What is MATLAB

- high-level language (garbage collecting, var-len structures)
- BASIC-like syntax, with elements from C, GUI IDE
- basic data type: 2- or 3-dimensional floating-point matrix
- most operators and functions work on entire matrices
  \[\Rightarrow\] hardly ever necessary to write out loops
- uses internally highly optimized numerics libraries
  (BLAS, LAPACK, FFTW)
- comprehensive toolboxes for easy access to standard algorithms from
  many fields: statistics, machine learning, image processing, signal
  processing, neural networks, wavelets, communications systems
- very simple I/O for many data/multimedia file formats
- popular for experimental/rapid-prototype number crunching
- widely used as a visualization and teaching tool
What MATLAB is not

- not a computer algebra system
- not a strong general purpose programming language
  - limited support for other data structures
  - few software-engineering features;
    typical MATLAB programs are only a few lines long
  - not well-suited for teaching OOP
  - limited GUI features
- not a high-performance language (but fast matrix operators)
  got better since introduction of JIT compiler (JVM)
- not freely available (but local campus licence)

Open-source MATLAB alternatives

Similar to MATLAB, subset compatible: GNU Octave, SciLab, FreeMat

Other high-level languages for technical computing:

- **R** – focus on statistics and plotting
  https://www.r-project.org/
- **Python** – a full-featured programming language. Modules:
  - `numpy` – numerical arrays, fast linear algebra
  - `matplotlib` – MATLAB-like plotting functions
    https://matplotlib.org/
  - `SciPy` – scientific computing, `Pandas` – data analysis, etc.
- **Julia** – modern, fast, full-featured, compiled, interactive language
  https://julialang.org/
  - MATLAB-inspired syntax (especially for arrays)
  - combines dynamic and static type systems, multiple dispatch
  - LLVM backend, can also call C, C++, Python, R, Fortran functions
  - LISP-like metaprogramming, rich flexible type system
- others: LuaJIT (SciLua), Perl Data Language (PDL), OCaml (Owl)

*Jupyter* is a popular browser-based notebook environment for recording and presenting experiments in Julia, Python, R, . . .
Local availability

MATLAB is installed and ready to use on

- Intel Lab, etc.: MCS Windows
- Intel Lab, etc.: MCS Linux (/usr/bin/matlab)
- CL MCS Linux server: ssh -X linux.cl.ds.cam.ac.uk
- MCS Linux server: ssh -X linux.ds.cam.ac.uk
- Computer Laboratory managed Linux PCs
  cl-matlab -> /usr/groups/matlab/current/bin/matlab

Campus license (666637) allows installation on staff/student home PCs (Linux, macOS, Windows):

- Includes full suite of \( \approx 180 \) toolboxes: Statistics and Machine Learning, Signal Processing, Image Processing, Image Acquisition, Bioinformatics, Control Systems, Wavelets, Deep Learning, Audio System, GPU Coder, Instrument Control, RF, ...
- Installation requires setting up a https://uk.mathworks.com/ account with your @cam.ac.uk email address.

Documentation

- Full documentation built in: start matlab then type
  - `doc` – to browse built-in hypertext manual
  - `doc command` – to jump to a specific manual page (e.g. `plot`)
  - `help command` – to show plain-text summary of a command
- Read first: `doc` → MATLAB → Getting Started
- Tutorial videos:
  https://uk.mathworks.com/videos.html
- Documentation also available online (HTML and PDF):
  - https://uk.mathworks.com/help/matlab/
  - https://uk.mathworks.com/help/ – toolboxes

Locally installed MATLAB may be behind the latest release. If you spot problems with the MCS MATLAB installation, please do let the lecturer know (→ mgk25@cl.cam.ac.uk).
MATLAB matrices (1)

Generate a “magic square” with equal row/column/diagonal sums and assign the resulting $3 \times 3$ matrix to variable $a$:

```matlab
>> a = magic(3)
a =
     8  1  6
     3  5  7
     4  9  2
```

Assignments and subroutine calls normally end with a semicolon. Without, MATLAB will print each result. Useful for debugging!

Results from functions not called inside an expression are assigned to the default variable `ans`. Type `help magic` for the manual page of this library function.

MATLAB matrices (2)

Colon generates number sequence:

```matlab
>> 11:14
ans =
     11  12  13  14
```

```matlab
>> -1:1
ans =
     -1   0   1
```

```matlab
>> 3:0
ans =
Empty matrix: 1-by-0
```

Specify step size with second colon:

```matlab
>> 1:3:12
ans =
     1   4   7  10
```

```matlab
>> 4:-1:1
ans =
     4   3   2   1
```

```matlab
>> 3:-0.5:2
ans =
     3.0000  2.5000  2.0000
```

Single matrix cell: $a(2,3) == 7$. Vectors as indices select several rows and columns. When used inside a matrix index, the variable `end` provides the highest index value: $a(\text{end, end} - 1) == 9$. Using just `:` is equivalent to `1:end` and can be used to select an entire row or column.
MATLAB matrices (3)

Select rows, columns and submatrices of a:

```matlab
>> a(1,:)
ans =
 8 1 6

>> a(:,1)
ans =
8
3
4

>> a(2:3,1:2)
ans =
3 5
4 9
```

Matrices can also be accessed as a 1-dimensional vector:

```matlab
>> a(1:5)
ans =
8 3 4 1 5

>> a(6:end)
ans =
9 6 7 2

>> b = a(1:4:9)
ans =
8 5 2

>> size(b)
ans =
1 3
```

MATLAB matrices (4)

Use [ ] to build new matrices, where , or space as a delimiter joins submatrices horizontally and ; joins them vertically.

```matlab
>> c = [2 7; 3 1]
c =
2 7
3 1

>> d = [a(:,end) a(1,:)]
d =
6 8
7 1
2 6

>> e = [zeros(1,3); a(2,:)]
e =
0 0 0
3 5 7
```

Mask matrix elements:

```matlab
>> find(a > 5)
an =
1
6
7
8

>> a(find(a > 5)) = 0
a =
0 1 0
3 5 0
4 0 2
```
Review: matrix multiplication

\[
\begin{pmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{pmatrix}
\begin{pmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{pmatrix}
\cdot
\begin{pmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{pmatrix}
\begin{pmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{pmatrix}
\]

Each element of the matrix product is the scalar product of the corresponding row in the first factor and the corresponding column in the second factor.

Review: inner and outer product of vectors

**Special cases of matrix multiplication**

\[
(\vdots \vdots \vdots \vdots \vdots) \cdot (\vdots)
\]

Row vector times column vector:

\[
\begin{pmatrix}
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\end{pmatrix}
\cdot
(\vdots \vdots \vdots \vdots \vdots)
\]

Column vector times row vector:
MATLAB matrices (5)

Operators on scalars and matrices:

```
>> [1 1; 1 0] * [2 3]'
ans =
  5
  2
>> [1 2 3] .* [10 10 15]
ans =
 10   20   45
```

Inner and outer vector product:

```
>> [2 3 5] * [1 7 11]'
ans =
 78
>> [2 3 5]’ * [1 7 11]
ans =
  2  14  22
   3  21  33
   5  35  55
```

The imaginary unit vector $\sqrt{-1}$ is available as both $1i$ and $1j$, and matrices can be complex.

Related functions: real, imag, conj, exp, abs, angle

Plotting

```
x = 0:20;
y = 0.5 - 0.5*cos(2*pi * x/20);
stem(x, y);
title('20-point raised cosine');
```

```
x = 0:0.1:10;
t = exp(t * (j - 1/3));
plot(t, real(x), t, imag(x));
grid; legend('real', 'imaginary')
```

Plotting functions plot, semilogx, semilogy, loglog all expect a pair of vectors for each curve, with $x$ and $y$ coordinates, respectively.

Use saveas(gcf, 'plot2.eps') to save current figure as graphics file.
2D plotting

```matlab
xl = -20:0.3:20;
yl = -20:0.3:20;
[x, y] = meshgrid(xl, yl);
r = sqrt(x.^2 + y.^2);
s = sin(r) ./ r; s(find(r==0)) = 1;
plot3(x, y, s);
grid on;
nimagesc(xl, yl, s, [-1 1]);
colormap(gray);
set(gca, 'DataAspectRatio', [1 1 1]);
```

Some common functions and operators

*  
^  
/  
\  
\  *  
\  \  inv  
\  \  A/ B = AB \(^{-1}\), A \(\backslash\) B = A \(^{-1}\)B, A \(^{-1}\)  
\  \  +, -, *, .*, ./, .^  
\  \  element-wise add/sub/mul/div/exp  
\  \  ==, \(\approx\), <, >, <=, >=  
\  \  relations result in element-wise 0/1  
length, size  
\  \  size of vectors and matrices  
zeros, ones, eye, diag  
\  \  all-0, all-1, identity, diag. matrices  
xlim, ylim, zlim  
\  \  set plot axes ranges  
xlabel, ylabel, zlabel  
\  \  label plot axes  
audioread, audiowrite, sound  
\  audio I/O  
csvread, csvwrite  
\  comma-separated-value I/O  
imread, imwrite, image,  
imagesc, colormap  
\  bitmap image I/O  
plot, semilog{x,y}, loglog  
\  2D curve plotting  
conv, conv2, xcorr  
\  1D/2D convolution,  
\  cross/auto-correlation sequence  
fft, ifft, fft2  
\  discrete Fourier transform  
sum, prod, min, max  
\  sum up rows or columns  
cumsum, cumprod, diff  
\  cumulative sum or product,  
\  differentiate row/column  
find  
\  list non-zero indices  
figure, saveas  
\  open new figure, save figure
Functions and m-files

To define a new function, for example \( \text{decibel}(x) = 10^{x/20} \), write into a file `decibel.m` the lines

\[
\text{function } f = \text{decibel}(x) \\
\text{\hspace{1cm}} \% \text{ DECIBEL}(X) \text{ converts a decibel figure } X \text{ into a factor} \\
\text{\hspace{1cm}} f = 10 .^\left( \frac{x}{20} \right);
\]

Only the function that has the same name as the m-file in which it is defined can be called from outside the file; all other functions are only visible inside the file. The \texttt{function} keyword sets the variable whose value will be returned and lists the parameter variables.

The m-file must be in the current directory (\texttt{cd}) or MATLAB’s search path (\texttt{path}) to become accessible.

Use \texttt{edit db} to edit the m-file, \texttt{help db} to show the first comment lines and \texttt{type db} to show its source text.

M-files can also contain just sequences of statements instead of a function definition. These are called simply by typing their name.

Example: generating an audio illusion

Generate an audio file with 12 sine tones of apparently continuously exponentially increasing frequency, which never leave the frequency range 300–3400 Hz. Do this by letting them wrap around the frequency interval and reduce their volume near the interval boundaries based on a raised-cosine curve applied to the logarithm of the frequency.

First produce a 2 s long waveform in which each tone raises 1/12 of the frequency range, then concatenate that into a 60 s long 16-bit WAV file, mono, with 16 kHz sampling rate. Avoid phase jumps.

Parameters:

\[
\begin{align*}
\text{fs} & = 16000; \quad \% \text{ sampling frequency [Hz]} \\
\text{d} & = 2; \quad \% \text{ time after which waveform repeats [s]} \\
\text{n} & = 12; \quad \% \text{ number of tones} \\
\text{fmin} & = 300; \quad \% \text{ lowest frequency} \\
\text{fmax} & = 3400; \quad \% \text{ highest frequency}
\end{align*}
\]
Example solution:

```matlab
t = 0:1/fs:d-1/fs; % timestamps for each sample point
% normalized logarithm of frequency of each tone (row)
% for each sample point (column), all rising linearly
% from 0 to 1, then wrap around back to 0
l = mod(((0:n-1)/n)' * ones(1, fs*d) + ones(n,1) * (t/(d*n)), 1);
f = fmin * (fmax/fmin).^l; % freq. for each tone and sample
p = 2*pi * cumsum(f, 2) / fs; % phase for each tone and sample
% make last column a multiple of 2*pi for phase continuity
p = diag((2*pi*floor(p(:,end)/(2*pi))) ./ p(:,end)) * p;
s = sin(p); % sine value for each tone and sample
% mixing amplitudes from raised-cosine curve over frequency
a = 0.5 - 0.5 * cos(2*pi * l);
w = sum(s .* a)/n; % mix tones together, normalize to [-1, +1]

w = repmat(w, 1, 3); % repeat waveform 3x
spectrogram(w, 2048, 1800, 2048, fs, 'yaxis'); ylim([0 fmax/1e3*1.1]) % plot
w = repmat(w, 1, 20); % repeat waveform 20x
audiowrite('ladder.wav', w, fs, 'BitsPerSample', 16); % make audio file
```

A variant of this audio effect, where each tone is exactly one octave (factor 2 in frequency) from the next, is known as the Shepard–Risset glissando.

What changes to the parameters would produce that?
<table>
<thead>
<tr>
<th>MATLAB</th>
<th>Julia</th>
<th>NumPy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>vector size</strong></td>
<td>(1,n)</td>
<td>[1 2 3]</td>
</tr>
<tr>
<td></td>
<td>(n,1)</td>
<td>[1; 2; 3]</td>
</tr>
<tr>
<td></td>
<td>(n)</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>j to n step k</td>
<td>j:k:n</td>
</tr>
<tr>
<td><strong>matrix</strong></td>
<td>[1 2; 3 4]</td>
<td>[1 2; 3 4]'</td>
</tr>
<tr>
<td>1 matrix</td>
<td>ones(2, 2)</td>
<td>ones(2, 2)</td>
</tr>
<tr>
<td>identity matrix</td>
<td>eye(2, 2)</td>
<td>I</td>
</tr>
<tr>
<td>diagonal matrix</td>
<td>diag([1 2 3])</td>
<td>Diagonal([1, 2, 3])</td>
</tr>
<tr>
<td>transpose</td>
<td>A.'</td>
<td>transpose(A)</td>
</tr>
<tr>
<td>complex conj. transpose</td>
<td>A'</td>
<td>A'</td>
</tr>
<tr>
<td>concat hor.</td>
<td>[1 2] [1 2]</td>
<td>[1 2] [1 2]</td>
</tr>
<tr>
<td>matrix to vector</td>
<td>A(:)</td>
<td>A[:])</td>
</tr>
<tr>
<td>flip left/right</td>
<td>fliplr(A)</td>
<td>reverse(A, dims=2)</td>
</tr>
</tbody>
</table>
| broadcast a function | f=@(x) x.*2; f(x) | f(x) = x.^2; f(x) | def f(x):
|                 |               |                                 |   return x**2 |
| element A_{2,2} | A(2, 2)       | A[2, 2]                         | A[1, 1] |
| rows 1 to 4     | A(1:4, :)     | A[1:4, :)                       | A[0:4, :) |
| matrix multiplication | A * B       | A * B                          | A @ B |

[https://cheatsheets.quantecon.org/](https://cheatsheets.quantecon.org/)