

Chapter 04 - Debugging and Improving Performance.

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Slide

This chapter provides techniques for maintenance, troubleshooting and debugging of MATLAB applications. We will use a variety of approaches to diagnose problems, identify common errors and evaluate code performance. We will also look at strategies for writing code with performance in mind, including vectorisation techniques and managing memory effectively in MATLAB. The idea is that we have previously developed and tested algorithms, which may now be fine-tuned to improve performance. This can be done safely in the presence of existing unit tests. **A common situation for many people is to inherit code from others which may require debugging and maintenance.** In this chapter there are two examples. The **first example** will assume that we have inherited a "black box" algorithm which we are expected to use. However, the code does not currently work, so it is necessary to debug it first. The **second example** will focus on vectorisation and memory management strategies to improve code performance. In this chapter we will use integrated MATLAB development tools to diagnose errors and identify potential for performance improvement. We will also write vectorised MATLAB code.

Outline:

- Tools for diagnosing errors
- Directory reports
- Breakpoints
- Tools for measuring performance
- Timing functions
- The MATLAB Profiler
- Improving performance
- Vectorisation strategies
- Vectorising operations on cells and structures
- Memory preallocation
- Efficient memory management

Reference files for this chapter:

- ../findBestPredictors.mlx
- ../S04_Vectorisation.mlx
- ../Reference/F04_*.m
- ../Reference/S04_Compact.m
- ../Reference/S04_CellData.mat
- ../Reference/S04_StructData.mat

Copy `findBestPredictorsOriginal.mlx` from root directory into `/work` and rename to `findBestPredictors.mlx`

Course Example: Best BMI Predictors.

Let's assume that we have inherited code from another person. Possibly this person is another researcher in the same department, or a former work colleague, or a research supervisor. In any case, we have been left with some code that we would like to use (possibly adapt or modify for our specific needs). Unfortunately, the code does not work as it stands, so we will need to go through a debugging process to repair it.

We have a function, `findBestPredictors`, which is intended to identify the two best predictor variables from the medical data (excluding BMI and actual and reported height and weight) for the purpose of classifying an individual's BMI category. When working correctly, `findBestPredictors` should return a table of results (one observation for each pair of predictor variables) and render a visualisation of the classified data for the best pair of predictor variables.

```
% View the non-functional version of findBestPredictors.  
edit findBestPredictors
```

Take a look at the function

- *Can look at the main function and get a good idea of what the code does*
- *Detail has been split into functions*
- *Note comments and useful variable names for readability*

Look at the documentation for `try/catch` to see examples of using `try/catch` blocks to catch exceptions.

Show doc try

Gives MException object

```
% Attempt to invoke the function.  
try  
    predictorRankings = findBestPredictors();  
catch MExc  
    disp(MExc.message)  
end
```

This produces an error message, so the code does not work as intended. We need to start debugging. This chapter is intended to provide a typical workflow a programmer may follow when debugging code.

Directory Reports.

Directory reports may be used as a first step to obtain an overview of particular aspects of files in a given directory (folder). Directory reports are available in the MATLAB section of the Apps tab. Note that these reports are specific to a given directory.

As a first step, we can produce a Code Analyzer Report listing all Code Analyzer warnings for each file in the current folder. This will help us to fix syntactical and other errors present in the current code.

Recommended activity: run a Code Analyzer Report to generate a summary of all Code Analyzer warnings and errors.

Select Code Analyzer report from Apps tab. Make sure only findBest Predictors in folder

Take a look at the output - don't correct at the moment. Show that more immediate way is to look at warning/error bars in editor:

Analyzing Code in the Editor.

The MATLAB Editor has various integrated tools intended for code debugging. The status box in the upper right-hand corner provides an indication of the current status of the code. Green means that there are no detectable errors in the code; orange means that there is potential for unexpected results or poor performance, and red means that there are errors which currently will prevent the code from running.

Fix missing ; warning in getPairs and syntax error then use checkcode as below to see remaining.

A summary of the code issues can be obtained from the Code Analyzer Report as described above. This analysis can also be done programmatically using the CHECKCODE function:

Show that this is more convenient as output is in output window

```
checkcode('findBestPredictors')

% Recommended activity: understand, diagnose and fix all warnings
% identified from the Code Analyzer Report (or obtained via the CHECKCODE
% function). This will require knowledge of preallocation (see the
% following section for more information). The functions CELL and NCHOOSEK
% may come in useful here.
%
% See the file F04_findBestPredictors_V1.
```

Function might be unused - leave for now - could be legacy function?

Renderer - talk about sustainability and code becoming obsolete

Others are to do with memory allocation etc. Not so easy to understand what's going on until have run and can see what the data is.

```
% Attempt to invoke the function.
predictorRankings = findBestPredictors();
```

Correct filename

Run again - unrecognised field Meddata error. Doesn't show in workspace because was in function so no longer have access to that workspace - concept of scope. Cleared when leave function.

Entering Debug Mode.

Now that we have fixed all of the existing Code Analyzer warnings, we might hope that the code now runs as expected.

```
try
    predictorRankings = findBestPredictors();
catch MExc
    disp(MExc.identifier)
end
```

It doesn't, which is not that surprising. The Code Analyzer only performs a static check of the code; it is unable to detect run-time errors. Many run-time errors are most easily debugged by viewing the workspace of the function during execution. In MATLAB, this can be achieved by entering debug mode. If we want to enter debug mode automatically in the presence of an error, use the following command:

Type dbstop if error in command window then run function from command window

```
dbstop if error

% This can be cleared using:
dbclear if error
```

Breakpoints may also be inserted manually in the MATLAB Editor by clicking on the line number beside each line of code. Conditional breakpoints may be set by modifying the breakpoint using the right-click menu. This enables the programmer to enter debug mode only when a certain condition is satisfied.

Show expanding 'run to here' area and show visible when debug paused. (Right click on line numbers at side).

Recommended activity: diagnose the run-time problems with LOAD and accessing structure fields.

Rerun (with dbstop if error still on) and correct getPairs error.

How can we prevent similar errors from occurring in the future? (The EXIST and ISFIELD functions may be useful here.)

If file hasn't loaded don't want to continue with rest of program.

Add: look at help exist for return values

```
if exist('S02_MedData.mat', 'file') ~= 2
    error('findBestPredictors:MissingDataFile', 'Unable to locate S02_MedData.mat')
end

if ~isfield(X, 'MedData')
    error('findBestPredictors:MissingVariable', ...
        'Unable to find variable MedData in MAT-file.')
end
```

See the file F04_findBestPredictors_V2 for a version of the code which fixes the first two run-time errors involving LOAD and accessing structure fields.

Resolving Dependencies.

Many applications, especially larger applications, consist of multiple functions and code files. These functions may call each other, as well as other MATLAB or toolbox functions. Resolving all dependencies can be challenging. If we try to call our function at this stage, we are faced with a dependency problem:

```
try
    predictorRankings = findBestPredictors();
catch MExc
    disp(MExc.identifier)
end
```

Note that the WHICH command can help us determine which function or variable is being referenced in a given command:

```
which findBestPredictors
which getpairs in findBestPredictors
which getPairs in findBestPredictors
```

Running a Dependency Report on the directory may also help to diagnose and resolve the "undefined function" error we obtained above.

Recommended activity: run the Dependency Analyzer on the directory to understand the dependency problem. Fix the problem.

Preallocation of Memory.

We now have a program which runs but the remaining warnings indicate that it may not be efficient.

Show varPairs changing size warning and look at code changing array size.

Slide for preallocation of memory and cells.

MATLAB allows variables to be resized dynamically, for example, during the individual iterations of a loop. This is convenient, but in some cases can lead to poor performance. Preallocating memory in advance is the recommended approach. For numeric arrays, preallocation can be done using the zeros/ones/NaN function. Note that it is important to preallocate for the correct data type. All numeric data types are supported by zeros and ones; NaN may initialise double or single values. Cells and structures may be preallocated using the cell, struct and repmat functions.

Go back to warnings for growing loop in getPairs and pre-allocate varPairs:

```
varPairs = cell( nchoosek( size(Xtab,2), 2), 2);
```

Last entry is number of columns

Number of rows is the number of combinations of variable names in Xtab

nchoosek finds number of combinations of N things take k at a time. size(Xtab,2) finds number of columns (2nd dimension).

Point out increase in speed.

Debugging Completion.

After fixing the dependency problem, we now have a function that works.

```
predictorRankings = findBestPredictors();
```

Diagnosing Performance.

This is good news - we can get started using this function for our own needs. However, as well as debugging code to remove errors, it is also good practice to investigate performance aspects of the code. Just because code works and gives the correct results, it does not mean that it cannot be improved by refactoring.

Options for evaluating code performance include the following techniques.

- The tic/toc stopwatch timing functions provide the total system time elapsed between commands. Use this technique to time small blocks of code (not complete functions).
- The timeit function provides an accurate estimate of the time required to run a function. This works by repeatedly calling the function and estimating an average run time based on known behaviour of MATLAB function invocation.
- Using the MATLAB Profiler (see the next section).

The MATLAB Profiler.

The MATLAB Profiler is intended to provide a more in-depth breakdown of the time spent executing code. It produces a fully hyperlinked HTML report which details the number of calls, the total time and the self time for each function. Using the profiler results can help to identify bottlenecks in code performance.

There is a video describing its use here: [Profiler video](#)

Recommended activity: open the profiler and profile the working version of findBestPredictors.

Either use the code below or run the Profiler from the Apps tab.

```
profile on
predictorRankings = findBestPredictors();
profile off
profile viewer
```

Identify potential code bottlenecks using the profile results.

Reorganise the update of the uitable data in the local visualisation function, by removing the get/set commands and performing the data update only once, at the end of the loop.

uitable creates table user interface component - slow to get and set every time

```
% Preallocate array before loop
% uitableData = NaN(numel(yTest), 2);

% Add instead of two currentData lines
% Update data at end of loop
% uitableData(k, :) = [predictedClass, actualClass];

% Move out of loop and change last parameter name
% Finally set after loop
% set(uthResults, 'Data', uitableData)
```

See the file F04_findBestPredictors_Final for reference.

At this point, we have now completed a sample workflow for debugging and performance-tuning a MATLAB application. In the remainder of the chapter we will discuss additional techniques for improving performance of code, focussing on vectorisation and memory management.

Vectorisation.

MATLAB is an array-based language, and as such all vector and matrix operations are optimised for performance. Replacing sequences of scalar operations performed in loops with smaller numbers of vector and matrix operations is referred to as vectorisation. This process can lead to more readable and efficient code.

Again, let's assume that we have been handed some code written by someone else. We are now interested in improving its performance and readability, given that we have been through the debugging and profiling stages to remove errors and more obvious bottlenecks.

Copy S04_VectorisationOriginal into /work and rename to S04_Vectorisation

```
edit S04_Vectorisation
```

Recommended activity: vectorise the code in the first section of calculations by using standard mathematical operations. Next, we will use standard table functionality (VARFUN) to vectorise common mathematical and statistical operations on tabular data.

1st section: Put tic/toc around loops - vectorise

2nd section: Step through one loop to show what it's doing

varfun Apply a function to each variable of a table or a timetable.

B = varfun(FUN,A)

B = varfun(FUN,A,'PARAM1',val1,'PARAM2',val2,...)

Replace whole section with:

```
requiredStatsFun = @(V) [mean(V), std(V)];  
heightStats = varfun(requiredStatsFun, MedData, ...  
    'InputVariables', 'Height', ...  
    'GroupingVariables', {'Sex', 'Ethnicity'});
```

To extend - add min(V) to statsFun

add {'Height', 'Weight'} to input variables

See the file S04_Compact for reference here.

Vectorising Operations on Cells and Structures.

There are situations when working with cell and structure arrays when it becomes necessary to apply a function to the contents of each cell or structure field. In this situation, it is possible to vectorise the operations using `CELLFUN` or `STRUCTFUN`. These functions allow a function to be applied to an entire cell or structure.

For example, the following commands will apply the `length` function to every element of the cell array `C`:

```
Clengths = cellfun(@length, C);
```

Note that the function to apply to the array is specified using a function handle.

By default, `cellfun`, assumes that the output of the function (applied to a single cell element) is a scalar. If so, `cellfun`, returns a vector of these individual values. If not, use the `UniformOutput` option to return the results as a cell array:

```
sz = cellfun(@size, C, 'UniformOutput', false)
```

UniformOutput and false are a pair - false indicates output as cell arrays

Recommended activity: vectorise the code in the remaining sections of the S04_Vectorisation medical data calculation script using `CELLFUN` and `STRUCTFUN`.

Show that C is a cell array & step through

Replace with:

BMI_stats{:} gets all elements

cat(1, BMI_stats) converts from 1x3 to 3x1 - 1 gives dim to concatenate along

```
requiredStats = {@numel, @median, @iqr, @skewness, @kurtosis};  
requiredStatsFun = @(V) [numel(V), median(V), iqr(V), skewness(V), kurtosis(V)];  
BMI_stats = cellfun(requiredStatsFun, C, 'UniformOutput', false);  
  
BMI_stats = [ [ {'Category/Statistic'}, requiredStats]; ...  
    LTW_cats.', num2cell( cat(1, BMI_stats{:}) )];
```


Similar for structures - leave them to look at this.

See the file S04_Compact for reference here.

Memory Anatomy.

On a Windows system, the MEMORY command can be used to obtain available memory information. Calling the MEMORY function with two outputs produces two structures which contain user and system information, respectively.

```
[user, sys] = memory;  
disp(user)  
disp(sys)
```

Copy-on-Write Behaviour.

When assigning one variable to another, MATLAB does not create a copy of that variable until it is necessary. Instead, it creates a reference. A copy is made only when code modifies one or more values in the reference variable. This behaviour is known as copy-on-write behaviour and is designed to avoid making copies of large arrays unless it is necessary. For example:

Run MemoryAnatomy.m

```
clear  
m = memory;  
disp('Memory available (GB):')  
disp(m.MemAvailableAllArrays/1073741824)  
  
A = rand(6e3);  
m = memory;  
disp('Memory available (GB):')  
disp(m.MemAvailableAllArrays/1073741824)  
B = A;  
% This is only a reference at the moment, so available memory should  
% remain constant.  
m = memory;  
disp('Memory available (GB):')  
disp(m.MemAvailableAllArrays/1073741824)  
B(1, 1) = 0;  
% Now that we have made a change, copy-on-write should kick-in.  
m = memory;  
disp('Memory available (GB):')  
disp(m.MemAvailableAllArrays/1073741824)
```

In-Place Optimisation.

An in-place optimisation conserves memory by using the same variable for an output argument as for an input argument. This is valid only when the input and output have the same size and type, and only within functions. When working on large data and memory is a concern, in-place optimisations could be used to attempt to

conserve memory use. However, in some situations, it is not possible to have a true in-place optimisation, because some temporary storage is necessary to perform the operation.

Recommended activity: open and explain the `inPlaceExample` function. See the reference file `"inPlaceExample"`.

Run function from command line - let it run without debugger

```
inPlaceExample()
```