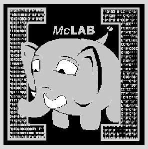
*Mc*LAB: A toolkit for static and dynamic compilers for MATLAB



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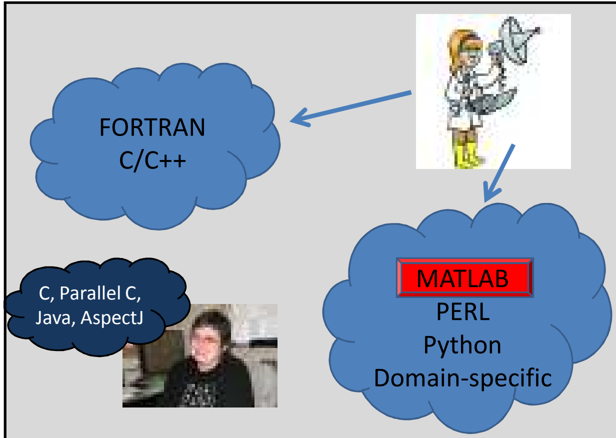
Overview

- Why MATLAB?
- Overview of the McLAB tools
- McVM – a Virtual Machine and Just-In-Time (JIT) compiler
- McFOR – translating MATLAB to FORTRAN95



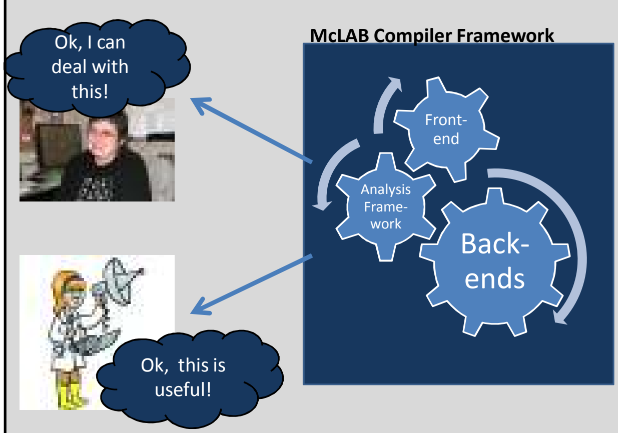
Culture Gap

Scientists / Engineers

- Comfortable with informal descriptions and "how to" documentation.
- Don't really care about types and scoping mechanisms, at least when developing small prototypes.
- Appreciate libraries, convenient syntax, simple tool support, and interactive development tools.

Programming Language / Compiler Researchers

- Prefer more formal language specifications.
- Prefer well-defined types (even if dynamic) and well-defined scoping and modularization mechanisms.
- Appreciate "harder/deeper/more beautiful" programming language/compiler research problems.

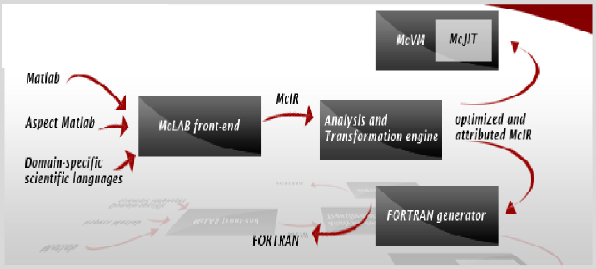


Goals of the McLab Project

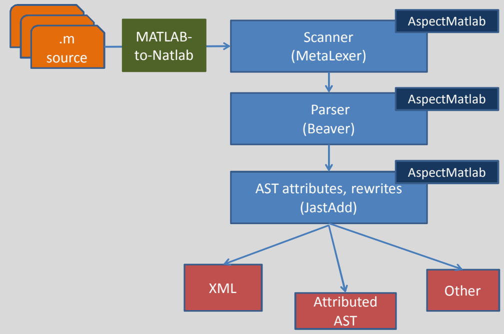
- Improve the understanding and documentation of the semantics of MATLAB.
- Provide front-end compiler tools suitable for MATLAB and language extensions of MATLAB.
- Provide a flow-analysis framework and a suite of analyses suitable for a wide range of compiler/soft. eng. applications.
- Provide back-ends that enable experimentation with JIT and ahead-of-time compilation.

Enable PL, Compiler and SE Researchers to work on MATLAB

McLAB – Overall Structure

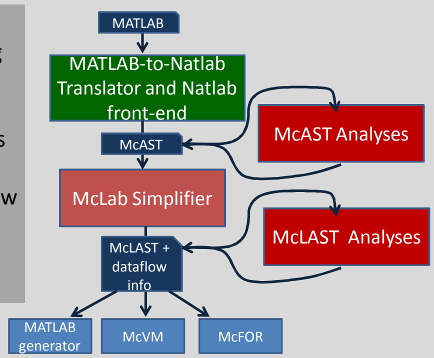


McLAB Extensible Front-end



Analysis Engine

Analyses are written using an Analysis Framework that supports forward and backward flow analysis over McAST and McLAST.



How to build the back-ends?

- No official language specification.
- Closed-source implementations, including the library.

Back-end #1: MATLAB generator

- McLAB can be used as a source-to-source translator:
  - source-level optimizations like loop unrolling
  - source-level refactoring tool
- McLAB can generate:
  - xml files (used to communicate with McVM)
  - text .m files
- Comments are maintained to enable readable output.

Back-end #2: McVM with JIT compiler

- Based on Maxime Chevalier-Boisvert's M.Sc. thesis, McGill, published in CC 2010.
- Currently being extended by Nurudeen Lameed and Rahul Garg, Ph.D. candidates, McGill.

McVM-McJIT

- The dynamic nature of MATLAB makes it very suitable for a VM/JIT.
- MathWorks' implementation does have a JIT, although technical details are not known.
- McVM/McJIT is an open implementation aimed at supporting research into dynamic optimization techniques for MATLAB.

Design Choices for JITs

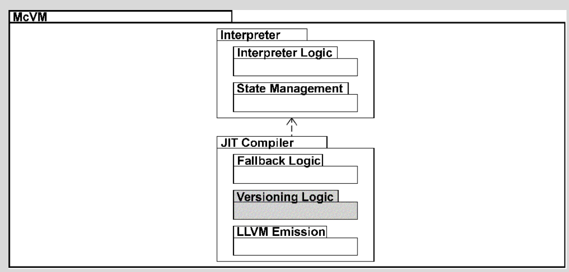
1. Interpreter + JIT compiler with various levels of optimizations.
2. Fast JIT for naïve code generation + optimizing JIT with various levels of optimizations.

- McVM uses the 1st option because it simplifies adding new features, if a feature is not yet supported by the JIT it can back-up to the interpreter implementation, which is easy to provide.

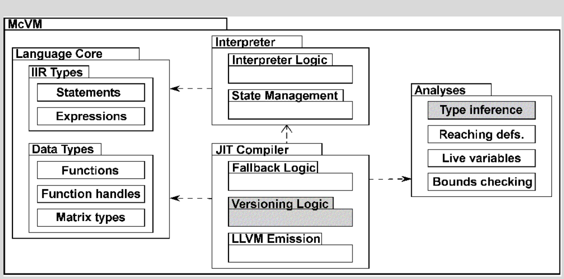
McVM Design

- A basic, but fast, interpreter for the MATLAB language.
- A garbage-collected JIT Compiler as an extension to the interpreter.
- Easy to add new data types and statements by modifying only the interpreter.
- Supported by the LLVM compiler framework and some numerical computing libraries.
- Written entirely in C++; interface with the McLAB front-end via a network port.

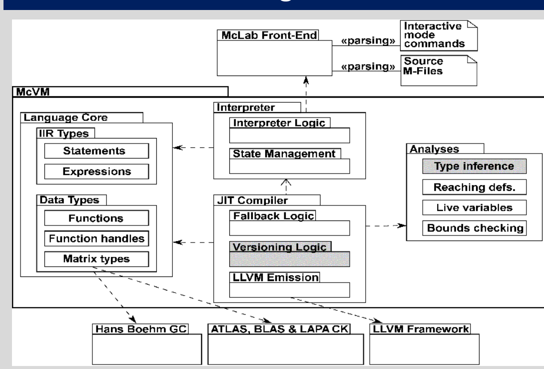
McVM Organization



McVM Organization



McVM Organization



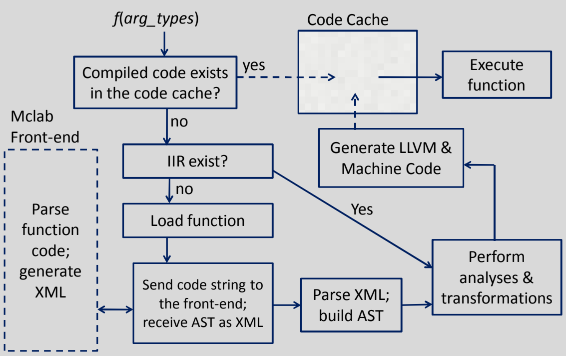
MATLAB Optimization Challenges

```
float sumvals(float start, float step, float
stop)
{
      float i = start;
      float s = i;

      while (i < stop)
      {
            i = i + step;
            s = s + i;
      }

      return s;
}
```


MATLAB Optimization Challenges

```
function s = sumvals(start, step, stop)
      i = start;
      s = i;

      while i < stop
            i = i + step;
            s = s + i;
      end
end

function caller()
      a = sumvals(1, 1, 10^6);
      b = sumvals([1 2], [1.5 3], [20^5 20^5]);
      c = [a b];

      disp(c);
end
```


McJIT: Executing a Function



Just-In-Time Specialization (1)

```
>> a = sumvals(1, 1, 10^6);

>> b = sumvals([1 2], [1.5 3], [20^5 20^5]);

>> a = sumvals(1, 1, 500);

>> c = [a b];

>> disp(c);
```


Just-In-Time Specialization (2)

```
>> a = sumvals(1, 1, 10^6);
  Interpreter.runCommand("a = sumvals(1, 1, 10^6);");
    Interpreter.callFunction(sumvals, [1, 1, 10^6]);
      JIT.callFunction(sumvals, [1, 1, 10^6]);
```


Just-In-Time Specialization (3)

```
JITCompiler.callFunction(sumvals, [1, 1, 10^6]);
  sumvalsJIT = JITCompiler.compileFunction(sumvals, [<scalar int>, <scalar int>, <scalar int>]);
    function s = sumvals(start <scalar int>, step <scalar int>,
        stop <scalar int>)
        i = start;
        s = i;

        while i < stop
            i = i + step;
            s = s + i;
        end
    end
```

Just-In-Time Specialization (4)

```
JITCompiler.callFunction(sumvals, [1, 1, 10^6]);

    sumvalsJIT = JITCompiler.compileFunction(sumvals, [<scalar int>, <scalar int>, <scalar int>]);

        function s <scalar int> = sumvals(start <scalar int>, step <scalar int>,
            stop <scalar int>)

            i <scalar int> = start;
            s <scalar int> = i;

            while i < stop
                i <scalar int> = i + step;
                s <scalar int> = s + i;
            end
        end
```


Just-In-Time Specialization - 2nd example

```
>> a = sumvals(1, 1, 10^6);

>> b = sumvals([1 2], [1.5 3], [20^5 20^5]);

>> a = sumvals(1, 1, 500);

>> c = [a b];

>> disp(c);
```


JIT – second specialization (1)

```
JITCompiler.callFunction(sumvals, [[1 2], [1.5 3], [20^5 20^5]]);

    sumvalsJIT2 = JITCompiler.compileFunction(sumvals, [<1x2 int>, <1x2 real>, <1x2 int>]);

        function s = sumvals(start <1x2 int>, step <1x2 real>,
            stop <1x2 int>)

            i <1x2 int> = start;
            s <1x2 int> = i;

            while (i <1x2 int>) < (stop <1x2 int>)
                i <1x2 real> = i + step;
                s <1x2 real> = s + i;
            end
        end
```


JIT – second specialization (2)

```
JITCompiler.callFunction(sumvals, [[1 2], [1.5 3], [20^5 20^5]]);

    sumvalsJIT2 = JITCompiler.compileFunction(sumvals, [<1x2 int>, <1x2 real>, <1x2 int>]);

        function s <1x2 real> = sumvals(start <1x2 int>, step <1x2 real>,
            stop <1x2 int>)

            i <1x2 int> = start;
            s <1x2 int> = i;

            while (i <1x2 real>) < (stop <1x2 int>)
                i <1x2 real> = i + step;
                s <1x2 real> = s + i;
            end
        end
```


JIT – third specialization same as first

```
>> a = sumvals(1, 1, 10^6);

>> b = sumvals([1 2], [1.5 3], [20^5 20^5]);

>> a = sumvals(1, 1, 500);

>> c = [a b];

>> disp(c);
```

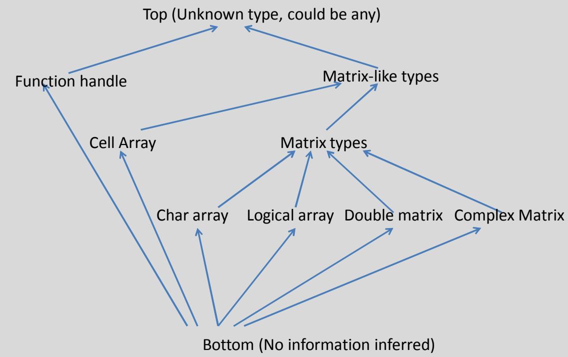

Type and Shape Inference

- In MATLAB, work with incomplete information
  - Dynamic loading: working with incomplete program
  - Dynamic typing : variables can change type
- Know argument types, what can we infer?
  - Propagate type info to deduce locals type and return type
- Forward dataflow analysis
  - Based on abstract interpretation
  - Structure-based fixed point
  - Annotates AST with type info

Flow Analysis Summary

- Start from known argument types
- Propagate type information forward
- Use a transfer function for each expression
  - Transfer functions provided for all primitive operators
  - Library functions provide their own transfer functions
  - Function calls resolved, recursively inferred
- Assignment statements can change var. types
- Merge operator
  - Union + filtering

Lattice of McVM types



Type Abstraction Properties

- Collection of simple abstractions
  - Specific features computed in parallel
- Represent variable types with 8-tuples:

```
<overallType, is2D, isScalar, isInteger,
     sizeKnown, size, handle, cellTypes>
```


Type Abstraction Properties

```
a = [1 2];
```

```
type(a) =
     <overallType = double, is2D = T, isScalar = F,
     isInteger = T, sizeKnown = T, size = (1,2),
     handle = null, cellTypes = {}>
```


Variable Types: Type Sets

```
if (c1)
    a = [1 2];
elseif (c2)
    a = 1.5;
else
    a = 'a';
end
```

```
type(a) = {
<overallType = double, is2D = T, isScalar = F,
  isInteger = T, sizeKnown = T,   size = (1,2),
  handle = null, cellTypes = {}>,
<overallType = double, is2D = T, isScalar = T,
  isInteger = F, sizeKnown = T,   size = (1,1),
  handle = null, cellTypes = {}>,
<overallType = char, is2D = T, isScalar = T,
  isInteger = T, sizeKnown = T,   size = (1,1),
  handle = null, cellTypes = {}>
}
```


Type Set Filtering

```
type(a) = {
  <overallType = double, is2D = T, isScalar = F,
   isInteger = T, sizeKnown = T, size = (1,2),
   handle = null, cellTypes = {}>,

  <overallType = double, is2D = T, isScalar = T,
   isInteger = F, sizeKnown = T, size = (1,1),
   handle = null, cellTypes = {}>
}
```

Becomes:

```
type(a) = {
  <overallType = double, is2D = T, isScalar = F,
   isInteger = F, sizeKnown = F, size = (),
   handle = null, cellTypes = {}>
}
```

Transfer Functions

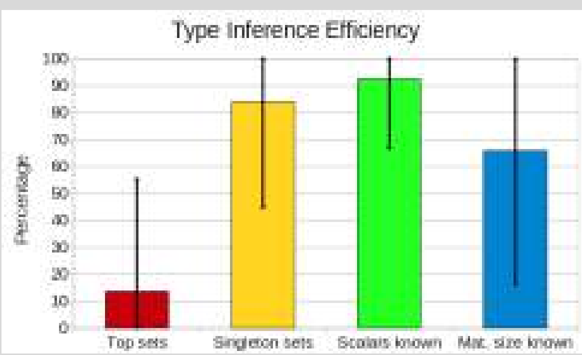
```
a = 5 * 10e11;
b = 1.0e12 * [0.8533 1.7067];
c = [a b];
```

```
type(a) = {
  <overallType = double, is2D = T, isScalar = T, isInteger = T,
     sizeKnown = T, size = (1,1), handle = null, cellTypes = {}>
}

type(b) = {
  <overallType = double, is2D = T, isScalar = F, isInteger = F,
     sizeKnown = T, size = (1,2), handle = null, cellTypes = {}>
}

type([a b]) = {
  <overallType = double, is2D = T, isScalar = F,isInteger = F,
     sizeKnown = T, size = (1,3), handle = null, cellTypes = {}>
}
```

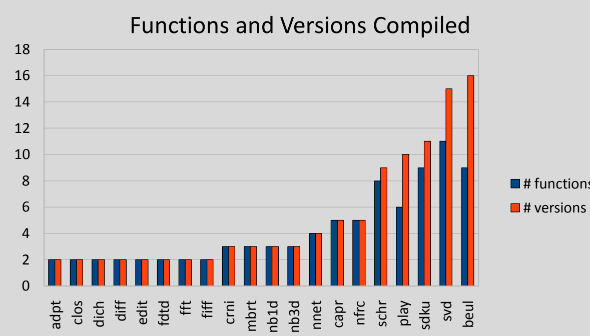

Experimental Results

- 20 benchmark programs
  - FALCON, OTTER, etc. Some made by McLAB
- Measured
  - Dynamic availability of type info.
  - Number of versions compiled
  - Compilation time
    - 0.55s per benchmark, on average

Results of Type Analysis



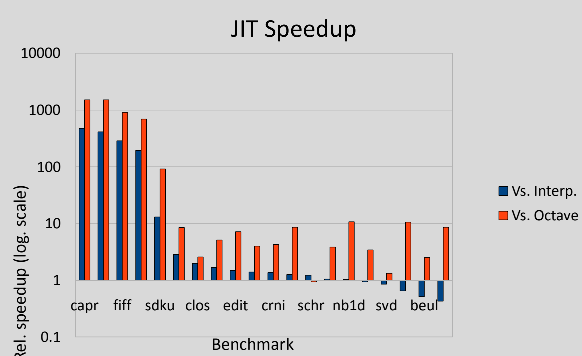
How many versions...



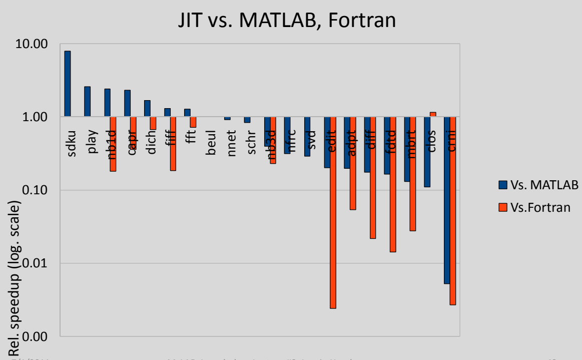
Performance Results

- Experimental setup
  - Core 2 Quad Q6600, 4GB RAM
  - Ubuntu 9.10, kernel 2.6.31, 32-bit
  - All timings averaged over 10 runs
- Comparing
  - McVM interpreter, McVM JIT w/ spec.
  - MATLAB R2009a
  - GNU Octave 3.0.5
  - McFor / GNU Fortran 4.4.1

Results (Speed-up vs Interpreters)



Results (Speed-up vs MATLAB, McFOR)



About Slow Benchmarks

- `crni` benchmark takes 1321s to execute in McVM, 6.95s in MATLAB
  - ~4x faster than Octave, but still slow
- Why?
  - Scalars known 68.7%, one of the lowest ratios
  - Unknown types propagated through entire benchmark
- Weakness of type inference system to be fixed in future work

Back-end #3: McFOR FORTRAN95 generator

- First version of McFOR based on Jun Li's M.Sc. thesis, McGill.
- Current version under development by Anton Dubrau, M.Sc. candidate, McGill.

Goals of McFOR

- Handle as large a sub-set of MATLAB as possible, while staying in the "static" setting.
- Generate code that can be effectively compiled by modern FORTRAN compilers.
- Make the generated code readable by programmers.
- Allow longer compile times and whole program analysis.
- Limit the need for type annotations.

Challenges

- Determining which identifiers are variables and which are functions.
- Finding static types which match those of FORTRAN.
- Mapping high-level MATLAB array operations to the FORTRAN95 equivalents.
- Handling reshaping implicit in MATLAB operations, including concatenation.

Handling Incompatible Types

Alpha Nodes

```
x = 0;
if  (i>0)
  S1: x = foo(i);
else
  S2: x = bar(i);
end
x = alpha(S1,S2);
y = x;
```

Eliminating Alpha Nodes

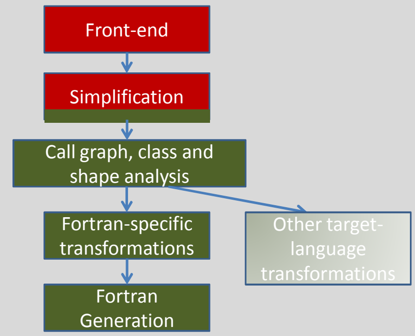
```
x = 0;
if (i>0)
  x = foo(i);
  y = x;
else
  x1 = bar(i)
  y = x1;
end
```

Value Range Propagation

MATLAB
```
n = floor(11.5);  //n =[n,n]
for i = 1:n       // i=[1,n]
  x = 1+2*i;      // x=[3,1+2*n]



  A(x) = i;       // Size(A)=
end                    1+2*n
n = fix(n/2);     // n = [n,n]

A(n+1) = n;
```

FORTRAN
```
n = foor(10.5);
DO i = 1,n
  x = (1+(2*i));
  IF((.NOT.ALLOCATED(A))) THEN
    ALLOCATE(A((1+(2*n))));
  END IF
  A(x) = i;
END DO
n = fix(n/2);
ARRAYBOUNDSCHECKING(A,[n+1]);
A(n+1) = n;
```


Basic structure of 2nd generation McFOR



Related Work

- Procedure cloning: Cooper et al. (1992)
- MATLAB type inference: Joisha & Banerjee (2001)
  - Suggested for error detection
- MATLAB Partial Evaluator: Elphick et al. (2003)
  - Source-to-source transformation
- MaJIC: JIT compilation and offline code cache (2002)
  - Speculative compilation MATLAB to C/Fortran
- Psyco: Python VM with specialization by need (2004)
- TraceMonkey: JIT optimization of code traces (2009)

Ongoing Work

- McVM:
  - profile-guided optimization and re-optimization with on-stack replacement
  - target GPU/multi-core
- McFOR:
  - "decompile" to more programmer-friendly FORTRAN95
  - refactoring toolkit to help restructure "dynamic" features to "static" features

Conclusions

- McLAB is a toolkit to enable PL, Compiler and SE research for MATLAB
- front-end for language extensions
- analysis framework
- three back-ends including McVM and McFOR

`http://www.sable.mcgill.ca/mclab`

Intermediate Representation

EXTRA SLIDES

Internal Intermediate Representation

- A simplified form of the Abstract Syntax Tree (AST) of the original source program
- It is machine independent
- All IIR nodes are garbage collected

IIR: A Simple MATLAB Program

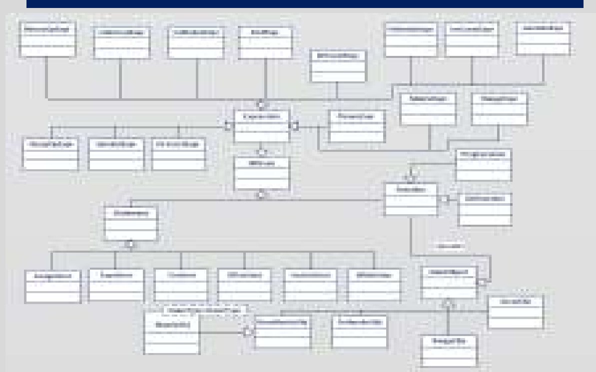
.m file

```
function a = test(n)
  a =  zeros(1,n);
  for i = 1:n
    a(i) = i*i;
  end
end
```

IIR form

```
function [a] = test(n)
  a = zeros(1, n);
  $t1 = 1; $t0 = 1;
  $t2 = $t1; $t3 = n;
  while True
    $t4 = ($t0 <= $t3);
    if ~$t4
      break;
    end
    i = $t0;
    a(i) = (i * i);
    $t0 = ($t0 + $t2);
  end
end
```


McVM Project Class Hierarchy (C++ Classes)



Supported Types

- Logical Arrays
- Character Arrays
- Double-precision floating points
- Double-precision complex number matrices
- Cell arrays
- Function Handles