Matlab and Programming

Programming basics and algorithms

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Part I

Matlab introduction

Today's outline

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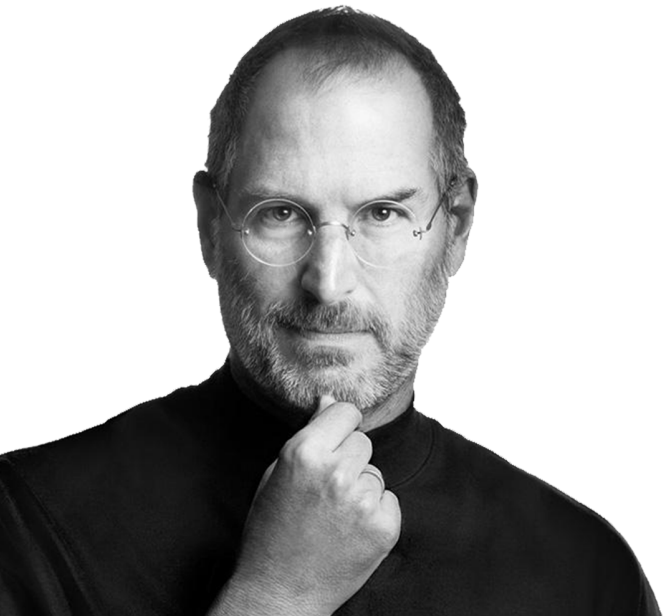
Programming

"Everybody in this country should learn to program a computer, because it teaches you to think.."

—Steve Jobs



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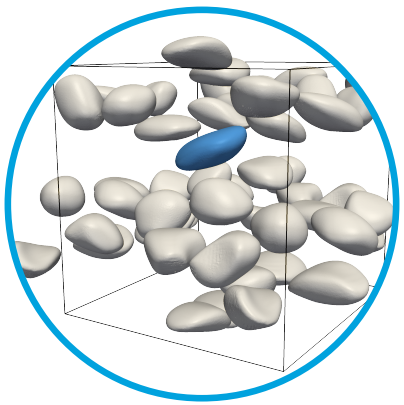
- Scientific techniques depend in an increasing fashion upon computer programs and simulation methods



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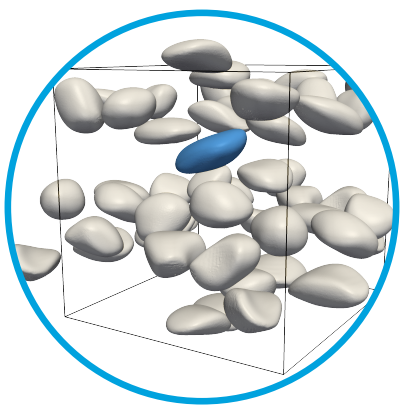

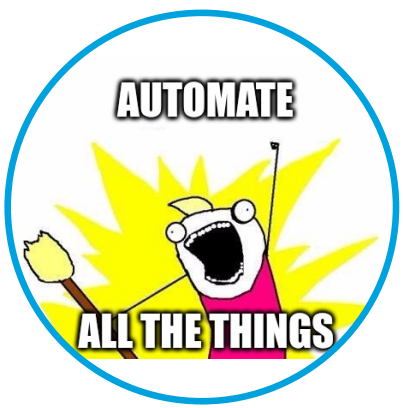

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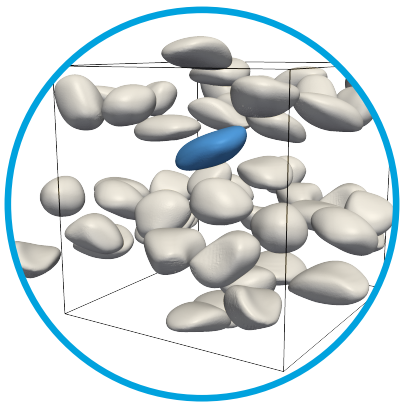
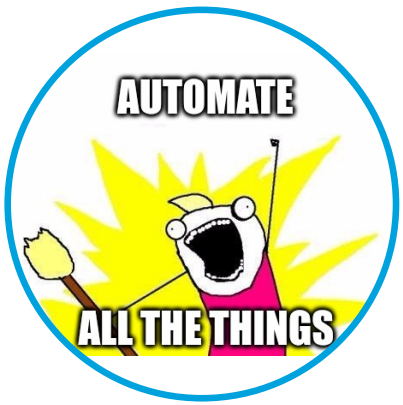
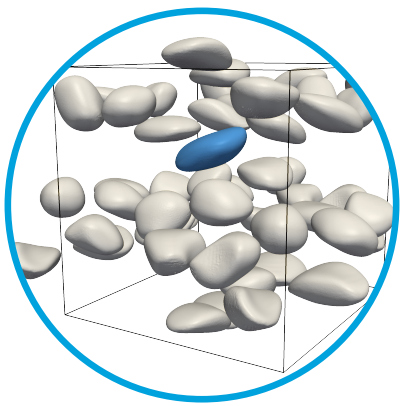
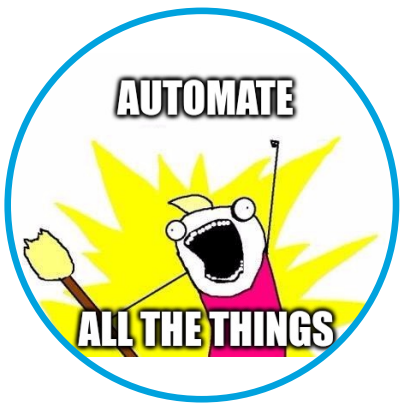




Why?

- Scientific techniques depend in an increasing fashion upon computer programs and simulation methods
- Knowledge of programming allows you to automate routine tasks
- Ability to understand algorithms by inspection of the code
- Learn to think by dissecting a problem into smaller bits





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>> 8/a-b
>> sin(a)         % Mathematical functions can be used
>> sin(0.5*pi)    % pi is an internal Matlab variable
>> 1/0            % Infinity is a thing ...
>> sqrt(-1)       % ... as are imaginary numbers
```

Introduction to programming

What is a program?

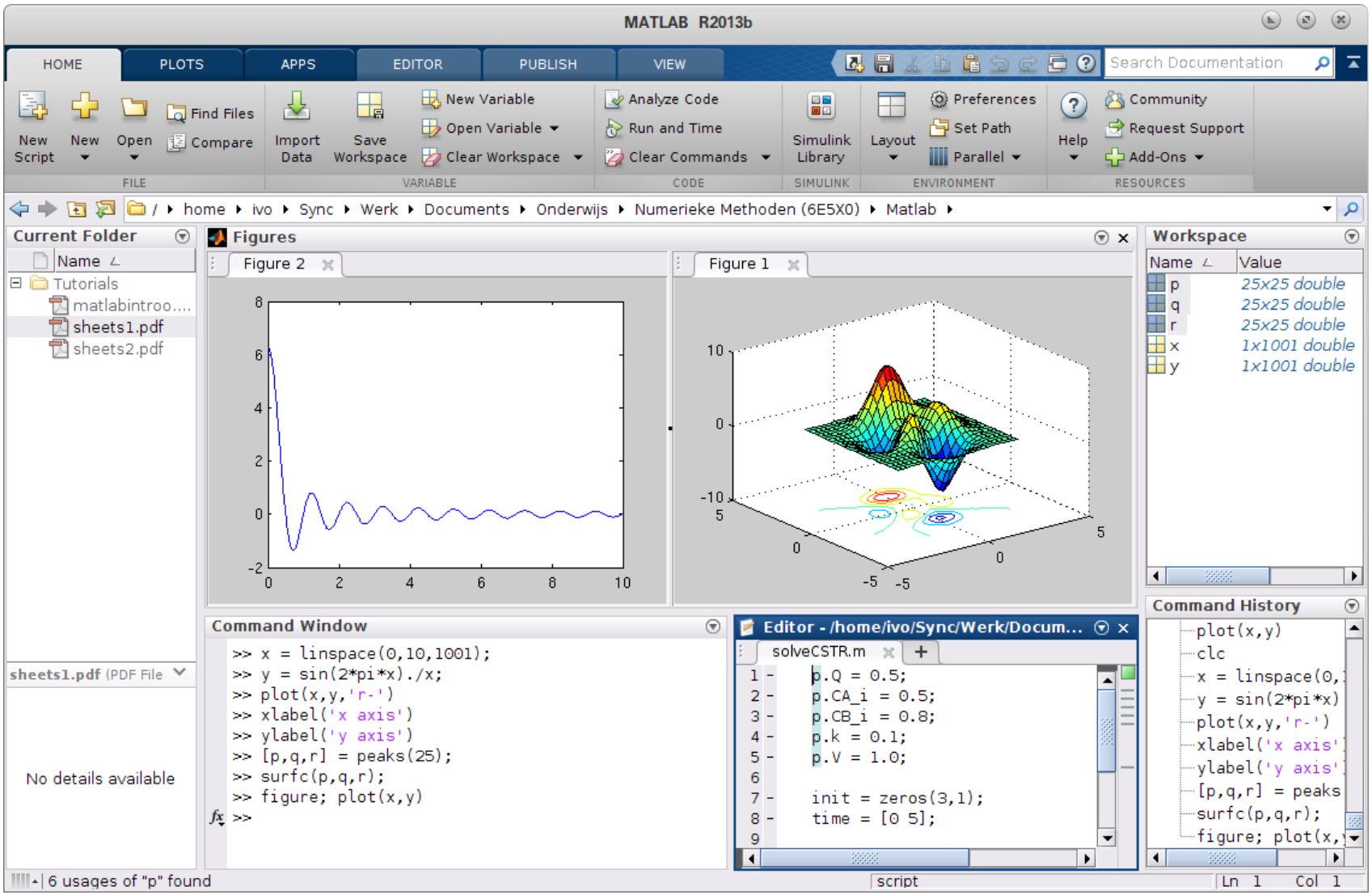
A program is a sequence of instructions that is written to perform a certain task on a computer.

- The computation might be something mathematical, a symbolic operation, image analysis, etc.

Program layout

1. Input (Get the radius of a circle)
2. Operations (Compute and store the area of the circle)
3. Output (Print the area to the screen)

Versatility of Matlab

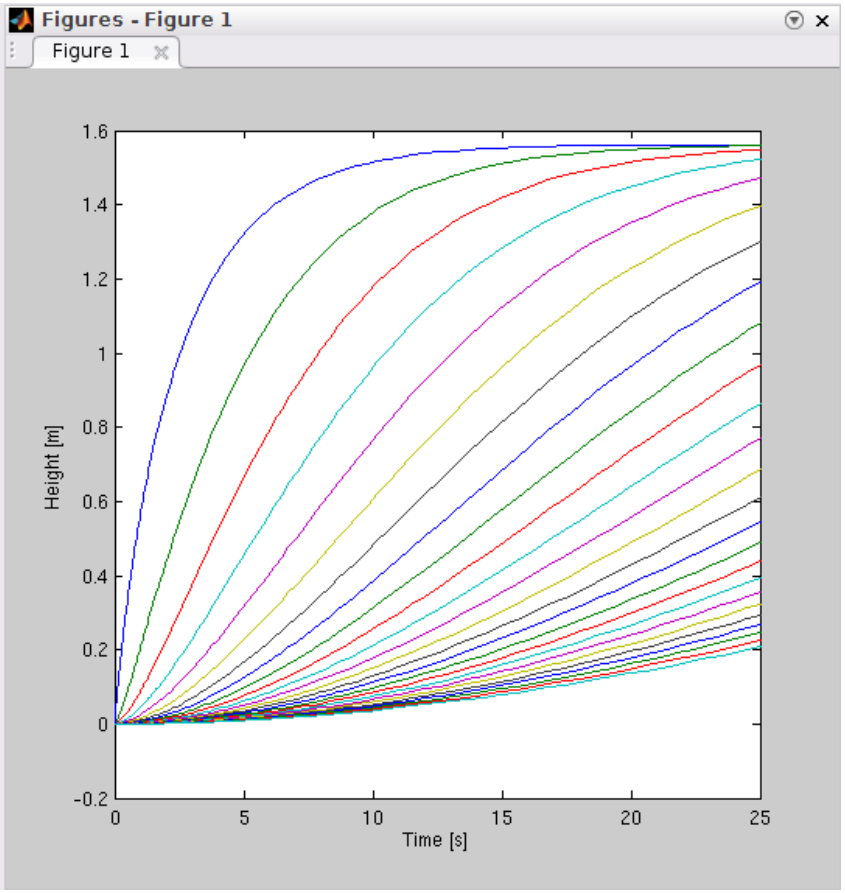


Versatility of Matlab: ODE solver

Editor - /mnt/data/BittorrentSync/Werk/Documents/Onderwijs/Pra...

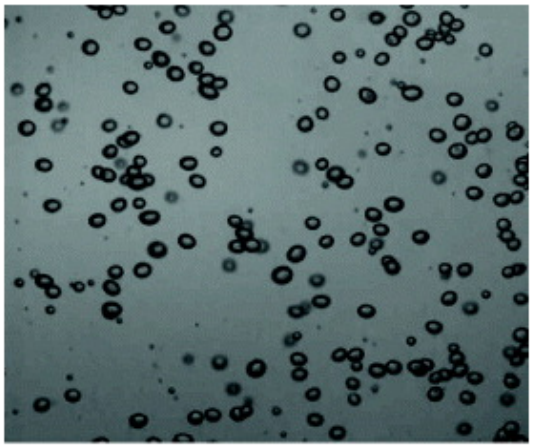
solveTankSeries.m | tankSeries.m

```
1 -    p.F0 = 1.0;
2 -    p.K = 0.8;
3 -    p.N = 25;
4 -    p.A = 1.0;
5
6 -    init = zeros(p.N,1);
7 -    time = [0 25];
8
9 -    [t,h] = ode45(@tankSeries,time,init,[],p);
10
11 -   plot(t,h);
12 -   xlabel('Time [s]');
13 -   ylabel('Height [m]');
```



Versatility of Matlab: Image analysis

```
I = imread('bubbles.png');
BW = rgb2gray(I);
E = edge(BW, 'canny');
F = imfill(E, 'holes');
result = regionprops(F);
```



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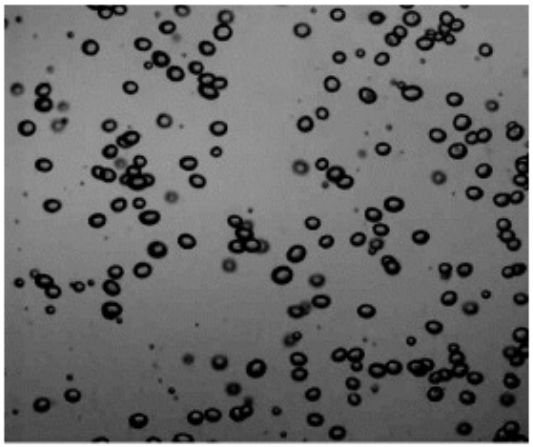

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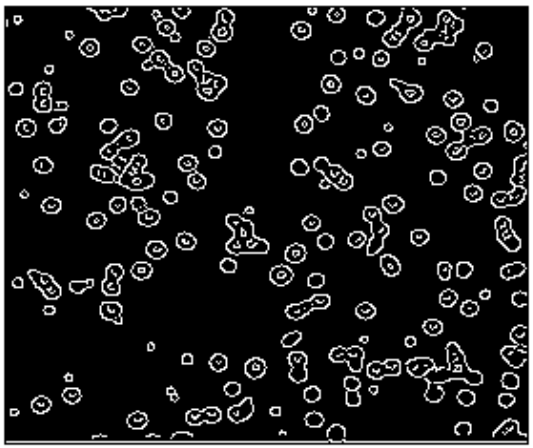

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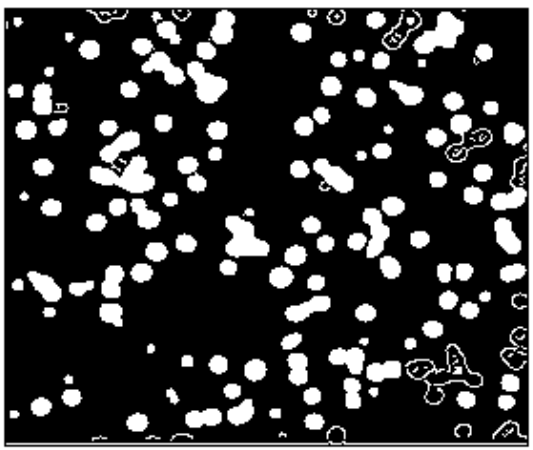
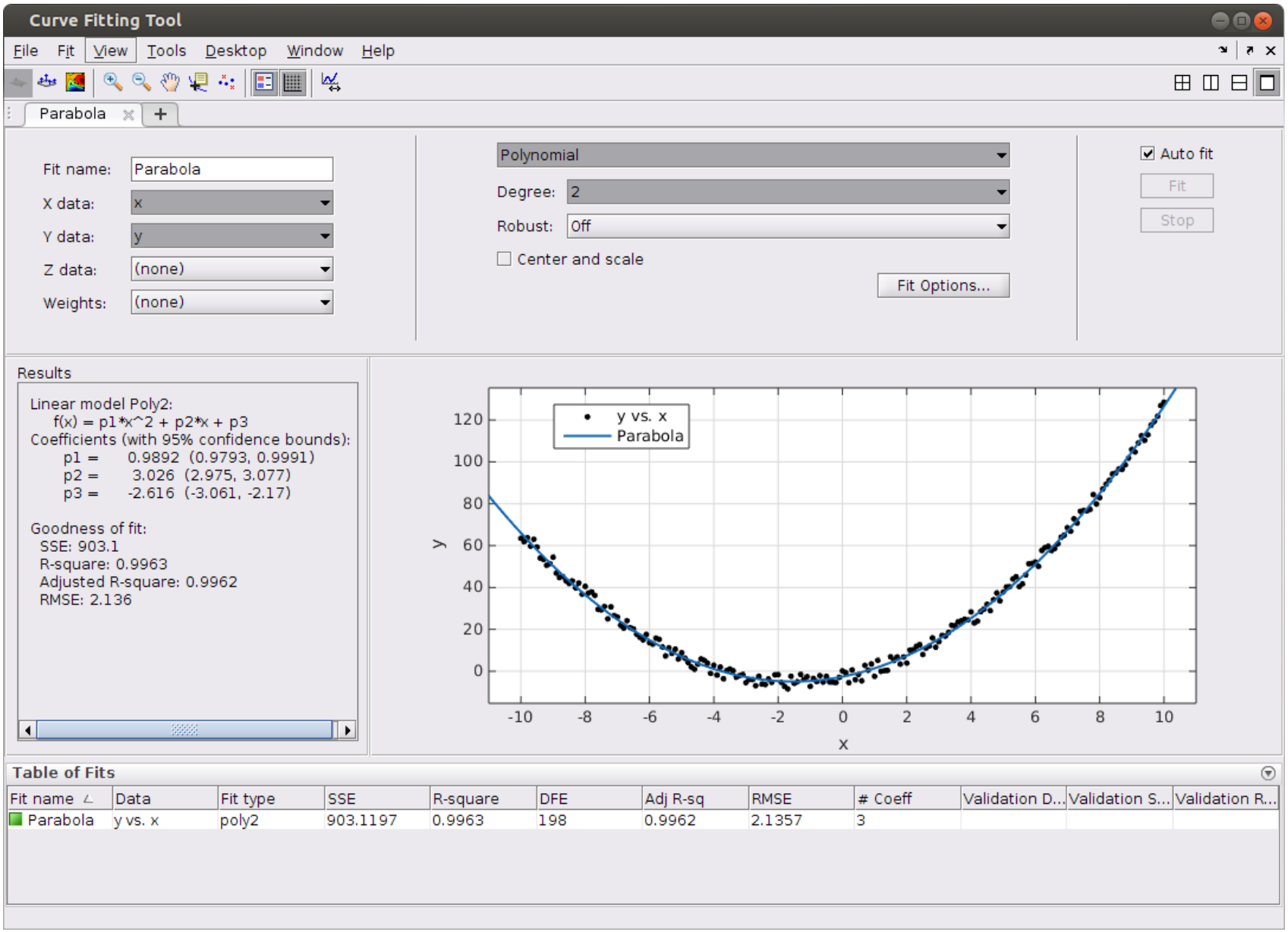


Versatility of Matlab: Curve fitting



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- Search the web!

Today's outline

Terminology

Variable Piece of data stored in the computer memory, to be referenced and/or manipulated

Function Piece of code that performs a certain operation/sequence of operations on given input

Operators Mathematical operators (e.g. `+` `-` `*` or `/`), relational (e.g. `<` `>`or `==`, and logical operators (`&&`, `||`)

Script Piece of code that performs a certain sequence of operations without specified input/output

Expression A command that combines variables, functions, operators and/or values to produce a result.

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- If you don't assign a variable, it will be stored in `ans`
- Clearing the workspace is done with `clear`.

Datatypes and variables

Matlab uses different types of variables:

Datatype	Example
`string`	`'Wednesday'`
`integer`	`15`
`float`	`0.15`
`vector`	`[0.0; 0.1; 0.2]`
`matrix`	`[0.0 0.1 0.2; 0.3 0.4 0.5]`
`struct`	`sct.name = 'MyDataName'`
	`sct.number = 13`
`logical`	`0` (false)
	`1` (true)

About variables

- Matlab variables can change their type as the program proceeds (this is not common for other programming languages!):

```
>> s = 'This is a string'
s =
This is a string
>> s = 10
s =
     10
```

- Vectors and matrices are essentially *arrays* of another data type. A vector of `struct` is therefore possible.
- Variables are *local* to a function (more on this later).

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A row vector:

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Transposing vectors:

```
>> w = v'
```

Vectors in Matlab (2)

Manual definition may be cumbersome. A colon (:) generates a list:

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>> a = 1:10        % Default stride is 1
>> x = -1:.1:1     % start:stride:stop specifies list
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```

Or (by supplying a vector instead of a scalar):

```
>> y([1 4:7]) = 16:20 % equivalent to y([1 4 5 6 7]) =
     [16 17 18 19 20]
```

Practice

Given a vector

$$x = [2\ 4\ 6\ 8\ 10\ 12\ 14\ 16\ 18\ 20\ 30\ 40\ 50\ 60\ 70\ 80]$$

- Find a way to define the vector without typing all individual elements

Practice

Given a vector

$$x = [2\ 4\ 6\ 8\ 10\ 12\ 14\ 16\ 18\ 20\ 30\ 40\ 50\ 60\ 70\ 80]$$

- Find a way to define the vector without typing all individual elements
- Investigate the meaning of the following commands:

```
>> y = x(5:end)
>> y(4)
>> y(4) = []
>> sum(x)
>> mean(x)
>> std(x)
>> max(x)
>> fliplr(x)
>> diff(x)
```

Operations on vectors (1)

```
>> e = 1:5
>> f = 2*e
>> g = 4*f + 20
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To compute elementwise POWER, use POWER (.^) instead.
```

Matlab uses matrix operations by default, we should use a dot operator to make operations element-wise for `*`, `/` and `^`.

```
>> e.^2
```

Operations on vectors (2)

To demonstrate the matrix product:

```
>> p = [1; 1; 1]
>> q = [1 2 3]
>> p*q   % which is not equal to q*p
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```

All kinds of mathematical functions on vectors typically operate on elements:

```
>> x = linspace(0,2*pi,100);
>> s = sin(x)
>> e = exp(x)
```

Building blocks: Mathematics and number manipulation

Programming languages usually support the use of various mathematical functions (sometimes via a specialized library). Some examples of the most elementary functions in Matlab:

Command	Explanation
`cos(x), sin(x), tan(x)`	Cosine, sine or tangens of x
`mean(x), std(x)`	Mean, st. deviation of vector x
`exp(x)`	Value of the exponential function e^x
`log10(x), log(x)`	Base-10/Natural logarithm of x
`floor(x)`	Largest integer smaller than x
`ceil(x)`	Smallest integer that exceeds x
`abs(x)`	Absolute value of x
`size(x)`	Size of a vector x
`length(x)`	Number of elements in a vector x
`rem(x,y)`	Remainder of division of x by y

Printing results

You can prevent displaying the outcome of a command by adding a semi-colon at the end of a line:

```
>> c = linspace(0,10,11);
>> length(c)
>> c
>> size(c)
```

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```
>> c = linspace(0,10,11);
>> length(c)
>> c
>> size(c)
```

Altering the display format can be done using the `format` command:

```
>> format compact % loose
>> format long    % short
```

Simple plotting

Make a plot of the following table

T (°C)	5	20	30	50	55
μ (Pa·s)	0.08	0.015	0.009	0.006	0.0055

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>> T = [ 5 20 30 50 55 ]
>> mu = [ 0.08 0.015 0.009 0.006 0.0055]
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```
>> plot(T,mu)
```

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>> xlabel('Temperature [^\circC]')
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>> title('Experiment 1')
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>> plot(T,mu,'*')
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>> plot(T,mu,'r--')
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```
>> plot(T,mu,'ko-','LineWidth',2)
```

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>> xlabel('Temperature [^\circC]')
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Practice

Create plots of the following functions in a single figure for $x \in \{0, 2\pi\}$:

$$y_1 = \cos x$$

$$y_2 = \arctan x$$

$$y_3 = \frac{\sin x}{x}$$

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Strategies to draw multiple graphs in 1 figure:

```
>> plot(x,y1,x,y2,x,y3)
```

```
>> plot(x,y1)
>> hold on; % Maintain drawn plots in current figure
>> plot(x,y2)
>> plot(x,y3) % The 'hold-property' was already set
```

Matrices in Matlab

Matrix A is defined as:

$$A = \begin{bmatrix} 8 & 1 & 6 \\ 3 & 5 & 7 \\ 4 & 9 & 2 \end{bmatrix}$$

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```

Elements can be accessed/manipulated by the following syntax:

```
>> A(3,1) % Third row, first column, also A(3)
>> A(3,:) = [2 4 8] % Set entire third row
>> A(:,3) % Print third column
>> A(A>5) = 2 % Set elements by condition
```

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In Matlab:

```
>> A = [ 8 1 6; 3 5 7; 4 9 2]
```

Elements can be accessed/manipulated by the following syntax:

```
>> A(3,1) % Third row, first column, also A(3)
>> A(3,:) = [2 4 8] % Set entire third row
>> A(:,3) % Print third column
>> A(A>5) = 2 % Set elements by condition
```

There are a few functions that help creating matrices:

```
>> A = zeros(4)   % A 4x4 matrix with zeros
>> A = ones(4,1) % A 4-element vector with ones
>> A = eye(3)     % Identity matrix of 3x3
>> A = rand(3,4) % A 3x4 matrix with random numbers
```

Practice

- Find a *short* Matlab expression to create the following matrix:

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 9 & 7 & 5 & 3 & 1 & -1 & -3 \\ 4 & 8 & 16 & 32 & 64 & 128 & 256 \end{bmatrix}$$

Practice

- Find a *short* Matlab expression to create the following matrix:

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- Investigate the command `max(A)`. What does it give?

Today's outline

Building blocks: conditional statements

`if`-statement: Check whether a (set of) condition(s) is met.

Building blocks: conditional statements

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```
num = floor (10 * rand + 1);
guess = input ('Your guess please : ');
if ( guess ~= num )
  disp (['Wrong, it was ',num2str(num),'. Kbye.']);
else
    disp ('Correct !') ;
end
```

Building blocks: conditional statements

`if`-statement: Check whether a (set of) condition(s) is met.

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else
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end
```

Other relational operators

==	is equal to
<=	is less than or equal to
>=	is greater than or equal to
<	is less than
>	is greater than

Combining conditional statements

&&	and
||	or
xor	exclusive or

Building blocks: loops

`for`-loop: Performs a block of code a certain number of times.

Building blocks: loops

`for`-loop: Performs a block of code a certain number of times.

```
>> p(1) = 1;
>> p(2) = 1;
>> for i = 2:10
p(i+1) = p(i)+p(i-1);
end
>> p
p =
    1    1    2    3    5    8   13   21   34   55   89
```

Building blocks: indeterminate repetition

`while`-loop: Performs and repeats a block of code until a certain condition.

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`while`-loop: Performs and repeats a block of code until a certain condition.

```
num = floor (10* rand +1) ;
guess = input ('Your guess please : ');

while ( guess ~= num )
    guess = input ('That is wrong. Try again ... ');
end

if (isempty(guess))
    disp('No number supplied - exit');
else
    disp ('Correct!');
end
```

Example algorithm

Compute the factorial of N: $N! = N \cdot (N-1) \cdot (N-2) \cdots 2 \cdot 1$

How to deal with this?

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Z = Z*3;
Z = Z*4;
... etc ...
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For-loop

```
Z = 1;
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end
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... etc ...
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For-loop

```
Z = 1;
for i = 1:N
    Z = Z*i;
end
```

While-loop

```
Z = 1;
i = 1;
while (i<=N)
    Z = Z*i;
    i = i+1;
end
```

Note: `N` must be set beforehand!

Note: Pay attention to the relational operators!

Building blocks: case selection

`switch`-statement: Selects and runs a block of code.

Building blocks: case selection

`switch`-statement: Selects and runs a block of code.

```
[dnum,dnam] = weekday(now);
switch dnum
    case {1,7}
        disp('Yay! It is weekend!');
    case 6
        disp('Hooray! It is Friday!');
    case {2,3,4,5}
        disp(['Today is ' dnam]);
    otherwise
        disp('Today is not a good day...');
end
```

Input and output

Many programs require some input to function correctly. A combination of the following is common:

- Input may be given in a parameters file ("hard-coded")

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```

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```
>> a = input('Please enter the number ');
```

- Input may be read from a file, e.g.

```
>> data = getfield(importdata('myData.txt', ' ',
    4), 'data');
>> numdata = xlsread('myExcelDataFile.xls');
```

Input and output

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    4), 'data');
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```

- There are many more advanced functions, e.g. `fread`, `fgets`, ...

Input and output

Output of results to screen, storing arrays to a file or exporting a graphic are the most common ways of getting data out of Matlab:

- Results of each expression are automatically shown on screen as long as the line is not ended with a semi-colon;

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- Save variables automatically (scripted):

```
>> savefile = 'test.mat';
>> p = rand(1,10);
>> q = ones(10);
>> save(savefile,'p','q')
```

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>> savefile = 'test.mat';
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>> save(savefile,'p','q')
```

- More advanced functions can be found in e.g. `fwrite`, `fprintf`, ...

Today's outline

Functions - general

A function in a programming language is a program fragment that performs a certain task. Creating functions keeps your code clean, re-usable and structured.

- You can use functions supplied by the programming language, and define functions yourself
- Functions take one or more input parameters (*arguments*), and *return* an output (result).
  - If functions do not return a result, it is called a procedure
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- In Matlab, functions are defined as follows (2 output variables and 3 input arguments):

```
function [out1, out2] = myFunction(in1, in2, in3)
```

Functions - locality and arguments

- You are supplying arguments to a function because it does not have acces to previously defined variables. This is called *locality*.
  - This does not include global variables - but they're evil!
  - Local variables created in a function are not accessible to other functions unless they are returned or supplied as an argument!

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  - This does not include global variables - but they're evil!
  - Local variables created in a function are not accessible to other functions unless they are returned or supplied as an argument!

Example: write a function that takes 3 variables, and returns the average:

Approach 1

```
function res = avg1(a,b,c)
    mySum = a + b + c;
    res = mySum / 3;
end
```

Approach 2

```
function res = avg2(a,b,c)
    data = [a; b; c];
    res = mean(data);
end
```

Exercise: create a function

Compute $N! = N \cdot (N-1) \cdot (N-2) \cdots 2 \cdot 1$

Create a function of our while-loop approach with N the argument:

Original script

```
Z = 1;
i = 1;
while (i<=N)
    Z = Z*i;
    i = i+1;
end
```

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```
Z = 1;
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end
```

Function

```
function Z = fact_while(N)

Z = 1;
i = 1;
while (i<=N)
    Z = Z*i;
    i = i+1;
end

end
```

Functions - checking input

The function we created computes the factorial correctly!

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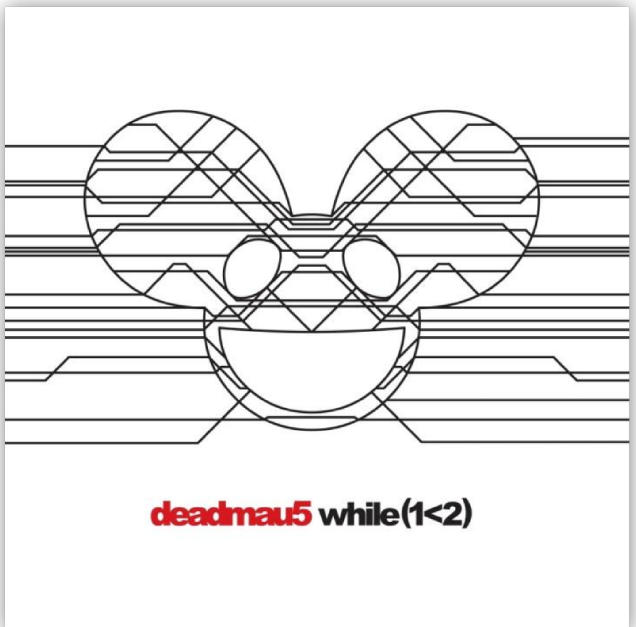

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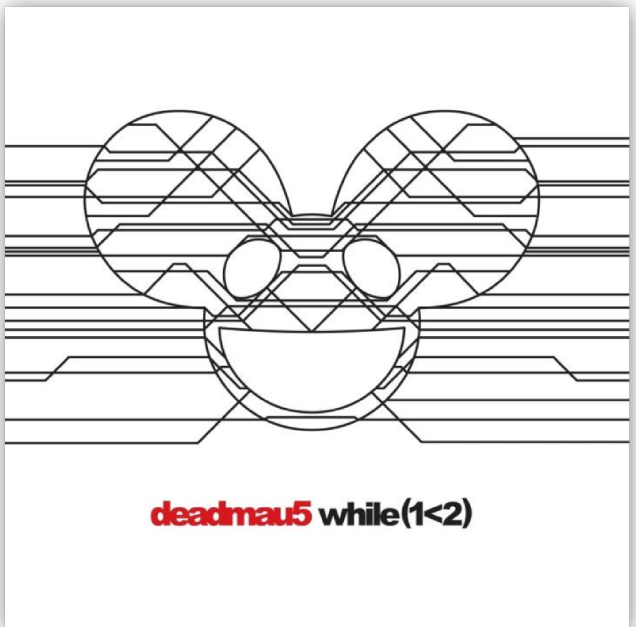

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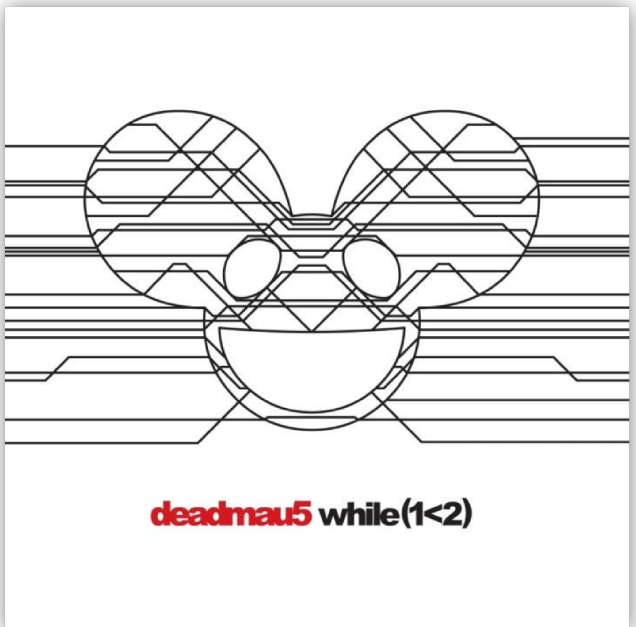

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Functions - checking input

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- In this case, we should check the user input to prevent an infinite loop:

```
if (fix(N)~=N) | (N<0)
    disp 'Provide a positive
         integer number!'
    return;
end
```

- If no check can be done before a while-loop, you may want to stop after x loops

Functions - checking input

The whole factorial function, including comments:

```
function Z = fact_while(N)
%% This function computes a factorial of input value N
% Usage  : fact_while(N)
% N      : value of which the factorial is computed
% returns: factorial of N

% Catch non-integer case
if (fix(N)~=N) | (N<0)
    disp 'Provide a positive integer number!'
    return;
end

Z = 1;
i = 1;
while (i<=N)
    Z = Z*i;
    i = i+1;
end
```

Recursion

- In order to understand recursion, one must first understand recursion

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- In order to understand recursion, one must first understand recursion
- A recursive function is called by itself (a function within a function)
  - This could lead to infinite calls;
  - A base case is required so that recursion is stopped;
  - Base case does not call itself, simply returns.

Recursion: example

```
function out = mystery(a,b)
if (b == 1)
    % Base case
    out = a;
else
    % Recursive function call
    out = a + mystery(a,b-1);
end
```

Recursion: example

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- What does this function do?

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- What does this function do?
- Can you spot the error?

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    out = a;
else
    % Recursive function call
    out = a + mystery(a,b-1);
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```

- What does this function do?
- Can you spot the error?
- How deep can you go? Which values of b don't work anymore?

Recursion: exercise

Create a function computing the factorial of N, based on recursion.

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Create a function computing the factorial of N, based on recursion.

```
function res = fact_recursive(x)

% Catch non-integer case
if (fix(x)~=x) | (x<0)
    disp 'You should provide a positive integer number
        only'
    return;
end

if (x > 1)
    res = x*fact_recursive(x-1);
else
    res = 1;
end

end
```

Part II

Code management

Today's outline

Today's outline

If anything sticks today, let it be this

Your code will not be understood by anyone

If anything sticks today, let it be this

Your code will not be understood by anyone

That includes future-you

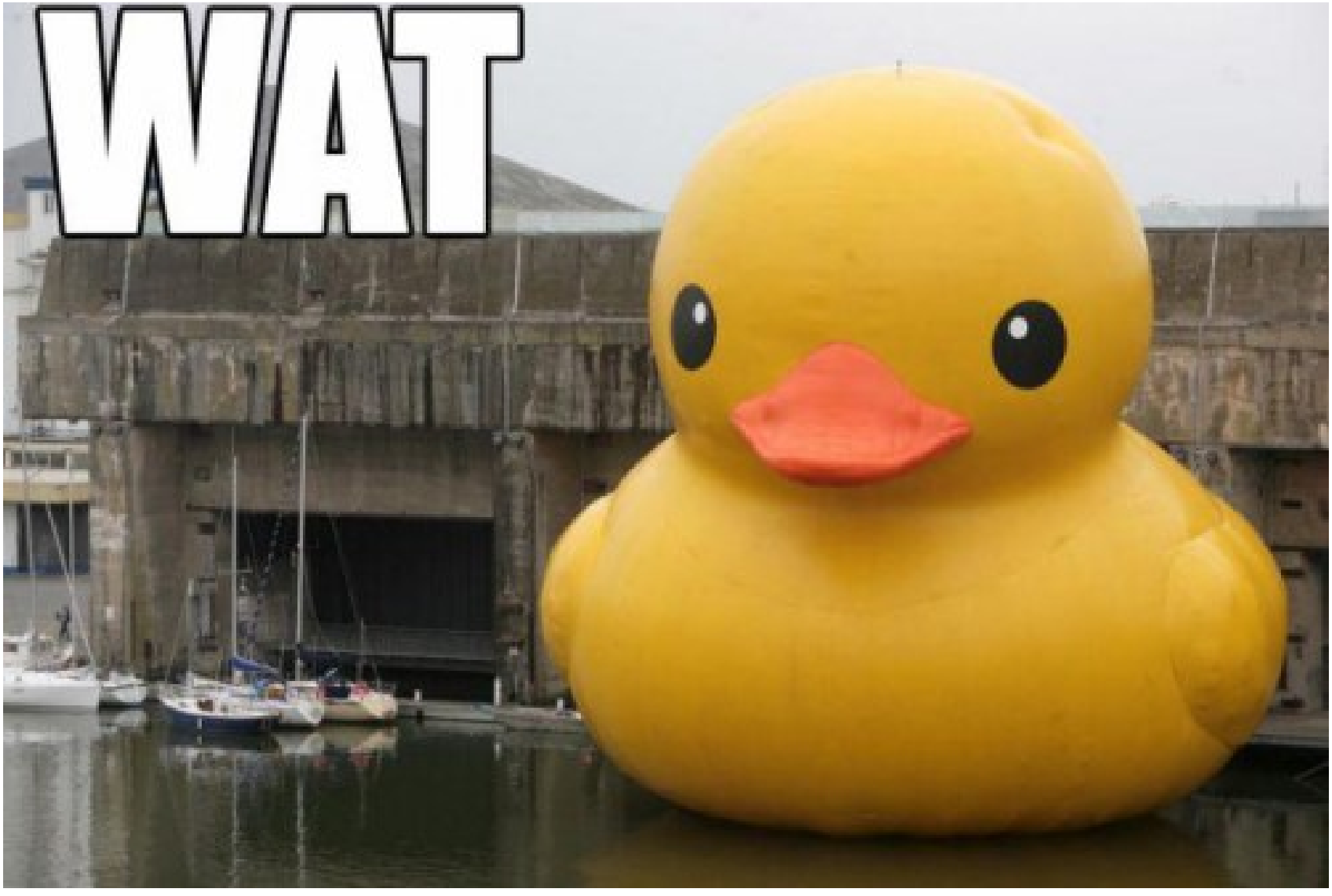
Code organization

- Optimization of a code is time-consuming and complicated
- The more you optimize your code, the less readable it becomes
- But... You can write it in a such way that it will be flexible and easy to maintain
- Especially important in team work
- Any person has its own handwriting. Any programmer has its own coding style.

The coding style ≡ handwriting...

Interpret the following code

```
s=checksc();
if(s==true)
a=cb();
b=cfrsp();
if(a<5)
if(b>5)
a=gtbs();
end
if(a>b)
ubx();
end
end
else
brn();
gtbs();
end
```


WAT

Let's change that a bit... Indentation

Let's change that a bit... Indentation

Shown here with 2 spaces of indentation, Matlab uses 4 by default!

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```

Readable variables and function names

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if (s == true)
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    end
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    brn();
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end
```

```
IAmFree = checkSchedule();
if (IAmFree == true)
  books = countBooks();
  shelfSize =
      countFreeSpaceShelf();
  if (books < 5)
    if (shelfSize > 5)
      books = goToBookStore();
    end
    if (books > shelfSize)
      useBox();
    end
  end
else
  burnBooks();
  goToBookStore();
end
```

Get rid of obscure constants in the code

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if (IAmFree == true)
  books = countBooks();
  shelfSize =
      countFreeSpaceShelf();
  if (books < maxShelfSize)
    if (shelfSize >
        minBooksNeeded)
      books = goToBookStore();
    end
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That's more like it!

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Writing readable code

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- When it doesn't, make sure to use comments. In Matlab, everything following `% is a comment`
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- Re-use working code (i.e. create functions for well-defined tasks).
- Documentation is also useful, but hard to maintain.

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- Re-use working code (i.e. create functions for well-defined tasks).
- Documentation is also useful, but hard to maintain. (Matlab comes with a function that generates reports from comments)

How not to comment

- Useless:

```
% Start program
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```
% Well... I do not know how to explain what is going on
% in the snippet below. I tried to code in the night
% with some booze and it worked then, but now I have a
% strong hangover and some parameters still need to be
% worked out...
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% with some booze and it worked then, but now I have a
% strong hangover and some parameters still need to be
% worked out...
```

- ...

```
% You may think that this function is obsolete, and doesn't seem to
% do anything. And you would be correct. But when we remove this
% function for some reason the whole program crashes and we can't
% figure out why, so here it will stay.
```

Adding comments to our program

```
IAmFree = checkSchedule();
if (IAmFree == true)
% Count books and amount of free space on a shelf.
% If minimum number of books I need is less than a
% shelf capacity, go shopping and buy additional
% literature. If the amount of books after the
% shopping is too big, use boxes to store them.
  books = countBooks();
  shelfSize = countFreeSpaceShelf();

  ...

else
  burnBooks();
  goToBookStore();
end
```

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Use consistent and sensible naming of functions and variables.

Today's outline

Errors in computer programs

The following symptoms can be distinguished:

- Unable to execute the program
- Program crashes, warnings or error messages
- Never-ending loops
- Wrong (unexpected) result

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Three error categories:

Syntax errors You did not obey the language rules. These errors prevent running or compilation of the program.

Runtime errors Something goes wrong during the execution of the program resulting in an error message (problem with input, division by zero, loading of non-existent files, memory problems, etc.)

Semantic errors The program does not do what you expect, but does what have told it to do.

Errors in computer programs

The following symptoms can be distinguished:

- Unable to execute the program
- Program crashes, warnings or error messages
- Never-ending loops
- Wrong (unexpected) result

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A convenient tool: the debugger

- No-one can write a 1000-line code without making errors
  - If you can, please come work for us
- One of the most important skills you will acquire is debugging.
- Although it can be frustrating, debugging is one of the most intellectually rich, challenging, and interesting parts of programming.
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"When you have eliminated the impossible, whatever remains, however improbable, must be the truth."
— A. Conan Doyle, The Sign of Four

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The debugger can help you to:

- Pause a program at a certain line: set a *breakpoint*
- Check the values of variables during the program
- Controlled execution of the program:
  - One line at a time
  - Run until a certain line
  - Run until a certain condition is met (conditional breakpoint)
  - Run until the current function exits
- Note: You may end up in the source code of Matlab functions!

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- Check Canvas (Matlab Crash Course section) for a movie that demonstrates the debugger.

About testcases (validation)

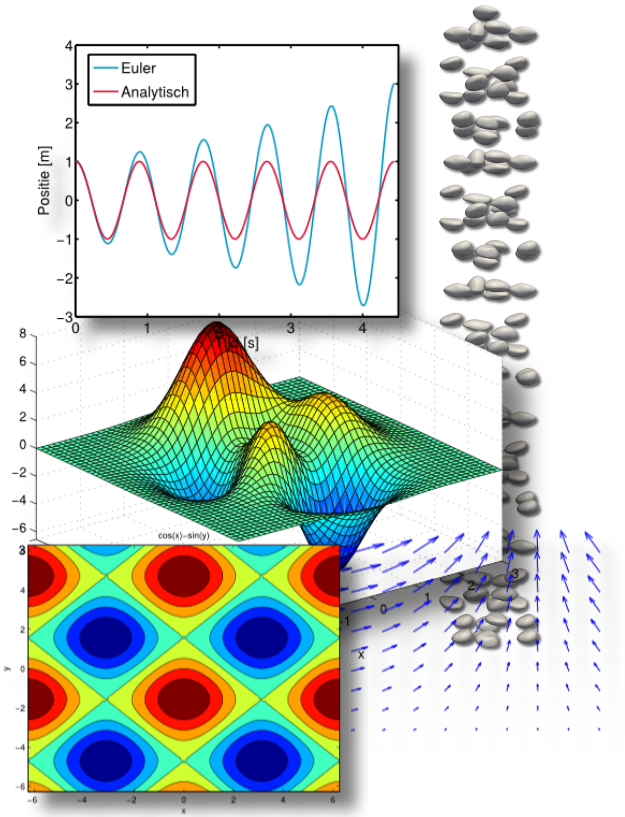
- Testcases: run the program with parameters such that a known result is (should be) produced.
- Testcases: what happens when unforeseen input is encountered?
  - More or fewer arguments than anticipated? (MatlAb uses `varargin` and `nargin` to create a varying number of input arguments, and to check the number of given input arguments
  - Other data types than anticipated? How does the program handle this? Warnings, error messages (crash), NaN or worse (a continuing program)?
- For physical modeling, we typically look for analytical solutions
  - Sometimes somewhat stylized cases
  - Possible solutions include Fourier-series
  - Experimental data

Today's outline

Data visualisation

Modeling can lead to very large data sets, that require appropriate visualisation to convey your results.

- 1D, 2D, 3D visualisation
- Multiple variables at the same time (temperature, concentration, direction of flow)
- Use of colors, contour lines
- Use of stream lines or vector plots
- Animations



Plotting

```
x = -5:0.1:5;
y = x.^2-4*x+3;
y2 = y + (2-4*rand(size(y)));
```

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subplot(2,1,1); plot(x,y,'-',x,y2,'r.');
xlabel('X'); ylabel('Y'); title('Graph and Scatter');
```

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subplot(2,1,1); plot(x,y,'-',x,y2,'r.');
xlabel('X'); ylabel('Y'); title('Graph and Scatter');
subplot(2,1,2); plot(x,abs(y-y2),'r-');
xlabel('X'); ylabel('Y'); title('Absolute error');
```
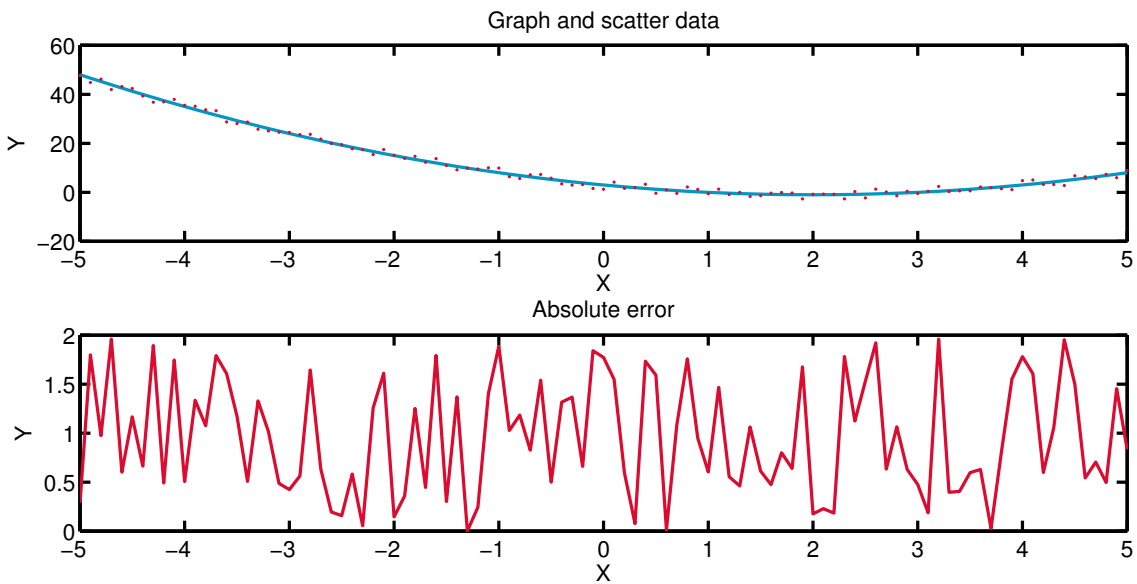
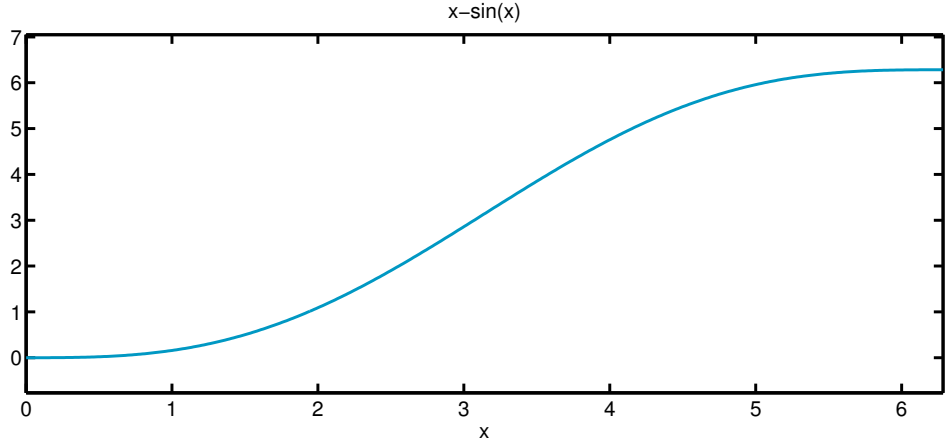



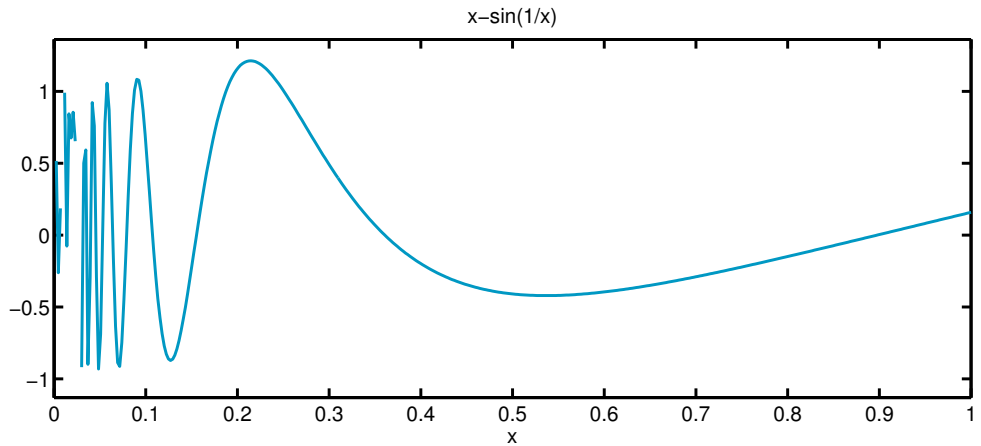
Plotting (2)

Easy plotting of functions can be done using the ezplot function:

```
ezplot('x-sin(x)', [0 2*pi]):
```

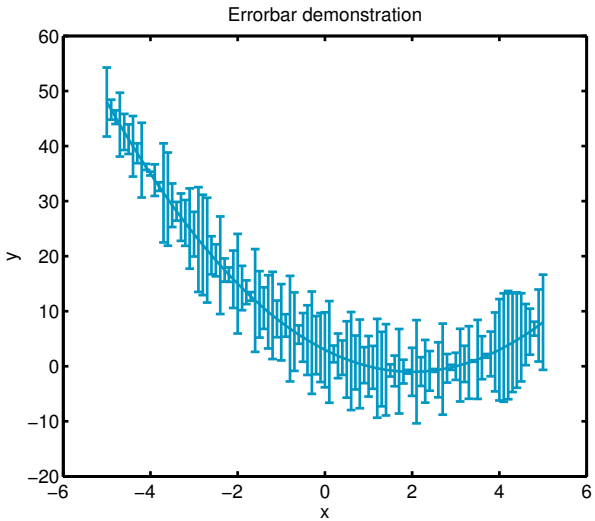


Be careful with steep gradients: `ezplot('x-sin(1/x)', [0 1])`



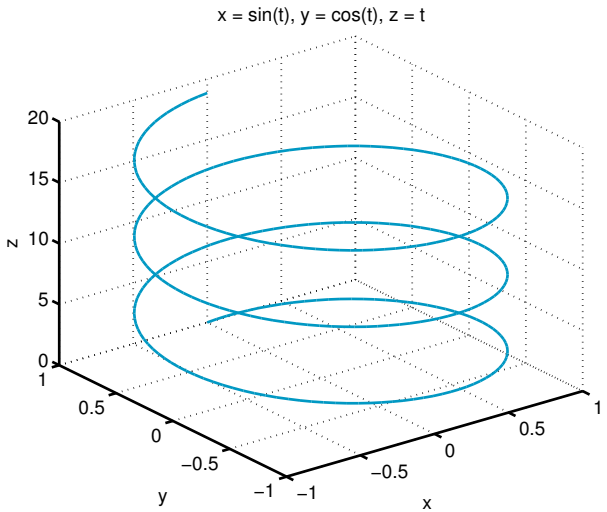
Other plotting tools

- Errorbars: `errorbar(x,y,err)`



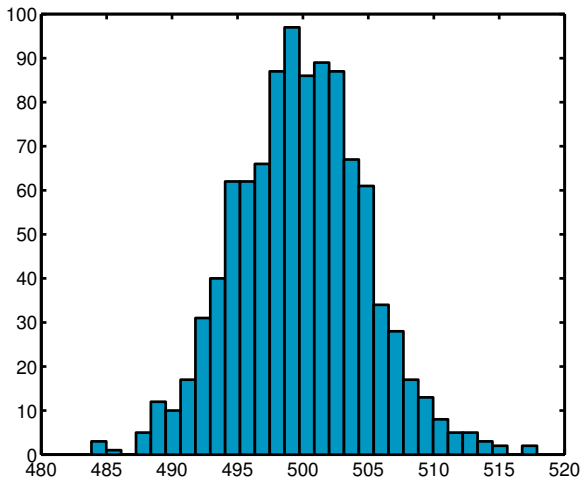
Other plotting tools

- Errorbars: `errorbar(x,y,err)`
- 3D-plots: `plot3(x,y,z)`



Other plotting tools

- Errorbars: `errorbar(x,y,err)`
- 3D-plots: `plot3(x,y,z)`
- Histograms: `histogram(x,20)`



Multi-dimensional data

Matlab typically requires the definition of rectangular grid coordinates using `meshgrid`:

```
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z = x .* y .* exp(-x.^2 - y.^2);
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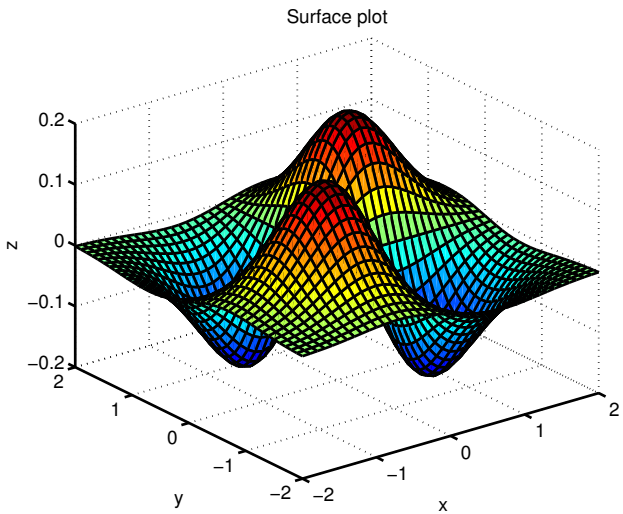
- Surface plot




```
surf(x,y,z);
```

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```
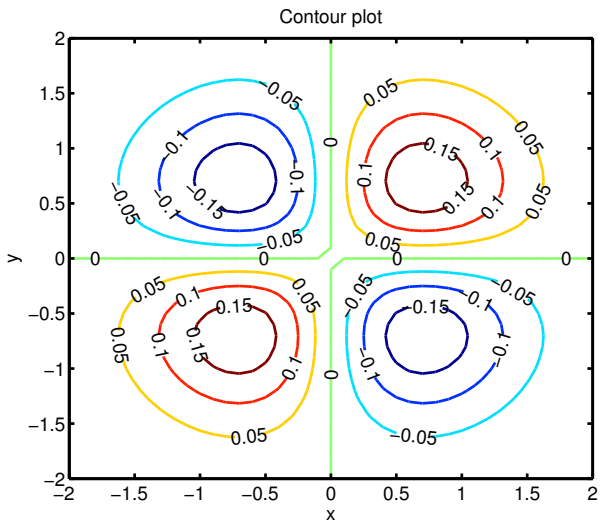

- Surface plot
- Contour plot




```
v=-0.5:0.05:0.5;
contour(x,y,z,v,'ShowText'
, 'on');
```

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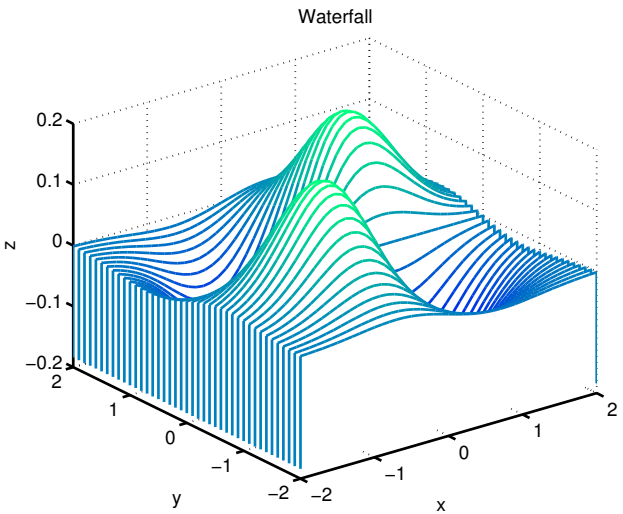
- Surface plot
- Contour plot
- Waterfall




```
waterfall(x,y,z);
colormap(winter);
```

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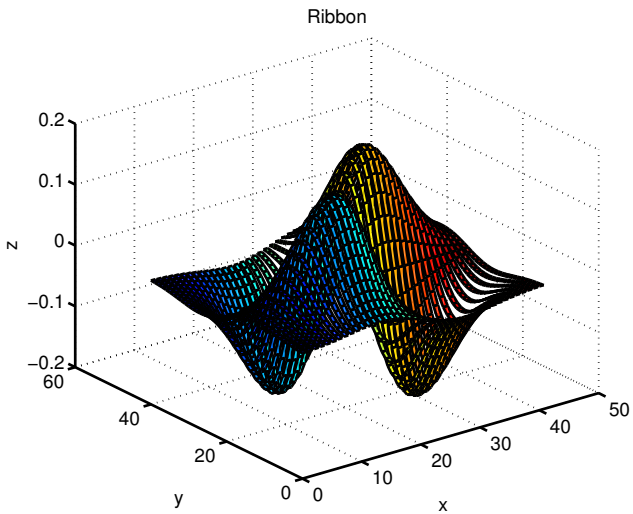
- Surface plot
- Contour plot
- Waterfall
- Ribbons




```
ribbon(z);
```

Vector data

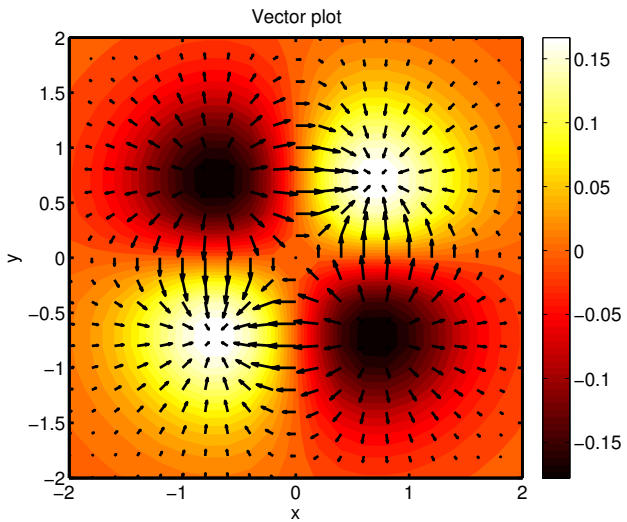
The gradient operator, as expected, is used to obtain the gradient of a scalar field. Colors can be used in the background to simultaneously plot field data:

```
[x y] = meshgrid(-2:0.2:2,
    -2:0.2:2);
z = x .* y .* exp(-x.^2 - y.^2)
[dx dy] = gradient(z,8,8)

% Background
contourf(x,y,z,30,'LineColor','
    none');
colormap(hot); colorbar;

axis tight; hold on;

% Vectors
quiver(x,y,dx,dy,'k');
```



Today's outline

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