `else` I.



- ▶ The most probable option should immediately follow the `if` statement.
- ▶ Only the `if` part is obligatory.
- ▶ The `else` part is carried out only in the case where other conditions are not fulfilled.
- ▶ If $N \times M$ matrix is part of the condition, the condition is fulfilled only in the case it is fulfilled for each element of the matrix.
- ▶ The condition may contain calling a function, etc.
- ▶ `if` conditions can be nested.

```
c = randi(100)
if mod(c, 2)
    disp('c is odd');
elseif c > 10
    disp('c is even, > 10')
else
    disp('c is even, <= 10')
end
```



Program Branching – if – elseif – else II.

- ▶ 40 students pass the test with following points:

```
points = randi(100, nStudents, 1);
```

- ▶ Count how many:
 - ▶ excellent students (with 80+ points),
 - ▶ average students (with 35–79 points),
 - ▶ poor students (with less than 35 points)

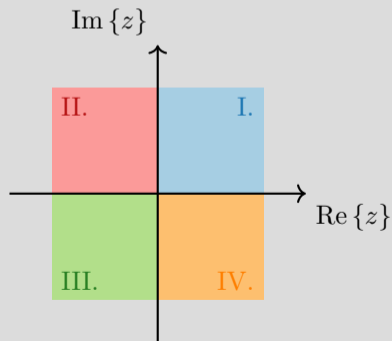
are visiting the class.

- ▶ Use `for` cycle, `if-else` statement and indexing for storing values of points.
- ▶ Can you come up with a more elegant solution? (`for` cycle is not always necessary.)



Program Branching – `if` – `elseif` – `else` III.

- ▶ Write a script generating a complex number z and determining to what quadrant the complex number belongs to.



```
phi = angle(z);  
quadrant = ceil(2*phi/pi + 4*(phi < 0))
```




Program Branching – switch – case I.

- ▶ Does a variable correspond to one of (usually many) values?
- ▶ Each `switch` must have at least one `case`, `otherwise` part is not required, but highly recommended (to deal somehow with unpredictable options).
- ▶ The commands in the part `otherwise` are carried out when none of the cases above apply.
- ▶ Suitable to evaluate conditions containing strings.
- ▶ If you want to learn more details on when to use `if` and when to use `switch`, visit:

▶ blogs.mathworks.com

```
c = 0.5*randi(100)
switch mod(c, 2)
    case 1
        disp('c is odd integer')
    case 0
        disp('c is even integer')
    otherwise
        disp('c is decimal number')
end
```



Program Branching – `switch` – `case` II.

- ▶ Depending on the given grade from important test, select the amount of money a student will receive as an reward:

Grade	Reward
1	1000
2	500
3	200
4	50
5	0

- ▶ Use `switch` – `case` statement.



Program Branching – `switch` – `case` III.

- ▶ Create a script that, given lengths of two sides of a right triangle, calculates the length of the third side (Pythagorean theorem).
 - ▶ Two sides are known together with string marking the type of unknown side ('leg' for leg or 'hyp' for hypotenuse).

```
%% HINT:  
clear, clc  
% input variables will be here  
% including type of unknown side  
switch type  
    case 'hyp'  
        % calculation here  
    case 'leg'  
        % calculation here  
    otherwise % unknown values  
        % return empty (default) values  
end
```



Program Branching – `switch` – `case` III.

- ▶ Create a script that, given lengths of two sides of a right triangle, calculates the length of the third side (Pythagorean theorem).
 - ▶ Two sides are known together with string marking the type of unknown side ('leg' for leg or 'hyp' for hypotenuse).

```
clear, clc
s1 = 4;
s2 = 3;
type = 'hyp';
switch type
    case 'hyp'
        c = sqrt(s1^2 + s2^2);
    case 'leg'
        a = sqrt(max(s1, s2)^2 - min(s1, s2)^2);
    otherwise
        c = 0; a = 0;
end
```



What Does the Script Do? I.

- ▶ Try to estimate what the script below assigns to `logResult` variable depending on input variable `vec` (a vector).
- ▶ Are you able to decide whether there is a MATLAB function doing the same?

```
% vec is a given vector
logResult = false;
m = 1;
while (m <= length(vec)) && (logResult == false)
    if vec(m) ~= 0
        logResult = true;
    end
    m = m + 1;
end
```



What Does the Script Do? II.

- ▶ Try to estimate what the script below assigns to `logResult` variable depending on input variable `mat` (a matrix).
- ▶ Are you able to decide whether there is a MATLAB function doing the same?

```
% mat is a given matrix
count = 0;
[mRows, nColumns] = size(mat);
for m = 1:mRows
    for n = 1:nColumns
        if mat(m, n) ~= 0
            count = count + 1;
        end
    end
end
logResult = count == numel(mat);
```



Example of Listing More Options In `switch - case`

- ▶ `switch` supports options listing
 - ▶ Evaluation of values A1 and A2 in the same way:

```
switch my_expression
  case {A1, A2}
    % do something
  otherwise
    % do something else
end
```



Infinite Loop – `for` Cycle (A Riddle)

- ▶ In this lecture we learned how to construct infinite loop with `while` cycle command (`>> while true, disp('ok'), end`).
 - ▶ Do you think, that the infinite loop can be constructed with the `for` cycle as well?
 - ▶ How?
 - ▶ Are there any restrictions? How many cycles will be performed and why?

Exercises

Exercise I.a



- Fibonacci sequence: $F_1 = 1$, $F_2 = 1$, $F_n = F_{n-1} + F_{n-2}$ for $n > 2$.

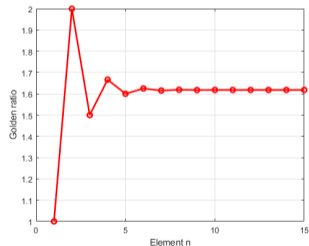
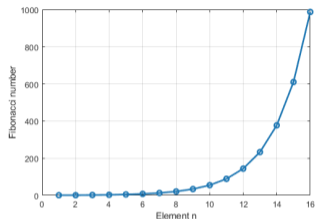


Exercise I.b

- ▶ Draw a script to calculate values of Fibonacci sequence up to a certain value limit.
 - ▶ plot the resulting series using function: `figure(1), plot(F, '-o')`
- ▶ Calculate the length of the Fibonacci spiral.
- ▶ Calculate approximations to the golden ratio:

$$\varphi = \lim_{n \rightarrow \infty} \frac{F_{n+1}}{F_n} = \frac{1 + \sqrt{5}}{2} \approx 1.618033$$

- ▶ plot it: `figure(2), plot(phi, '-or')`





Exercise II.a

- ▶ Create vector $\mathbf{v} \in \mathbb{C}^{4 \times 1}$ which contains one complex number from each quadrant.

$$\operatorname{Re}\{v_1\} > 0, \operatorname{Im}\{v_1\} > 0$$

$$\operatorname{Re}\{v_3\} < 0, \operatorname{Im}\{v_3\} < 0$$

$$\operatorname{Re}\{v_2\} > 0, \operatorname{Im}\{v_2\} < 0$$

$$\operatorname{Re}\{v_4\} < 0, \operatorname{Im}\{v_4\} > 0$$

- ▶ Prepare a code which can generate random complex number. Determine its quadrant and save it into \mathbf{v} . Repeat the process until vector \mathbf{v} is not full.



Exercise II.b

- ▶ Can you do the same without loop and program branching?



Exercise III.a

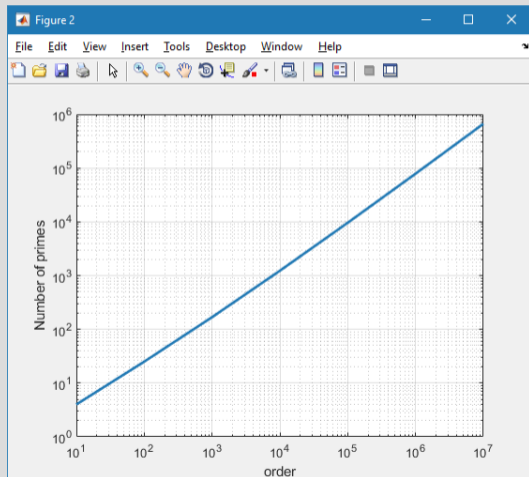
- ▶ Try to determine the density of prime numbers:
 - ▶ examine the functions `primes` generating prime numbers,
 - ▶ for the orders $10^1 - 10^7$ determine the primes density (*i.e.*, the number of primes up to 10, to 100, ..., to 10^7).
 - ▶ Outline the dependence using `plot`.
 - ▶ Display results in logarithmic scale,
 - ▶ `loglog(xData, yData)`.
 - ▶ How does the plot change?

```
%% density of prime numbers
clear, clc, close all
N = 7;
nPrimes = % allocate here
orders = % vector of orders 10^1-10^7
% your code here..
% ..
% ..
% ..
figure, plot(nPrimes)
figure, loglog(orders, nPrimes)
```



Exercise III.b

- ▶ Can the script be speeded-up?
- ▶ What does, in your view, have the dominant impact on computation time?
- ▶ Is it necessary to compute primes in every loop?





Exercise IV.a

- ▶ Following expansion holds true:

$$\arctan(x) = \sum_{n=0}^{\infty} (-1)^n \frac{x^{2n+1}}{2n+1} = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \frac{x^9}{9} - \dots$$

- ▶ Based on the expansion for $x = 1$ estimate value of π :

$$\arctan(1) = \frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \dots$$

- ▶ Determine the number of elements of the sum and computational time required to achieve estimation accuracy better than $1 \cdot 10^{-6}$.



Exercise IV.b

- ▶ Estimate value of π using following expansion:

$$\frac{\pi}{8} = \sum_{n=0}^{\infty} \frac{1}{(4n+1)(4n+3)} = \frac{1}{1 \cdot 3} + \frac{1}{5 \cdot 7} + \frac{1}{9 \cdot 11} + \dots$$

- ▶ Approximate value of π using following expansion with the expansion for $\arctan(x)$ from the previous slide:

$$\frac{\pi}{4} = 6\arctan\left(\frac{1}{8}\right) + 2\arctan\left(\frac{1}{57}\right) + \arctan\left(\frac{1}{239}\right)$$

- ▶ Determine the number of elements of the sum and computational time required to achieve estimation accuracy better than $1 \cdot 10^{-6}$.
- ▶ Compare all three solutions.



Exercise IV. – Solution

```
n1 = 0;
err = 1e-6;
estPi1 = 0;
while abs(estPi1 - pi/4) > err
    estPi1 = estPi1 + ...
        (-1)^n1 * 1/(2*n1+1);
    n1 = n1+1;
end % n1 = 250001
```

```
n2 = 0;
estPi2 = 0;
while abs(estPi2 - pi/8) > err
    estPi2 = estPi2 + ...
        1/((4*n2+1) * (4*n2+3));
    n2 = n2+1;
end % n2 = 62500
```

```
n3 = 0;
estPi3 = 0;
argumentValues = [1/8, 1/57, 1/239];
coefs = [6, 2, 1];
while abs(estPi3 - pi/4) > err
    estPi3 = 0;
    for iValue = 1:3
        x = argumentValues(iValue);
        n = 0:n3;
        y = sum((-1).^n .* x.^(2*n+1) ./ ...
            (2*n+1));
        estPi3 = estPi3 + coefs(iValue) * y;
    end
    n3 = n3 + 1;
end % n3 = 3
```

Questions?

B0B17MTB, BE0B17MTB – MATLAB
matlab@fel.cvut.cz

March 11, 2024
Summer semester 2023/24

This document has been created as a part of B(E)0B17MTB course.
Apart from educational purposes at CTU in Prague, this document may be reproduced, stored, or transmitted only with the prior permission of the authors.

Acknowledgement: Filip Kozák, Pavel Valtr, Michal Mašek, and Vít Losenický.