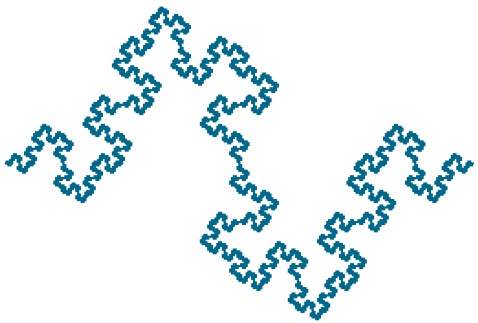
Adaptive Algorithms and Parallel Computing

Object-Oriented Programming in MATLAB (Primer)

Academic year 2014-2015



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Overview

Procedural programming

- Procedural programming languages (e.g. C) focus on defining *procedures* that implement the core logic of your problem.
- This is decoupled from identifying suitable *data structures*.
- Object-oriented programming (OOP) is a programming paradigm where the focus is on *representing* the domain of your problem using objects.
- An object encapsulates an internal state, and exposes some methods through an interface. In this sense, it combines handling data and operations.
- Note: a *class* is the source code, from which multiple *objects* are instantiated.

Benefits of OOP

Modularity
OOP forces the developer to design modular software.

Data encapsulation
An object can hide part of its information at run-time.

Logic encapsulation
It is not necessary to understand the internal logic of an object before using it.

Maintainability
OOP code is easier to maintain/document/debug.

Extensibility
Features such as *inheritance* makes OOP code easier to extend.

OOP in MATLAB

- Full support for OOP (with a completely rewritten syntax) was introduced in MATLAB R2008a.
- Since then, many basic functionalities have been re-introduced to be compatible with an OOP standard.
- As an example, the graphic engine from MATLAB R2014b is class-based (so-called HG2).
- MATLAB R2015a has introduced additional functionalities in term of editing capabilities.

Overview

Defining a class

A class is instantiated with the `classdef` keyword:

```
classdef Rectangle

    properties
        % Properties go here
    end

    methods
        % Methods go here
    end

end
```

The source code must go inside a file with the same name (e.g. 'Rectangle.m').

Defining a property

The internal state of the class is saved as *properties* of the class:

```
properties
   width;   % The width of the rectangle
   height;  % The height of the rectangle
end
```

MATLAB is *weakly typed*, meaning there is no need of defining the type of each property. A class without methods is equivalent to a `struct`.

```
>> r = Rectangle
r =
  Rectangle with properties:
    width: []
    height: []
```

```
>> r.width = 5
r =
  Rectangle with properties:
    width: 5
    height: []
```

Defining a constructor

An object is created by invoking a special method known as *constructor*. Let us define a custom constructor for our class:

```
methods
   function obj = Rectangle(w, h)
      obj.width = w;
      obj.height = h;
   end
end
```

The constructor has a very specific syntax. By default, MATLAB generates a default constructor with no input arguments. Since each class can only have a single constructor, our definition overrides the MATLAB one:

```
>> r = Rectangle(3, 2)
r =
  Rectangle with properties:
    width: 3
    height: 2
```

```
>> r = Rectangle
   Error using Rectangle (line 10)
   Not enough input arguments.
```

Defining a method

The third essential element of a class definition is a set of methods:

```
methods

   % Constructor goes here

    function p = get_perimeter(obj)
       p = 2*(obj.width + obj.height);
    end

  function obj = scale(obj, n)
      obj.width = n*obj.width;
      obj.height = n*obj.height;
  end
end
```

```
>> r = Rectangle(5, 3);
>> per = r.get_perimeter()
per =
    16
```

Overview

Defining a static method

A *static* method is associated to a class, but not to any specific instance of that class. Here is an example of a static method:

```
classdef Rectangle
   % Previous code goes here

   methods(Static)
      function s = get_description()
         s = 'Class for representing rectangles';
      end
   end
```

Note that a static method does not need an instance of the class as argument. In this way, you can call a static method without first declaring an object:

```
>> Rectangle.get_description()
   ans =
       'Class for representing rectangles'
```

Defining a constant property

A class in MATLAB can have a *constant* property (or more than one), i.e. a property whose value is never modified after the first assignment:

```
classdef Circle
   properties(Constant)
      pi = 3.14;
   end
   % Other definitions
end
```

```
>> Circle.pi
ans =
    3.1400

>> r.pi = 2
You cannot set the read-only property 'pi' of Rectangle.
```

Defining a private property

Finally, a MATLAB class can have one or more *private* properties, i.e. properties that should not be visible (nor modifiable) from the outside:

```
classdef Rectangle
    properties(Access = private)
        width;
        height;
    end
    % Other definitions go here
end
```

```
>> r = Rectangle(3,2)

r =
  Rectangle with no properties.
```

You can also have private methods (using an equivalent syntax). Similarly, you can have properties that are visible but not modifiable: [Specifying Property Attributes].

Overview

Writing the documentation

When documenting your class, you should be careful in respecting MATLAB conventions:

```
classdef Rectangle
    % Rectangle - Class for defining rectangles
    % This class can be used to define objects representing rectangles.
    % Initialize the class as:
    %   r = Rectangle(3, 2);
    % Then, [...].
    % See also: UINT32

    properties
        width;  % Width of the rectangle
        height; % Height of the rectangle
    end

    methods
        function p = get_perimeter(obj)
            % Compute the perimeter of the rectangle
            p = 2*(obj.width + obj.height);
        end
    end
end
```

Accessing the documentation

```
>> help Rectangle
  Rectangle - Class for defining rectangles
  This class can be used to define objects representing rectangles.
  Initialize the class as:
    r = Rectangle(3, 2);
  Then, [...].
  See also: uint32

>> help Rectangle.width
 width -  Width of the rectangle

>> help Rectangle.get_perimeter
  Compute the perimeter of the rectangle

>> % See for yourself
   doc Rectangle
```

Overview

Difference between handle and value classes

- All the classes that we defined up to now are *value* classes. When you pass a value class' object to a function, a *copy* is created (similarly when you assign to another variable).
- You can create *handle* classes that work in the opposite way. Passing an object of an handle class to a function passes a *reference* to the object itself.
- Value classes are useful when the semantics of your objects is similar to numerical classes or data structures. Similarly, handle classes are useful when there is often the need of sharing objects.
- This is especially confusing because the resulting syntax is mixed with respect to other common programming languages (e.g. Java or C++).

Defining an handle class

An handle class should *derive* from the basic `handle` class (more on this syntax later on):

```
classdef Rectangle < handle

    properties
        width;  % Width of the rectangle
        height; % Height of the rectangle
    end

    methods
        function obj = Rectangle(w, h)
            obj.width = w;
            obj.height = h;
        end

        function scale(obj, n)
            obj.width = n*obj.width;
            obj.height = n*obj.height;
        end

    end
end
```

Using an handle class

```
>> r = Rectangle(3, 2);
>> r2 = r;
>> r2.scale(2)
>> r2

r2 =

  Rectangle with properties:

     width: 6
    height: 4

>> r

r =

  Rectangle with properties:

     width: 6
    height: 4
```

Overview

What is an event?

- A very interesting aspect of handle classes is their ability of defining events.
- Roughly, an event is a specific message which is triggered at certain points in the code. This is known as notification.
- It is possible to associate one (or more) listeners (also known as callbacks) to a specific notification.
- In this way, you can define a dynamic behavior that is executed at runtime depending on how the class is used.
- As an example, we will show how to keep track of how many times a specific function is called.

Defining an event (1/3)

First of all, you must define any event that can be triggered using a similar syntax with respect to a property:

```
classdef Rectangle < handle

    events
        ComputePerimeter
    end

    % Other definitions

end
```

At this point, it is possible to trigger this event whenever required:

```
function p = compute_perimeter(obj)
   p = 2*(obj.width + obj.height);
   notify(obj, 'ComputePerimeter');
end
```

Defining an event (2/3)

We keep track of how many times the function is called by using an internal private counter:

```
properties(Access = private)
   nComputedPerimeter;
end
```

We add a property to initialize the counter and link the event to its specific listener:

```
function track_perimeter_method(obj)
   obj.nComputedPerimeter = 0;
   addlistener(obj, 'ComputePerimeter', @Rectangle.↩
        update_nComputedPerimeter);
end
```

Defining an event (3/3)

Finally, we define the listener:

```
methods(Static)
   function update_nComputedPerimeter(r, ~)
      r.nComputedPerimeter = r.nComputedPerimeter + 1;
   end
end
```

We also need a function to print the result:

```
function print_tracking_info(obj)
   fprintf('The ''get_perimeter'' function has been called %i times.\n'↩
        , obj.nComputedPerimeter);
end
```

The event in action

```
>> r = Rectangle(3, 2);
>> r.track_perimeter_method
>> r.compute_perimeter;
>> r.compute_perimeter;
>> r.print_tracking_info
The 'get_perimeter' function has been called 2 times.
>> r.nComputedPerimeter
You cannot get the 'nComputedPerimeter' property of Rectangle.
```

Overview

Overloading the times operator

By using OOP, it is possible to *overload* several basic MATLAB behaviors for your custom object. As an example, we can overload the operator $*$ for our rectangle class:

```
function r = mtimes(obj1,obj2)
   if(isa(obj1, 'Rectangle') && isnumeric(obj2))
      r = obj1.scale(obj2);
   elseif(isnumeric(obj1) && isa(obj2, 'Rectangle'))
      r = obj2.scale(obj1);
   else
      error('One operator must be a rectangle and the other numeric');
   end
end
```

Note that in our implementation we have to explicitly check for the order of the operands. There is a large number of overloadable operators: [MATLAB Operators and Associated Functions].

Rectangle multiplication

```
>> r = Rectangle(3, 2);
>> r = r*2
r =

  Rectangle with properties:

     width: 6
    height: 4

>> r = 1/2*r
r =

  Rectangle with properties:

     width: 3
    height: 2

>> r = 'a'*r
Error using Rectangle/mtimes (line 27)
One operator must be a rectangle and the other numeric
```

Overview

Indexing in MATLAB

Just like operators, every indexing operation in MATLAB has an associated function:

- `subsref`: subscripted reference, e.g. `A(1:3)` or `A{1:3}` or `A.area`.
- `subsasgn`: subscripted assignment, e.g. `A(3) = 1`.
- `subsindex`: subscripted indexing using an object.

Each of these functions can be overloaded to implement custom behavior.

Example: a class for damped oscillations

Consider the following class representing the function $y = \frac{\sin(x)}{x}$.

```
classdef DampedSine
    properties
        limit; % x-limit for function
    end
    methods
        function obj = DampedSine(limit)
            obj.limit = limit;
        end
        function v = get_value(obj, x)
            % Get the value of the function
            if(any(x < 0) || any(x > obj.limit))
                error('Argument is outside specified bounds');
            end
            v = sin(x)./x;
        end
        function plot(obj)
            % Plot the function
            x = 0:0.01:obj.limit;  plot(x, obj.get_value(x));
        end
    end
end
```

Overloading indexing

We can implement a custom indexing operation to create a sort of "callable" object:

```
function B = subsref(A,S)
   if(strcmp(S(1).type, '()') && length(S(1).subs) == 1)
      B = A.get_value(S(1).subs{1});
      if(length(S) > 1)
         B = builtin('subsref', B, S(2:end));
      end
   else
      B = builtin('subsref', A, S);
   end
end
```

```
>> ds = DampedSine(20);
>> ds.get_value(5)
ans =
   -0.1918
>> ds(5)
ans =
   -0.1918
```

Overview

Custom displaying

You can overload how a variable is displayed on the console:

```
function disp(obj)
   fprintf('Rectangle with width=%.2f and height=%.2f\n', obj.width, ↩
        obj.height);
end
```

```
>> r = Rectangle(3, 2)

r =

Rectangle with width=3.00 and height=2.00
```

There are many other custom behaviors that you can implement: [Customize MATLAB Behavior].

Overview

What is inheritance?

- Inheritance is a feature of OOP languages that lets one class to '*inherits*' the behavior from a specific super-class.
- This allows a strong amount of code reuse, and the possibility of creating hierarchies of classes for your application (e.g. the hierarchy of data types in MATLAB).
- You can think of class B inheriting from class A as the implementation of the semantic "B is-a A" (not to be confused with the classical "B has-a A").
- Closely connected is the idea of polymorphism: a single interface is declined in multiple forms, and the specific implementation is decided only at run-time.

An example of inheritance

A square "is-a" rectangle, whose width and height are equivalent:

```
classdef Square < Rectangle

    properties
    end

    methods

        function obj = Square(l)
            obj = obj@Rectangle(l, l);
        end

    end

end
```

Note the syntax of the call to a constructor of the super-class.

Method overriding

The class `Square` inherits all the behavior of its superclass, thus allowing a strong amount of code reusing between implementations:

```
>> s = Square(3);
>> s.compute_perimeter

ans =
    12
```

You can also override a specific method (in this case, for computational reasons):

```
classdef Square < Rectangle
   % ...
   methods
      % ...
      function p = compute_perimeter(obj)
         p = 4*obj.height;
      end
   end
end
```

Adding methods to the subclass

You can define methods that are exclusive of a particular subclass:

```
classdef Square < Rectangle
   % ...
   methods
      % ...
      function l = get_length(obj)
         l = obj.width;
      end
   end
end
```

```
>> s = Square(3);
>> s.get_length
ans =
     3
>> r = Rectangle(3, 2);
>> r.get_length
No appropriate method, property, or field
   get_length for class Rectangle.
```

Sealed and protected attributes

You can specify that a property (or method) is accessible only to classes inheriting the super-class:

```
classdef A
    properties(Access=protected)
        foo;
    end
end
```

Additionally, you can specify that a particular class cannot be inherited from:

```
classdef A (Sealed = true)
    % ...
end
classdef B < A
    % ERROR
end
```

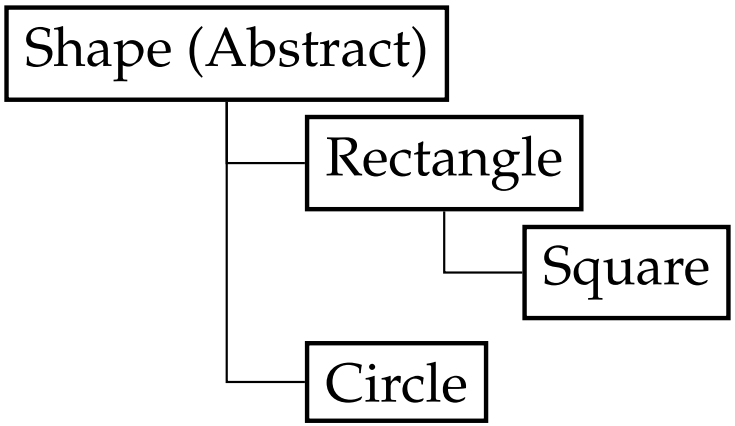
Overview

Abstract classes

Inheritance allows to define abstract classes. These cannot be instantiated, but they can:

- Abstract code from any specific sub-class.
- Provide an interface for a set of functions that any sub-class must implement.

Let us consider the following class hierarchy:



Defining the abstract class

```
classdef Shape
    properties
        n_sides;  % Number of sides
    end

    methods(Abstract=true)
        p = compute_perimeter(obj); % Compute the perimeter
        obj = scale(obj, n);        % Scale the object
    end

    methods
        function obj = Shape(n)
            obj.n_sides = n;
        end
        function print_info(obj)
            fprintf('This is a geometric shape with %.2f sides.\n', obj↩
                .n_sides);
        end
    end
end
```

Defining the first sub-class

```
classdef Rectangle < Shape
    properties
        width;  % Width of the rectangle
        height; % Height of the rectangle
    end
    methods

        function obj = Rectangle(w, h)
            obj = obj@Shape(4);
            obj.width = w;
            obj.height = h;
        end

        function obj = scale(obj, n)
            obj.width = n*obj.width;
            obj.height = n*obj.height;
        end

        function p = compute_perimeter(obj)
            p = 2*(obj.width + obj.height);
        end
    end
end
```

Defining a new sub-class

Note: the class for the Square is unchanged with respect to before.

```
classdef Circle < Shape
    properties
        radius;  % Radius of the circle
    end
    methods
        function obj = Circle(r)
            obj = obj@Shape(Inf);
            obj.radius = r;
        end

function obj = scale(obj, n)
   obj.radius = n*obj.radius;
end

        function p = compute_perimeter(obj)
            p = 2*pi*obj.radius;
        end
    end
end
```

Using the class hierarchy

```
>> r = Rectangle(3,2);
>> r.scale(2)

ans =

  Rectangle with properties:

      width: 6
     height: 4
    n_sides: 4

>> s = Shape(3);
Error using Shape
Abstract classes cannot be instantiated.
   Class 'Shape' defines abstract methods and/or properties.
```

Refactoring

We can see that the code of the `scale` method is semantically equivalent in all cases: it multiplies by n all properties, except the number of sides. We can, in principle, *abstract* this into the class `Shape` to provide a default implementation:

```
classdef Shape
   % ...
   function obj = scale(obj, n)
      pr = properties(class(obj));
      for ii = 1:length(pr)
         if(~strcmp(pr{ii}, 'n_sides'))
            obj.(pr{ii}) = n*obj.(pr{ii});
         end
      end
   end
   % ...
end
```

This is known as code refactoring.

Overview

Description of the example

As a final example, we implement a relatively simple (but with lot of possible extensions) filtering application. We have the following specifics:

- A class for generating the underlying system to be identified. For simplicity, the system is supposed to be linear, and the output corrupted with Gaussian noise.
- An abstract class for implementing any linear adaptive filter. One particular implementation of this class implementing the standard LMS filter with constant step size.
- One class taking care of plotting the results. For simplicity, we implement only one method for plotting the MSE in logarithmic scale.

Signal generation

```
classdef SignalGenerator
    % SignalGenerator - Class for generating input and output signals

    properties
        taps;       % taps of the filter
        noise_var;  % variance of the noise
        wo;         % optimal weights of the linear system
    end

    methods

        function obj = SignalGenerator(taps, noise_var)
            obj.taps = taps;
            if(nargin < 2)
                obj.noise_var = 0.01;
            else
                obj.noise_var = noise_var;
            end
            obj.wo = rand(taps, 1)*2 - 1;
        end

    end
end
```

Signal generation (cntd)

```
classdef SignalGenerator
        % ...

        function [X, d] = generate_signal(obj, N)

            % Generate signal of length N
            % The outputs are:
            %   X: a NxM input matrix, where M is the number of taps
            %   d: a Nx1 vector of output values, corrupted by noise

            X = randn(N, obj.taps);
            d = X*obj.wo + randn(N, 1)*sqrt(obj.noise_var);
        end

        % ...
end
```

Abstract class for filters

```
classdef AdaptiveFilter
    % AdaptiveFilter - Abstract class for adaptive filters

    properties
        w_estimated;    % Estimated weights
        error_history;  % Vector of a-priori errors
    end

    methods
        function obj = AdaptiveFilter(taps)
            obj.w_estimated = zeros(taps, 1);
        end

        % Here we need:
        %   1) one function for processing the full dataset one item
        %      at a time.
        %   2) one (abstract) function for implementing the single
        %      adaptation step.
    end

end
```

Abstract class for filters (cntd)

```
classdef AdaptiveFilter
    % ...
    methods
        % ...
        function obj = process(obj, X, d)
            % Process the overall signal X/d
            N = length(d);
            obj.error_history = zeros(N, 1);
            for ii = 1:N
                obj.error_history(ii) = d(ii) - X(ii, :)*obj.↩
                    w_estimated;
                obj = obj.adapt(X(ii, :)', d(ii), obj.error_history(ii)↩
                    );
            end
        end
    end

    methods(Abstract)
        obj = adapt(obj, x, y, e); % Signal adaptation step
    end

end
```

Least Mean-Square Filter

```
classdef LMSFilter < AdaptiveFilter
    % LmsFilter - Least Mean-Square adaptive filter with constant step ↩
        size

    properties
        step_size;  % Step size
    end

    methods
        function obj = LMSFilter(taps, step_size)
            obj = obj@AdaptiveFilter(taps);
            obj.step_size = step_size;
        end
        function obj = adapt(obj, x, ~, e)
            obj.w_estimated = obj.w_estimated + obj.step_size*e*x;
        end
    end

end
```

Helper function for plotting

```
classdef PlotHelper
    % PlotHelper - Helper class for plotting

    properties(Constant)
        font_size = 8;                  % Fontsize
        font_size_leg = 6;              % Font size (legend)
        font_name = 'TimesNewRoman';    % Font name
        line_width = 1;                 % LineWidth
    end

    methods(Static)

        function plot_MSE_db(xlab, ylab, leg, varargin)
            % Inputs are: x-label y-label, cell array of strings for ↩
                the
            % legend. Each additional input is a time-series to be ↩
                plotted.

            % Code goes here
        end
    end

end
```

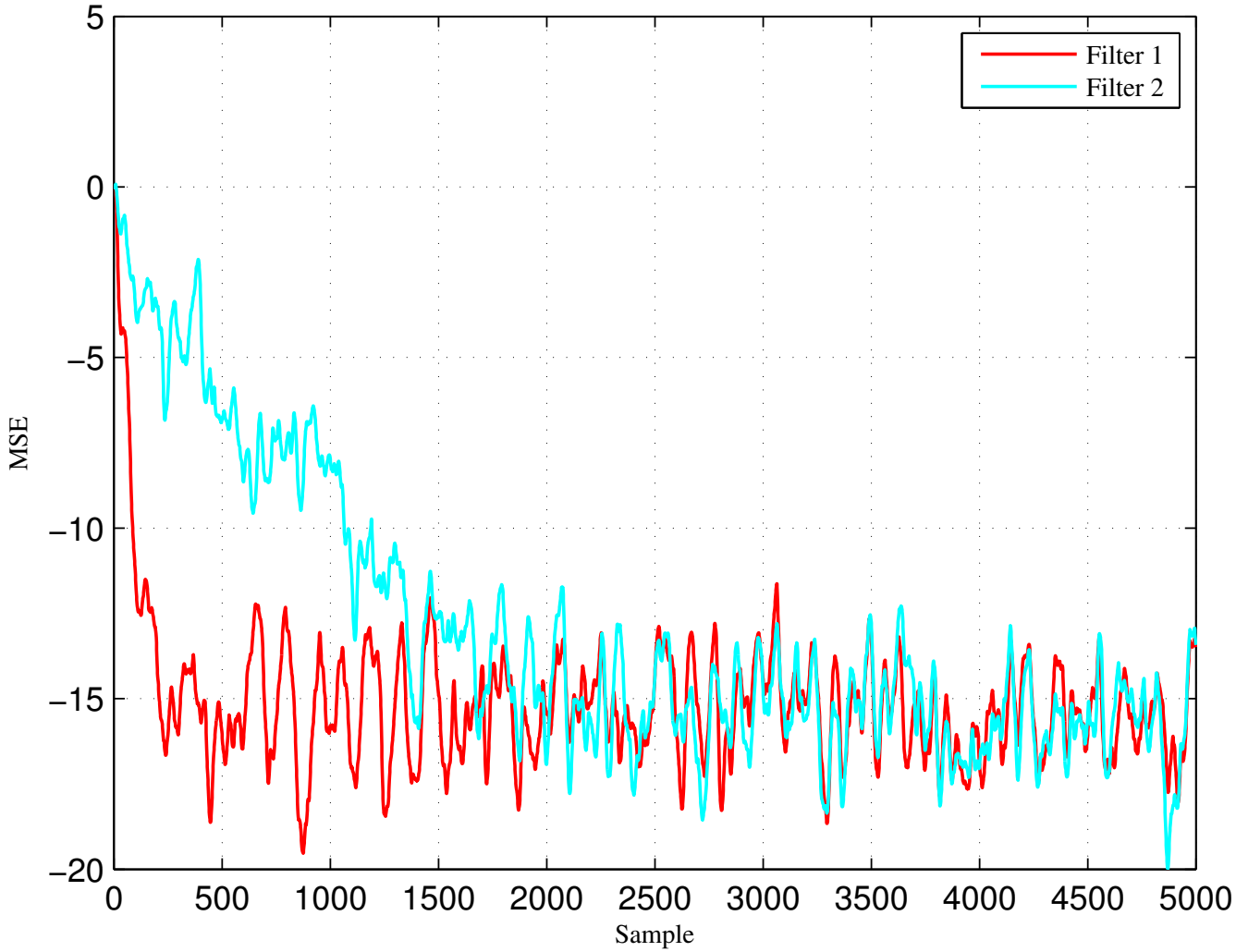
Helper function for plotting (cntd)

```
function plot_MSE_db(xlab, ylab, leg, varargin)
   % Each additional argument is a time series to be plotted

   % Simple filter for smoothing the results
   [bb, aa] = butter(2, 0.02 );

   N_series = length(varargin);

   cmap = hsv(N_series);
   figure(); hold on; box on; grid on;

   for ii = 1:N_series
      plot(filter(bb, aa, 10*log10(varargin{ii}.^2)), 'LineWidth', ↩
          PlotHelper.line_width, 'Color', cmap(ii, :));
    end

    xlabel(xlab, 'FontSize', PlotHelper.font_size, 'FontName', ↩
        PlotHelper.font_name);
    ylabel(ylab, 'FontSize', PlotHelper.font_size, 'FontName', ↩
        PlotHelper.font_name);
    legend(leg, 'FontSize', PlotHelper.font_size, 'FontName', ↩
        PlotHelper.font_name);

end
```

Testing the application

```
% Repeatable experiment
rng(1);

% Generate data for simulation
sg = SignalGenerator(5, 0.1);
[X, y] = sg.generate_signal(5000);

% Create two filters
f1 = LMSFilter(5, 0.01);
f2 = LMSFilter(5, 0.001);

% Adapt the filter
f1 = f1.process(X, y);
f2 = f2.process(X, y);

% Plot
PlotHelper.plot_MSE_db('Sample', 'MSE', {'Filter 1', 'Filter 2'}, f1.↩
    error_history, f2.error_history);
```

Result


Filter 1
Filter 2
MSE
Sample
5
0
−5
−10
−15
−20
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000