

Introduction to Plotting and Vectorization

This lab will provide an introduction to two dimensional plots. At the end, you should feel comfortable plotting functions of the form $f(x)$. You should find this useful not only for visualizing the solutions of ODEs, but also for plotting general data that might appear in other courses and work.

In the process we will also introduce the concept of vectorization, which is helpful for writing efficient and "clean" code. Vectorization is a concept found not only in MATLAB but also C/C++, Fortran, and other languages.

Opening the m-file lab1.m in the MATLAB editor, step through each part using cell mode to see the results. Compare the output with the PDF, which was generated from this m-file.

There are twelve (12) exercises in this lab that will be graded. Write your solutions in the template, including appropriate descriptions in each step. Save the .m file as lab1_<UTORid>.m and submit it online on Quercus. Also, submit a PDF of the output by generating html (by going to 'File', 'Publish') and then saving to a PDF called lab1_<UTORid>.pdf. Substitute your UTORid for [UTORid](#).

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Creating Vectors Explicitly

MATLAB plots vectors (also known as arrays) of data points. The first way to create vectors is to give MATLAB a list of values of the form:

```
x = [value1, value2, value3, ..., valueN];
```

We can then see the values in the array x by entering x without a semicolon or with the command `disp(x)`, with or without the semicolon.

Individual entries of the vector can be accessed with the command $x(i)$, where i is between 1 and the length of the array. If i is not in this range an error is thrown.

Examine the following commands and their output.

```
x = [.5, 1.0, 2.3, 4.0, 4.333, 5]; %These are arbitrary values
```

```
x
```

```
x = 1x6  
    0.5000    1.0000    2.3000    4.0000    4.3330    5.0000
```

```
disp(x)
```

```
    0.5000    1.0000    2.3000    4.0000    4.3330    5.0000
```

```
disp(x);
```

```
    0.5000    1.0000    2.3000    4.0000    4.3330    5.0000
```

```
x(1)
```

```
ans = 0.5000
```

```
x(2)
```

```
ans = 1
```

```
x(7)
```

```
Index exceeds the number of array elements. Index must not exceed 6.
```

Exercise 1

Objective: Observe a MATLAB error when you try to access an invalid index.

Details: Try to access elements of the vector `x`, created in the previous step at the command prompt `>>`. Try values of `i` outside the valid range. Try negative values, zero, and large positive values. Copy down the error message in each case, and report this in your submitted work as:

Error for negative index: % Array indices must be positive integers or logical values

Error for zero index: % Array indices must be positive integers or logical values

Error for positive index outside of the bounds: % Index exceeds the number of array elements. Index must not exceed 6.

Only include the error message as a comment (with the percent signs), DO NOT INCLUDE THE CODE IN YOUR SUBMISSION.

Plotting a Vector

Given a list (one dimensional array) of values we can plot them with the command `plot(x)`, with or without a semicolon. This will plot the points in the data set (`i`, `x(i)`).

```
plot(x)
```

Plotting Vector x against Vector y

To plot functions, we need two vectors: a set of `x` points and a corresponding set of `y` points. We now create a vector `y` and plot `x` against `y` with the command `plot(x,y)`.

If the two vectors are not the same size, MATLAB will throw an error.

```
y = [3.7, -3.4, 1.02, 2.2, .04, 1.0]; %These are arbitrary values
plot(x,y)
```

```
Error using plot
Vectors must be the same length.
```

Exercise 2

Objective: Create two vectors and plot one against the other.

Details: Explicitly create the vectors

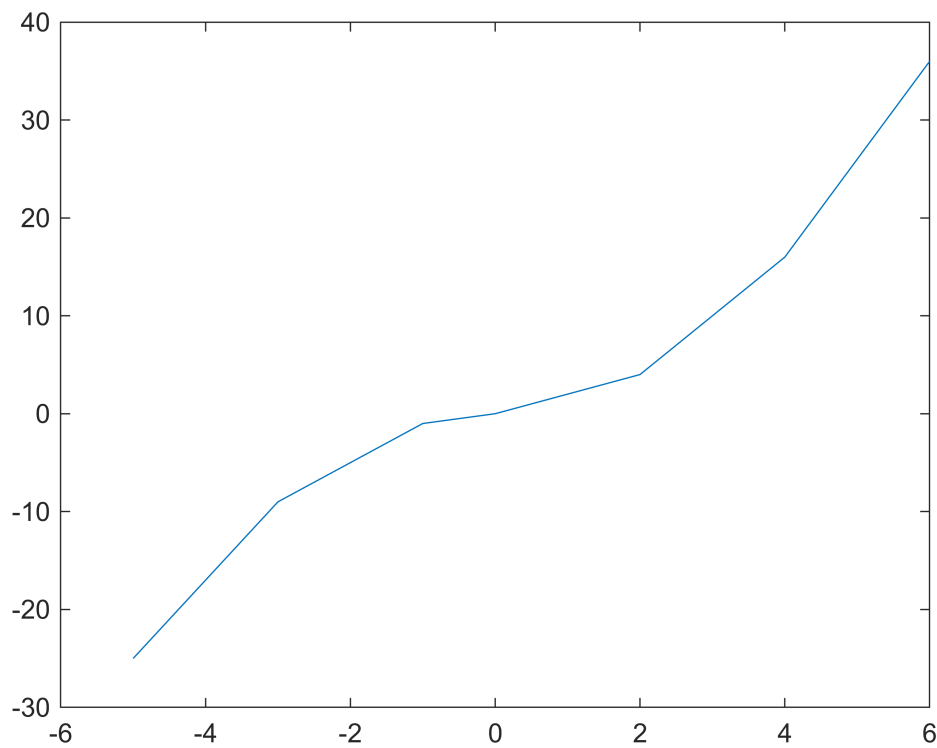
`x = [-5, -3, -1, 0, 2, 4, 6]`

and

`y = [-25, -9, -1, 0, 4, 16, 36]`

And plot `x` against `y`. Your submission should show both the creation of the vectors and the figure, as in the example.

```
x = [-5, -3, -1, 0, 2, 4, 6]; % Creation of x vector
y = [-25, -9, -1, 0, 4, 16, 36]; % Creation of y vector
plot(x,y); % Plot of x against y
```



Creating Vectors with For Loops

Entering the values by hand is tedious and error prone. We can use MATLAB's programming features to create them. Suppose we want to create a vector of N points between 0 and 1, equally spaced and inclusive. This would be useful if we wanted to evaluate a function, $f(x)$, at all of these values.

The distance between the points will be $h = (1 - 0)/(N-1)$, so that:

$$0 = x(1) = 0 * h < x(2) = 1 * h < \dots < x(j) = (j-1) * h < \dots < x(N) = (N-1) * h = 1$$

NOTE: if we wish to do this between two arbitrary points, $a < b$, instead of 0 and 1, the values would be: $h = (b - a)/(N-1)$ and $a = x(1) = a + 0 * h < x(2) = a + 1 * h < \dots < x(j) = a + (j-1) * h < \dots < x(N) = b$

We assign a value of N , compute h , preallocate a vector x , and then loop through the vector.

By 'preallocate' we mean 'set aside an array of the appropriate size in memory for future use'. Preallocation can be done with the command `x = zeros(N,1);`, which makes an array of length N in which all the entries are zero. Other options are possible, too.

```
N = 11;                %Alter this value to see different results
h = (1-0)/(N-1);
x = zeros(N,1);        %This creates a column vector.
%zeros(1,N) would create a row vector.

for j = 1:N
    x(j) = (j-1) * h;
end
disp(x);
```

```
0
0.1000
0.2000
0.3000
0.4000
0.5000
0.6000
0.7000
0.8000
0.9000
1.0000
```

Plotting $y = x^2$

As a first example of plotting a function, we plot $y = x^2$. Using the array `x` created in the last step, we populate a vector `y` such that $y(i) = x(i)^2$ and plot it.

```
y = zeros(N,1);        %Preallocate the array

for j = 1:N
    y(j) = x(j)^2;
end

disp(y);

plot(x,y)
```

Plotting $y = \sin(2 * \pi * x)$

MATLAB has a number of built in functions including the trigonometric functions (`sin`, `cos`, `arccos`,...), the exponential functions (`exp`), the natural logarithm function (`log`), hyperbolic functions (`sinh`, `cosh`), and others. The constant `pi` is also defined. For a full list of built in functions type `help elfun` at the MATLAB command line.

We create the vector `z` with $z(j) = \sin(2*\pi*x(j))$, using the same array as from the previous steps.

```
z = zeros(N,1);        %Preallocate the array
```

```

for j = 1:N
    z(j) = sin(2 * pi * x(j));
end

plot(x,z)

```

Exercise 3

Objective: Plot $x \cdot x$

Details: Using a for loop, create a vector x of 101 equally spaced points between -3 and 7, inclusive. Then create a vector y , such that $y(i) = \text{abs}(x(i)) \cdot x(i)$ using a for loop. Plot the results.

Your submission should include the code, as in the example, and appropriate comments.

```

N = 101; % Corresponds to the number of equally spaced points we want
d = (7+3)/(N-1); % Distance between each point is equal to the total distance divided by number of points
x = zeros(N,1); % Create a column vector for x
for j = 1:N % Run a for loop which gets correct value for each point in x
    x(j) = ((j-1) * d) - 3; % subtract 3 since the points should start from -3
end
disp(x);

```

```

-3.0000
-2.9000
-2.8000
-2.7000
-2.6000
-2.5000
-2.4000
-2.3000
-2.2000
-2.1000
-2.0000
-1.9000
-1.8000
-1.7000
-1.6000
-1.5000
-1.4000
-1.3000
-1.2000
-1.1000
-1.0000
-0.9000
-0.8000
-0.7000
-0.6000
-0.5000
-0.4000
-0.3000
-0.2000
-0.1000
0
0.1000
0.2000
0.3000
0.4000
0.5000

```

0.6000
0.7000
0.8000
0.9000
1.0000
1.1000
1.2000
1.3000
1.4000
1.5000
1.6000
1.7000
1.8000
1.9000
2.0000
2.1000
2.2000
2.3000
2.4000
2.5000
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3.6000
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4.3000
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4.9000
5.0000
5.1000
5.2000
5.3000
5.4000
5.5000
5.6000
5.7000
5.8000
5.9000
6.0000
6.1000
6.2000
6.3000
6.4000
6.5000
6.6000
6.7000
6.8000

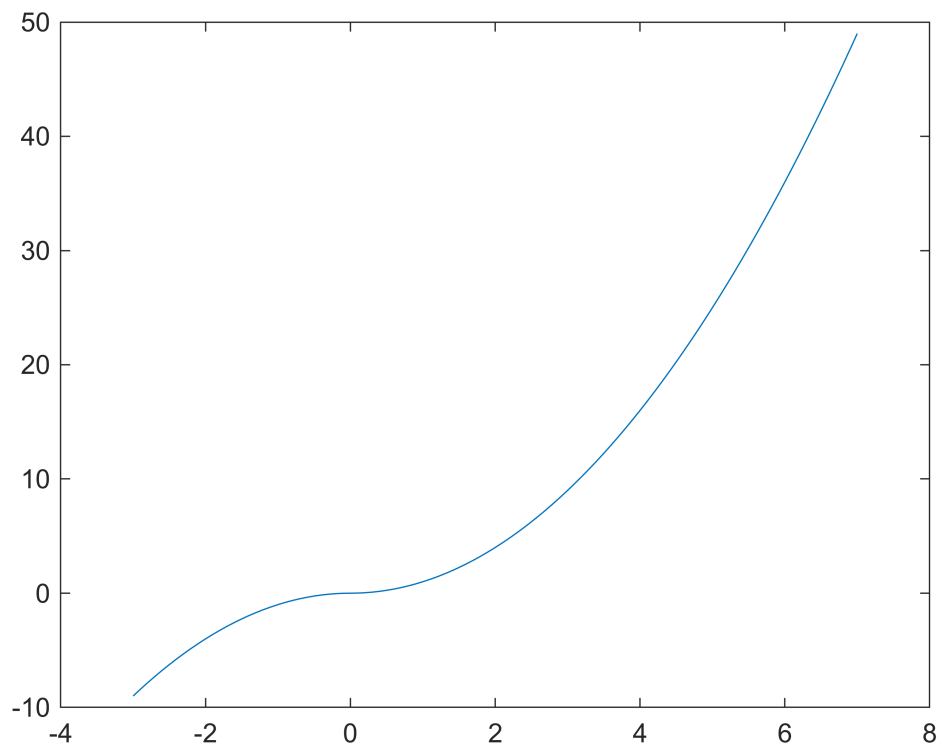
6.9000
7.0000

```
y = zeros(N,1); % Create a column vector for y
for i = 1:N % Run a for loop which computes and assigns correct value for each point in y
    y(i) = abs(x(i)) * x(i);
end
disp(y);
```

-9.0000
-8.4100
-7.8400
-7.2900
-6.7600
-6.2500
-5.7600
-5.2900
-4.8400
-4.4100
-4.0000
-3.6100
-3.2400
-2.8900
-2.5600
-2.2500
-1.9600
-1.6900
-1.4400
-1.2100
-1.0000
-0.8100
-0.6400
-0.4900
-0.3600
-0.2500
-0.1600
-0.0900
-0.0400
-0.0100
0
0.0100
0.0400
0.0900
0.1600
0.2500
0.3600
0.4900
0.6400
0.8100
1.0000
1.2100
1.4400
1.6900
1.9600
2.2500
2.5600
2.8900
3.2400
3.6100
4.0000
4.4100

4.8400
5.2900
5.7600
6.2500
6.7600
7.2900
7.8400
8.4100
9.0000
9.6100
10.2400
10.8900
11.5600
12.2500
12.9600
13.6900
14.4400
15.2100
16.0000
16.8100
17.6400
18.4900
19.3600
20.2500
21.1600
22.0900
23.0400
24.0100
25.0000
26.0100
27.0400
28.0900
29.1600
30.2500
31.3600
32.4900
33.6400
34.8100
36.0000
37.2100
38.4400
39.6900
40.9600
42.2500
43.5600
44.8900
46.2400
47.6100
49.0000

```
plot(x,y); % Plots results
```

Plotting Two Data Sets at Once

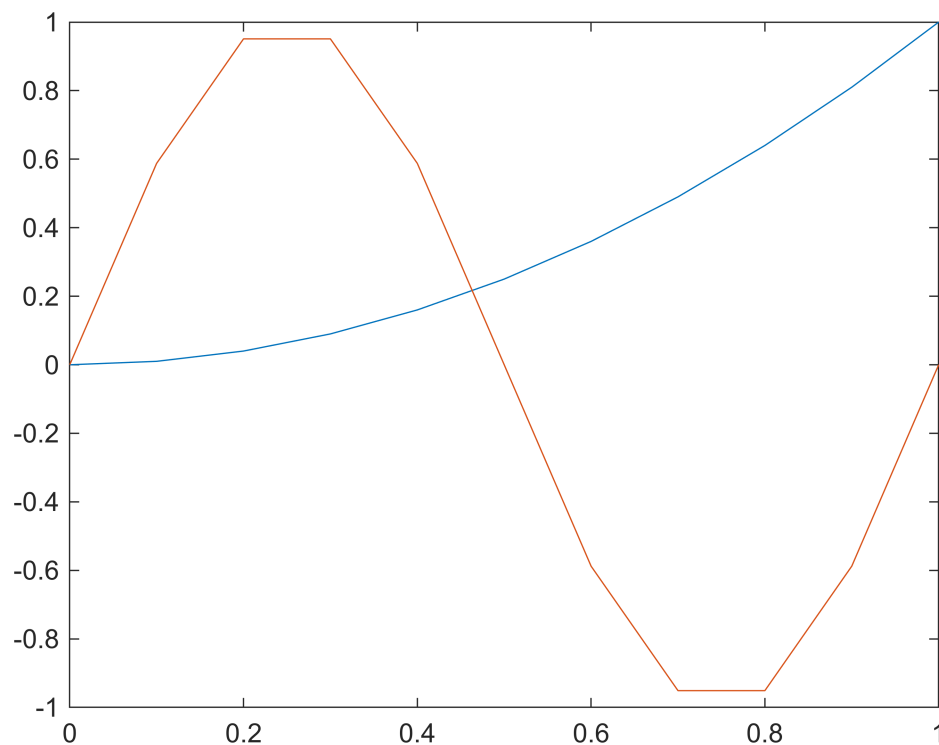
We can also plot the preceding two examples on the same figure with the command `plot(x, y, x, z)`. MATLAB will automatically put a different color on each line.

```
h=0.1           %redefine the variables x, y, z
```

```
h = 0.1000
```

```
x=0:h:1;        %because they might have been
y=x.^2;         %changed in exercise 3
z=sin(2*pi.*x); %
```

```
plot(x,y,x,z)
```



Annotating a Figure

It is easy to add a title, axis labels, and a legend to the preceding figure.

```
xlabel('x');
ylabel('f(x)');
title('Example plot of two functions plotted on the same figure');
legend('x^2', 'sin(2*pi*x)');
```

Using Help Effectively

You can obtain help on any routine at the command line by typing `help commandname`. As you may have noticed in the preceding figure, the legend was not placed in a convenient position. We will now use help to find out how to move the legend to the lower left corner, where it will be less obtrusive.

If you type `help legend` in the command window at the `>>` prompt, you'll see a section:

`LEGEND(...,'Location',LOC)` adds a legend in the specified location, `LOC`, with respect to the axes. `LOC` may be either a 1x4 position vector or one of the following strings:

'North'	inside plot box near top
'South'	inside bottom
'East'	inside right
'West'	inside left
'NorthEast'	inside top right (default)
'NorthWest'	inside top left
'SouthEast'	inside bottom right

'SouthWest'

inside bottom left

Thus, if we call legend again, with the option 'Location', 'SouthWest', it will move the legend to where we want.

%NOTE: The labels are entered again.

```
legend('x^2', 'sin(2*pi*x)', 'Location', 'SouthWest');
```

Vectorization - An Elegant Alternative to Loops

In the previous examples, we used for loops to fill our arrays with the values we wanted. This is very similar to what would be done in C/C++, Java, Fortran, and other languages.

MATLAB provides a faster way to perform these looped operations, using vectorization, which processes the entire vector as a single object. For example, given a vector x , we can get the sine of the values in x with the command `sin(x)`, which outputs another vector. This works with all built in MATLAB functions.

Multiplication, division, and exponentiation are handled differently. Instead of using $*$, $/$, and $^$, we must use $.*$, $./$, and $.^$ to indicate that we want the operation to be performed on each element. The reason for this change in the symbols is that MATLAB uses the symbols without the period for matrix multiplication, exponentiation, and other actions.

Vectorization yields more concise and less error prone code:

```
y = x.^2; %Alternatively, y = x .* x;
z = sin(2 * pi * x); %NOTE: Multiplication by the scalar 2*pi, does not
% require the .* operator. Why is that?

plot(x,y,x,z) %Verify that these are the same results
xlabel('x');
ylabel('f(x)');
title('Example plot of two functions computed by vectorization');
legend('x^2', 'sin(2*pi*x)', 'Location', 'SouthWest');
```

Speed Comparison

Historically, it was desirable both for clarity and speed to use vectorized operations in place of loops everywhere possible in MATLAB. Recent versions of MATLAB have reduced the speed advantage through the introduction of a Just in Time (JIT) compiler, parallel for loops, and other tools.

However, we can still demonstrate the speed advantage, and the benefit to clarity is already evident.

Timing is done with the `tic`, `toc` commands, which enclose the region we want to benchmark. The first output is the time for the construction done by looping, the second output is the time for construction done with vectorization.

```
clear y; %Clear the y array
tic; %Begin timing the construction and filling of the array

y = zeros(N,1);
```

```

for j = 1:N
    y(j) = x(j)^2;
end

toc;

clear y;    %Clear the y array
tic;
y = x.^2;
toc;

```

Exercise 4

Objective: Compare the speedup from vectorization for a larger vector.

Details: Create a vector x of 5000001 equally space points between -2 and 3, inclusive, using a for loop. Then time the construction of vector y , whose values are arctan of x , by a for loop and by vectorization. Be sure to clear y between the two runs. (Hint: use the help file to find the command for arctan!)

Your submission should include the code, as in the example, with appropriate comments.

```

N = 5000001; % Creating variable for number of spaces
d = (3+2)/(N-1); % Calculating distance between each point
x = zeros(N,1); % Create empty column vector for x

for j = (1:N) % For loop computing each point in x
    x(j) = ((j-1) * d) - 2;
end

tic; % start timing for for-loop
y = zeros(N,1); % Create an empty array for y
for i = (1:N) % Run a for loop computing the value of y for each value of x by taking the arctan
    y(i) = atan(x(i));
end
toc; % finish timing for for-loop

```

Elapsed time is 0.166035 seconds.

```

clear y; % Reset the array

tic; % start timing for vectorization
y = atan(x); % Use vectorization to obtain an array where all components are the arctan of each
toc; % end timing for vectorization

```

Elapsed time is 0.042989 seconds.

```

% For Loop Elapsed Time is: 0.142158 seconds
% Vectorization Elapsed Time is: 0.043356 seconds
% Therefore, vectorization is faster

```

Further Avoiding Loops with linspace

In the preceding examples, we will focus on the vector x , which was constructed with a for loop. MATLAB includes a routine for creating a vector of a given number, N , of equally spaced points between two values, a and b :

```
x = linspace(a, b, N);
```

No preallocation is necessary. The argument N is optional. If it is omitted MATLAB uses 100 points by default.

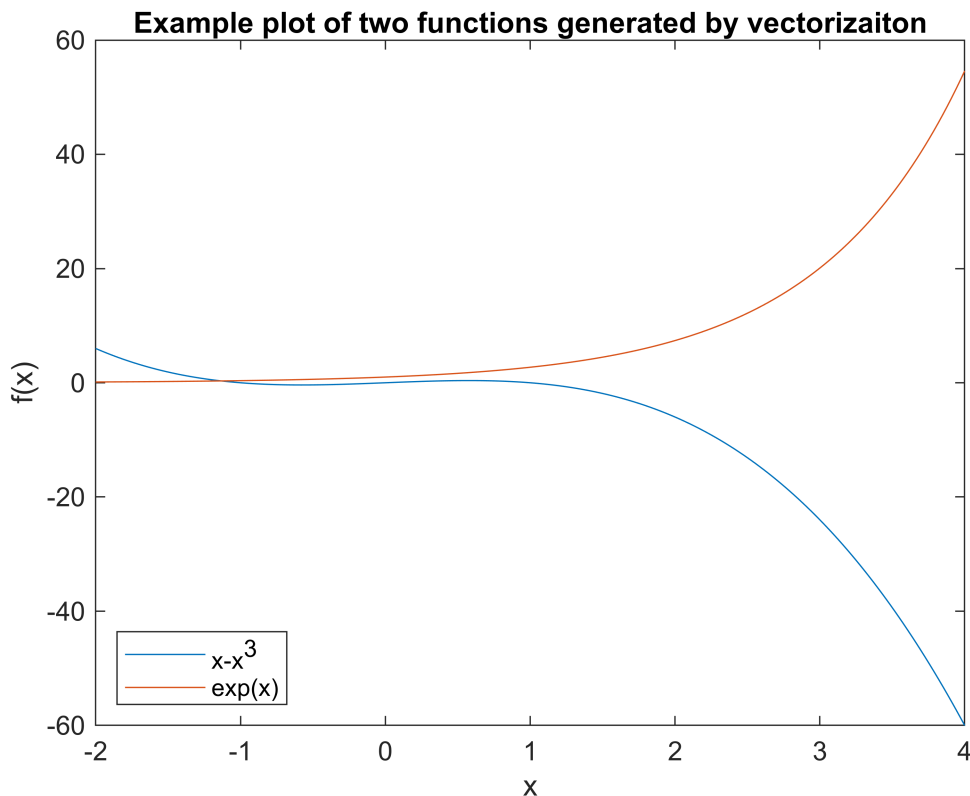
We will now use `linspace` to plot the functions $y = x - x^3$ and $y = \exp(x)$ in the range $[-2, 4]$ with 200 points.

```
clear all; %Clears all variables

x = linspace(-2,4, 200); %Create the array

y = x - x.^3;
z = exp(x);

plot(x,y,x,z) %Verify that these are the same results
xlabel('x');
ylabel('f(x)');
title('Example plot of two functions generated by vectorizaiton');
legend('x-x^3', 'exp(x)', 'Location', 'SouthWest');
```



Exercise 5

Objective: Solve an ODE and plot three particular solutions.

Details: Manually find the general solution of the ODE:

$$dy/dt + (2t)y = 1/\exp(t^2)$$

and the particular solutions for initial conditions $y(1) = -1$, $y(1) = 0$, and $y(1) = 1$. Plot these three particular solutions on the same axes letting the independent variable range from 1 to 5.

Once you have the three particular solutions you will need to:

1. Create a vector for the independent variable, t . Use `linspace` with a reasonable number of points (100 is fine).
2. Create vectors for the three solutions. Use vectorized operations.
3. Plot three solutions on the same axes, annotating the figure appropriately.

Your submission should include, in the description section, the general solution of the ODE and the three particular solutions. It should also have the appropriately commented code.

```
% General Solution to ODE:  $y(t) = t/(e^{t^2}) + A/(e^{t^2})$ 
% Particular Solution for  $y(1) = -1$ :  $y(t) = t/(e^{t^2}) + (-e-1)/(e^{t^2})$ 
% Particular Solution for  $y(1) = 0$ :  $y(t) = t/(e^{t^2}) - 1/(e^{t^2})$ 
% Particular Solution for  $y(1) = 1$ :  $y(t) = t/(e^{t^2}) + (e-1)/(e^{t^2})$ 

t = linspace(1, 5, 100); % Create an array of 100 equally spaced points from 1 to 5

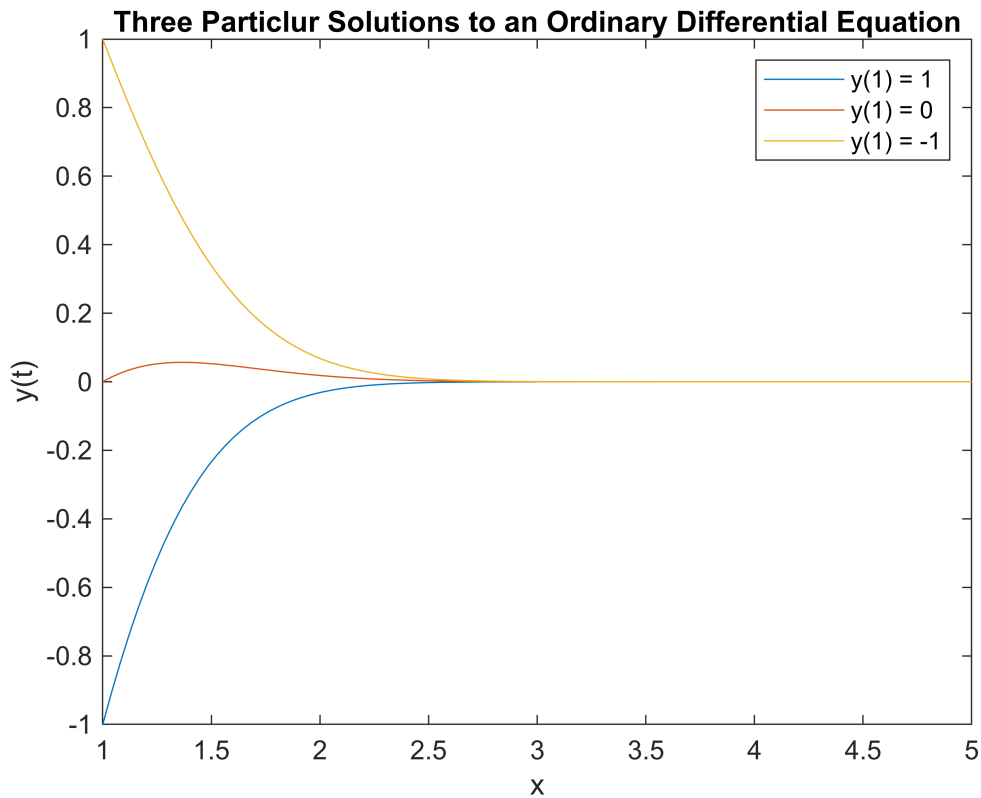
x = t./(exp(t.^2)) + (-exp(1)-1)./(exp(t.^2)) % Particular solution for  $y(1) = -1$ 
```

```
x = 1x100
    -1.0000    -0.9072    -0.8201    -0.7388    -0.6632    -0.5933    -0.5289    -0.4698 ...
```

```
y = t./(exp(t.^2)) - 1./(exp(t.^2)); % Particular solution for  $y(1) = 0$ 

z = t./(exp(t.^2)) + (exp(1)-1)./(exp(t.^2)); % Particular solution for  $y(1) = 1$ 

plot(t,x,t,y,t,z); % Plot of three particular solutions
xlabel('x');
ylabel('y(t)');
title('Three Particlur Solutions to an Ordinary Differential Equation');
legend('y(1) = 1', 'y(1) = 0', 'y(1) = -1');
```



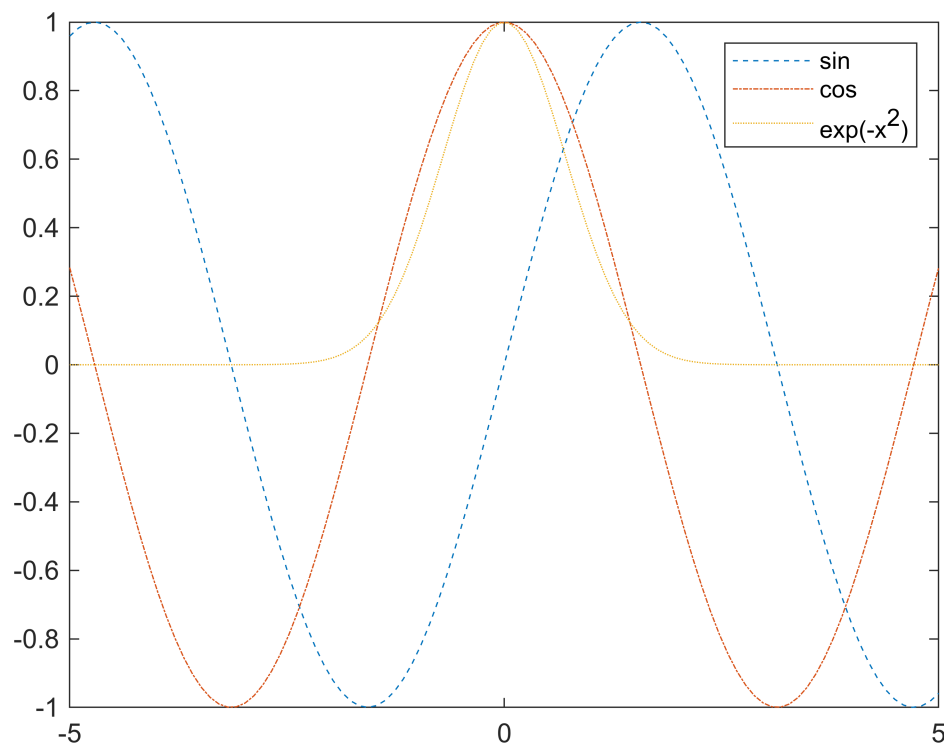
More Plotting Examples - Line Style

There are many plotting options available, including color, line style, and marker style. Some options can be found from the help `plot` command. This is done by including a command after each line.

In the first we example we will vary the line style.

```
x = linspace(-5,5);

%Plot three functions with different line styles. NOTE: the
%function can be put directly in the plot argument.
plot(x, sin(x), '--', x, cos(x), '-.', x, exp(-x.^2), ':');
legend('sin', 'cos', 'exp(-x^2)');
```



More Plotting Examples - Line Color

We can also control the color, mixing it with line style.

```
%Plot two functions, first in green and then in red.
x = linspace(-1,1);
plot(x, x.^3 .* sin(x), 'g', x, -x .* exp(x), 'r-');
legend('x^3 * sin(x)', '-x * exp(x)');
```

More Plotting Examples - Markers

Markers can be used at the individual points, with and without a line joining the points.

```
x = linspace(-4,4, 20);
plot(x, sin(x), 'x-', x, (x.^2)./(1+x.^2), '.');
legend('sin(x)', 'x^2/(1+x^2)');
```

Inline functions of one variable

Suppose we wish to construct the function:

$$f(x) = x * \sin(x)$$

In a way that MATLAB can understand and manipulate. This will let us compute values of $f(x)$, plot it, and create other functions from it.

This can be accomplished by defining an inline function of one variable, with the command:

function name = @(argument name) mathematical expression;

For this example, the function name is f, the argument name is x, and the mathematical expression is $x * \sin(x)$.

Consider the following examples, and take note of:

1. The use of vectorization in the definitions, 2. The different ways that the output can be displayed, 3. The different variable names.

```
f = @(x) x .* sin(x);  
  
x = 1;  
fprintf(' f(%g) = %g\n', x, f(x));
```

```
f(1) = 0.841471
```

```
fprintf(' f(%g) = %g\n', 1, f(1));
```

```
f(1) = 0.841471
```

```
disp(f(1));
```

```
0.8415
```

```
f(1)
```

```
ans = 0.8415
```

```
x = 2;  
fprintf(' f(%g) = %g\n', 2, f(2));
```

```
f(2) = 1.81859
```

```
fprintf(' f(%g) = %g\n', 2, f(2));
```

```
f(2) = 1.81859
```

```
disp(f(2));
```

```
1.8186
```

```
f(2)
```

```
ans = 1.8186
```

```
disp(f([1,2]))
```

```
0.8415    1.8186
```

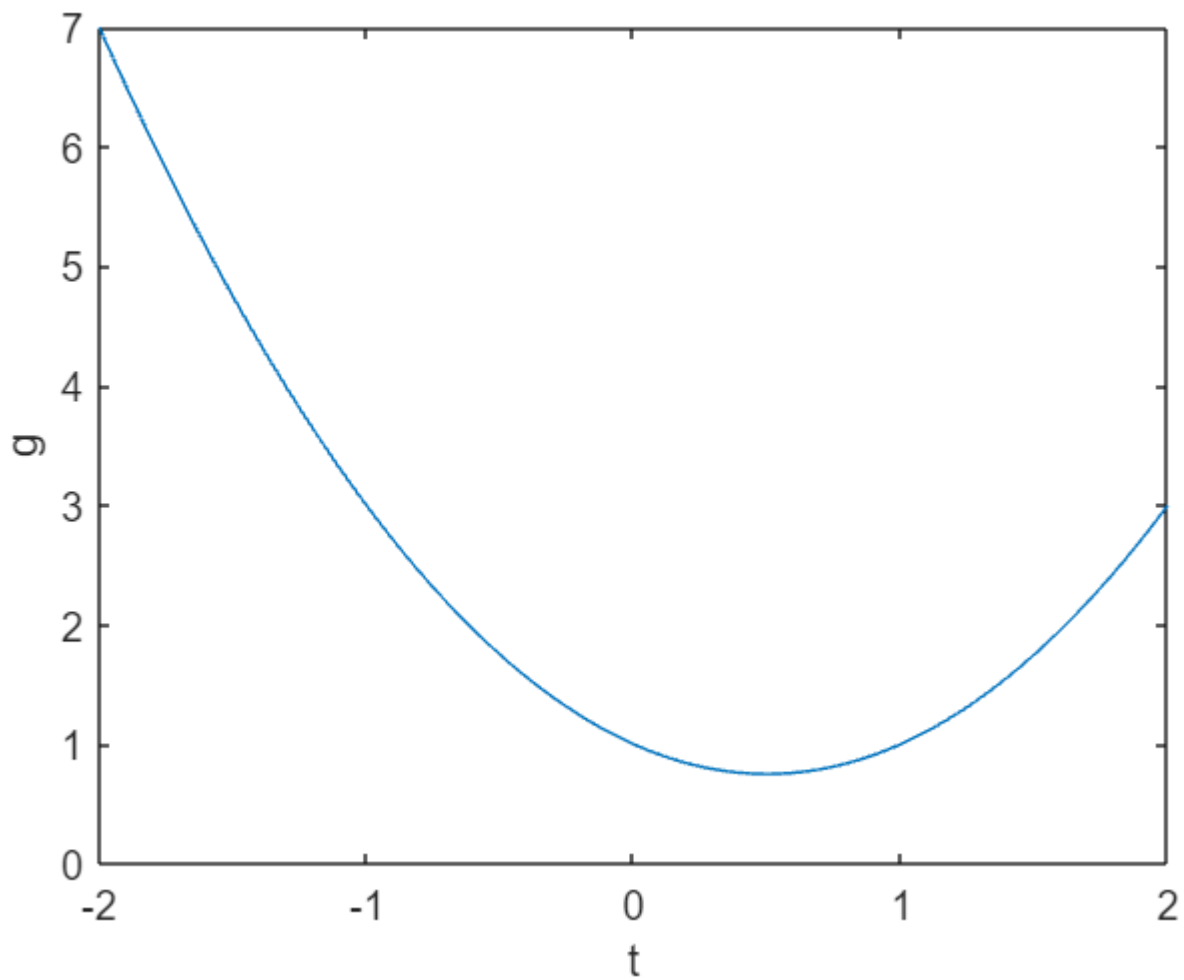
```
g = @(t) t.^2 - t +1;  
g(1)
```

ans = 1

g(2)

ans = 3

```
% Construct an array of 100 grid points from -2 to 2, and plot g(t).  
t = linspace(-2,2);  
plot(t, g(t));  
% Label axes  
xlabel('t');  
ylabel('g');
```



Exercise 6

Objective: Write and use an inline function of one variable.

Details: Define the inline function for

$$f(x) = (x^3 - \text{abs}(x)) * \ln(x^2+1)$$

Use this function to compute $f(0)$, $f(1)$, and $f(-1)$ and plot the function with 100 grid points from -5 to 5. Make sure to use vectorization in your definition, and label your axes.

Your submission should show the definition of the function, and the computation of these values.

```
f = @(x) (x.^3 - abs(x)) .* log((x.^2) + 1); % Definition of inline functions
```

```
x = 0;  
fprintf('f(%g) = %g\n', x, f(x)); % Computation of f(0)
```

```
f(0) = 0
```

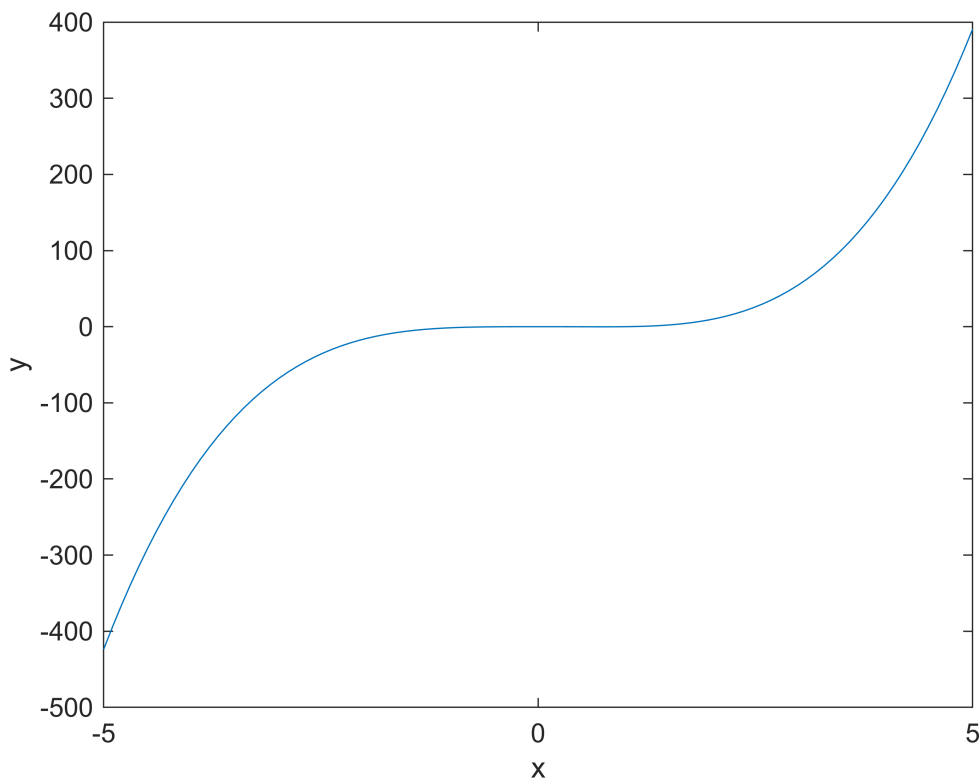
```
f(0);  
x = 1;  
fprintf('f(%g) = %g\n', x, f(x)); % Computation of f(1)
```

```
f(1) = 0
```

```
f(1);  
x = -1;  
fprintf('f(%g) = %g\n', x, f(x)); % Computation of f(-1)
```

```
f(-1) = -1.38629
```

```
f(-1);  
  
t = linspace(-5,5,100); % Create array of 100 equally spaced points from -5 to 5  
plot(t, f(t)); % Plot of function  
xlabel('x');  
ylabel('y');
```



Inline functions of two variables

Suppose we wish to solve the equation

$$x = y^3 + y$$

for y as a function of x . If we do this by root finding, then, given a value of x_0 , we need to find the root of the function

$$g(y) = f(x_0, y) = y^3 + y - x_0$$

We will accomplish this using inline functions.

Inline functions of two variables are defined as:

```
func = @(x,y) f(x,y);
```

where `func` is the name you wish to assign your function, and `f(x,y)` is the relevant expression.

Some examples of defining and using inline functions of two variables are given below.

```
f = @(x,y) y.^3 + y - x;
x = 0; y = 0;
fprintf(' f(x = %g, y = %g) = %g\n', x, y, f(x, y));
```

```
f(x = 0, y = 0) = 0
```

```
x = 0; y = 1;
fprintf(' f(x = %g, y = %g) = %g\n', x, y, f(x, y));
```

```
f(x = 0, y = 1) = 2
```

```
disp(f(x,y))
```

```
2
```

```
f(0,1)
```

```
ans = 2
```

```
h = @(t,u) t.^2 + sin(u);  
h(1, pi/2)
```

```
ans = 2
```

```
h(2, 2)
```

```
ans = 4.9093
```

Exercise 7

Objective: Write and use an inline function of two variables.

Details: Define the inline function for

$$f(x,y) = y + y^3 - \cos x + x^2 - x^4$$

Note that $f(x,y) = c$ is the implicit solution to

$$dy/dx = (4x^3 - 2x - \sin x)/(1+3y^2).$$

See Examples 1-3 of section 2.1 in Brannan and Boyce for similar examples.

Use this function to compute $f(0, 0)$, $f(\pi/2, 1)$, and $f(-1, -1)$. Make sure to use vectorization in your definition.

Your submission should show the definition of the function, and the computation of these values.

```
f = @(x,y) y + y.^3 - cos(x) + x.^2 - x.^4; % Definition of inline function
```

```
x = 0, y = 0;
```

```
x = 0
```

```
fprintf('f(x = %g, y = %g) = %g\n', x, y, f(x,y)); % Computation of f(0,0)
```

```
f(x = 0, y = 0) = -1
```

```
f(0,0);  
x = pi./2, y = 1;
```

```
x = 1.5708
```

```
fprintf('f(x = %g, y = %g) = %g\n', x, y, f(x,y)); % Computation of f(pi/2,1)
```

```
f(x = 1.5708, y = 1) = -1.62067
```

```
f(pi./2,1);  
x = -1, y = -1;
```

```
x = -1
```

```
fprintf('f(x = %g, y = %g) = %g\n', x, y, f(x,y)); % Computation of f(-1,-1)
```

```
f(x = -1, y = -1) = -2.5403
```

```
f(-1,-1);
```

Numerically solving an implicit equation

Given x_0 , we will now solve the equation

$$f(x_0, y) = y^3 + y - x_0 = 0$$

for y . This will be accomplished using `fzero`, which employs a more advanced form of Newton's method.

The minimal arguments needed for using `fzero` are:

```
fzero(function_handle, guess)
```

`function_handle` is an abstract data structure which directs MATLAB towards a function of a single variable that it will try to zero.

We need to tell MATLAB that it is trying to solve for the y argument. This is done by creating an inline function of one variable from the existing function, i.e.

```
g = @(y) f(x0, y)
```

And then having `fzero` try to solve

$$g(y) = 0$$

You can either define the new inline function and use it:

```
g = @(y) f(x0, y); y = fzero(g, guess);
```

or you can put the inline function argument directly in the function handle argument:

```
y = fzero(@(y) f(x0,y), guess);
```

The guess is an initial guess for what we anticipate y to be. Finding a good initial guess may require some experimentation. For this example, the guess may be quite poor, and the algorithm will still converge. For others, more care must be taken.

Note the various ways of constructing the inline function of one variable, and the different guesses.

```
f = @(x,y) y.^3 + y - x;  
  
x0 = 1;  
guess = 1;  
g = @(y) f(x0, y);
```

```
y = fzero(g, guess);
fprintf(' y(%g) = %g\n', x0, y);
```

```
y(1) = 0.682328
```

```
guess = 50;
y = fzero(g, guess);
fprintf(' y(%g) = %g\n', x0, y);
```

```
y(1) = 0.682328
```

```
x = 2;
g = @(y) f(x, y);
y = fzero(g, 2);
fprintf(' y(%g) = %g\n', x, y);
```

```
y(2) = 1
```

```
guess = 2;
y = fzero(@(y) f(2, y), guess);
fprintf(' y(%g) = %g\n', 2, y);
```

```
y(2) = 1
```

Exercise 8

Objective: Use `fzero` to solve an equation $f(x,y)=0$ for y at different values of x .

Details: Consider the function

$$f(x,y) = y + y^3 - \cos x + x^2 - x^4$$

Define the appropriate inline function and compute the single solution at $x = 0$ and the two positive solutions at $y = 1/2$.

You will need to experiment with different guesses to get these three solutions.

Your submission should show the definition of the function, and the computation of these three roots.

```
f = @(x,y) y + y.^3 - cos(x) + x.^2 - x.^4; % Definition of inline function
```

```
x0 = 0; % initial condition for x
guess = 50
```

```
guess = 50
```

```
g = @(z) f(x0, z);
z = fzero(g, guess); % Computing solution for x = 0
fprintf('z(%g) = %g\n', x0, z);
```

```
z(0) = 0.682328
```

```
y0 = 1/2; % initial condition of y
guess = 0.5 % Guess for first positive value
```

```
guess = 0.5000
```

```
g = @(z) f(z, y0);
z = fzero(g, guess); % Computing first positive solution for y = 1/2
fprintf('z(%g) = %g\n', y0, z);
```

```
z(0.5) = 0.567406
```

```
guess = 1.5 % Guess for second positive value
```

```
guess = 1.5000
```

```
z = fzero(g, guess); % Computing second positive solution
fprintf('z(%g) = %g\n', y0, z);
```

```
z(0.5) = 1.05844
```

Plotting the solution

Now we are ready to plot y as a function of x . We will construct an array of x values, solve for y at each value of x , and then plot the results. This will be accomplished with a for loop.

```
f = @(x,y) y.^3 + y - x;

% 50 points equally spaced from -5 to 2, inclusive
xvals = linspace(-5, 2, 50);

% Preallocate storage space for the solutions
yvals = zeros(size(xvals));

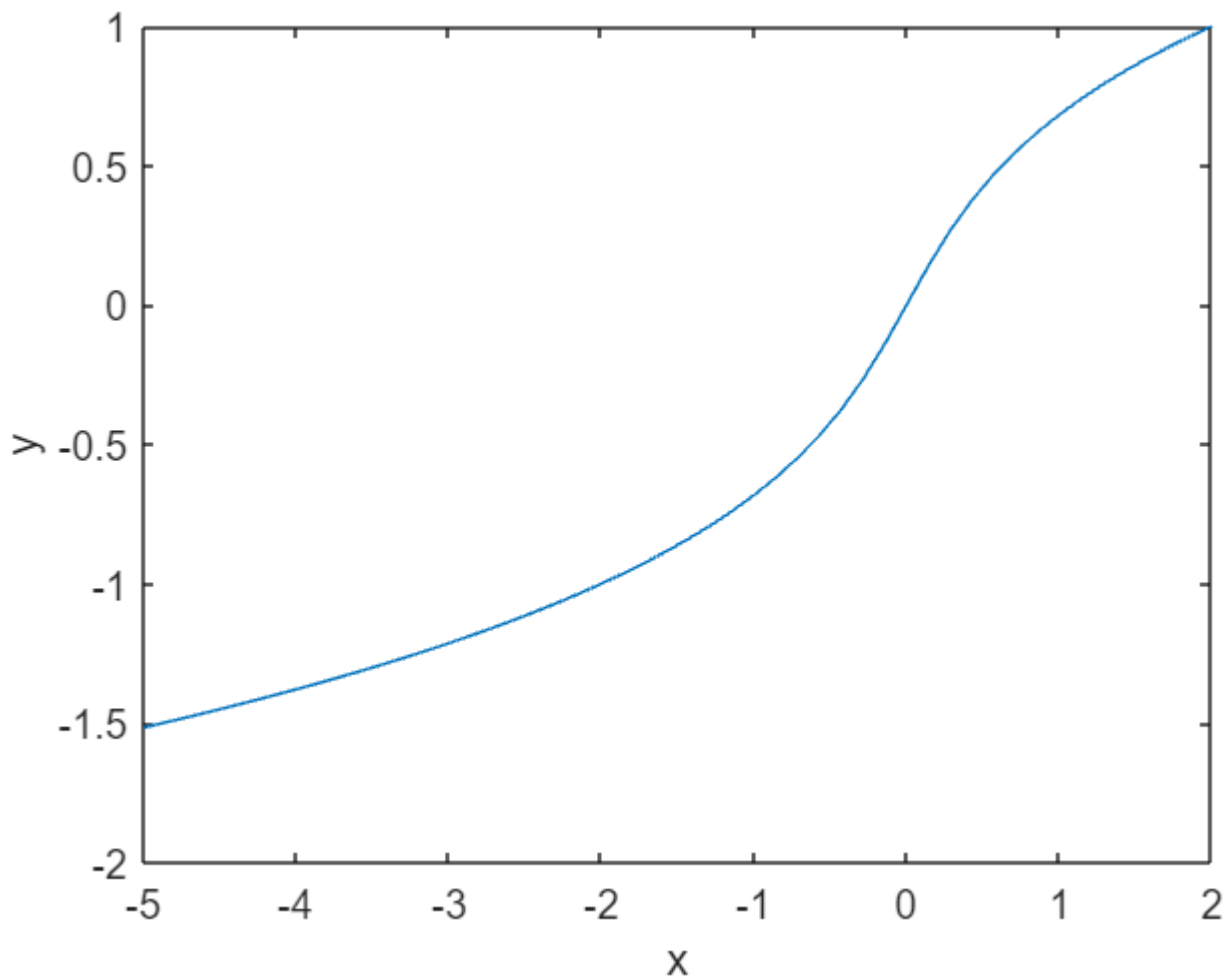
% Loop through all the values
for j = 1:length(xvals)

    yvals(j) = fzero(@(y) f(xvals(j), y), 0);

end

% Plot the results

plot(xvals, yvals);
xlabel('x');
ylabel('y');
```

Exercise 9

Objective: Plot a portion of an implicit equation.

Details: Plot the portion of the solution to

$$f(x,y) = y + y^3 - \cos x + x^2 - x^4$$

passing through the point $(0,0)$ for x from -2 to 2. Use 100 grid points.

You will need to be careful with the initial guess you use in solving the equation.

Your submission should show the definition of the function, the construction of the arrays, the for loop, and the resultant figure.

Label your axes.

```
% ADJUST FUNCTION TO ENSURE IT PASSES THROUGH (0,0)
f = @(x,y) y + y.^3 - cos(x) + x.^2 - x.^4; % define inline function

xvals = linspace(-2,2,100); % Create 100 evenly spaced x-values from -2 to 2
yvals = zeros(size(xvals)); % Create array for y-values
```

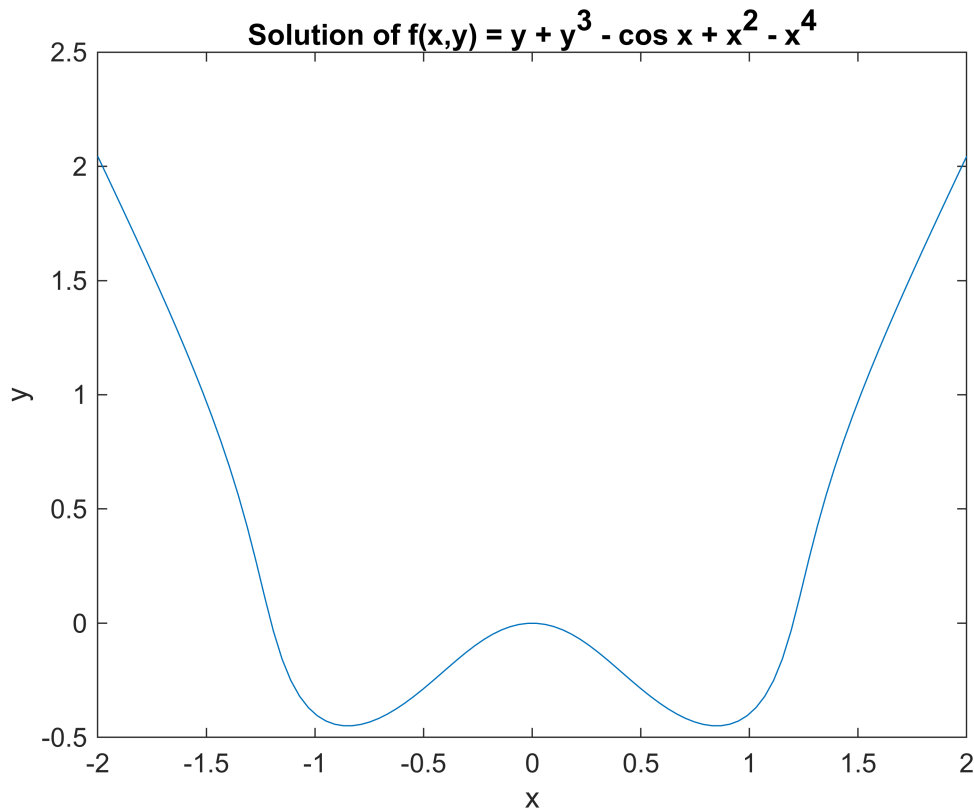
```

f1 = @(x,y) y + y.^3 - cos(x) + x.^2 - x.^4 + 1; % Adjust graph to pass through (0,0)

for i = 1:length(xvals)
    yvals(i) = fzero(@(y) f1(xvals(i), y), 0.05); % Solution of function from -2 to 2 passing t
end

plot(xvals, yvals); % Plot the graph
xlabel('x'); % x-axis label
ylabel('y'); % y-axis label
title('Solution of f(x,y) = y + y^3 - cos x + x^2 - x^4') % Graph title

```



Exercise 10

Objective: Solve a differential equation and plot a portion of it.

Details: Find the general implicit solution of the differential equation

$$dy/dx = (-\cos x + 3x^2) y$$

Plot the particular solution passing through $y(0) = 1$ using 100 grid points for x in $[-1.5, 1.25]$.

Be careful on your choice of guess. You will be penalized if MATLAB shows an error.

Your submission should show the general and particular solutions, in implicit form, in the comments, the definition of the appropriate inline functions, arrays, the for loop, and the figure.

Label your axes.

```

% dy/dx = (-cosx + 3x^2)y
% dy/y = (-cosx + 3x^2)x
% log(y) = -sinx + x^3 + C\

f = @(x,y) -log(y) - sin(x) + x.^3; % Definition of inline function
xvals = linspace(-1.5, 1.25, 100); % Creation of array containing 100 equally spaced points for
yvals = zeros(size(xvals)); % Creating array of zeros equal to size of xvals

for i = 1:length(xvals) % For loop to compute corresponding y value
    yvals(i) = fzero(@(y) f(xvals(i), y), 1);
end

```

```

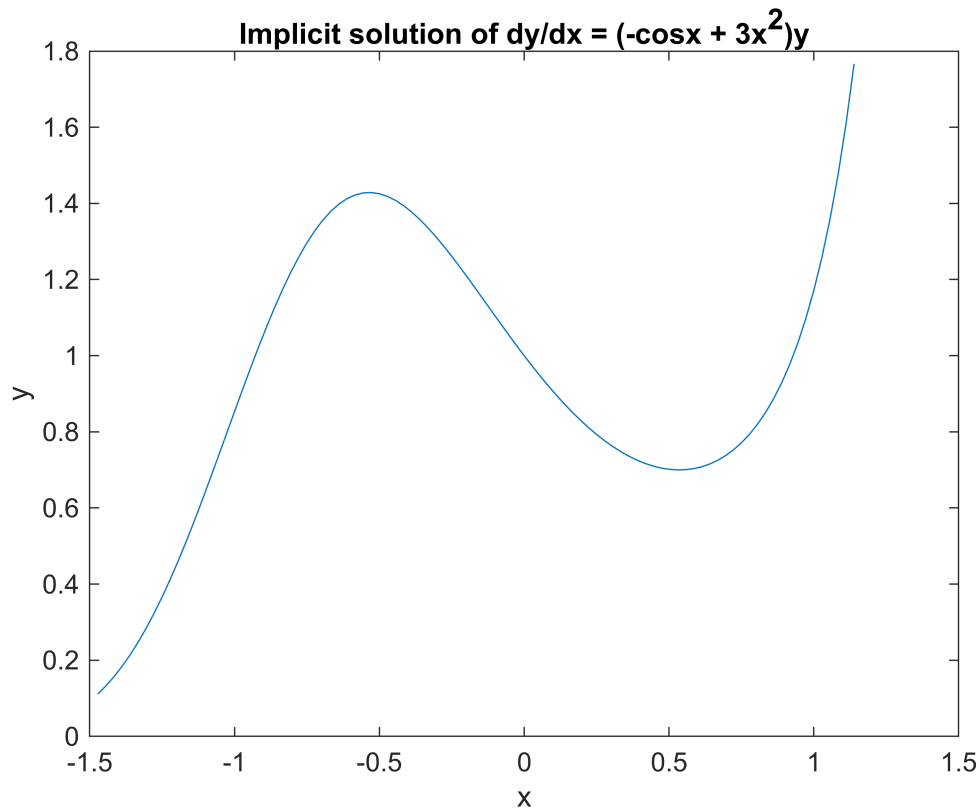
Exiting fzero: aborting search for an interval containing a sign change
because complex function value encountered during search.
(Function value at -0.28 is -1.1045-3.1416i.)
Check function or try again with a different starting value.
Exiting fzero: aborting search for an interval containing a sign change
because complex function value encountered during search.
(Function value at -0.28 is 1.9415-3.1416i.)
Check function or try again with a different starting value.
Exiting fzero: aborting search for an interval containing a sign change
because complex function value encountered during search.
(Function value at -0.28 is 2.0471-3.1416i.)
Check function or try again with a different starting value.
Exiting fzero: aborting search for an interval containing a sign change
because complex function value encountered during search.
(Function value at -0.28 is 2.1589-3.1416i.)
Check function or try again with a different starting value.
Exiting fzero: aborting search for an interval containing a sign change
because complex function value encountered during search.
(Function value at -0.28 is 2.2771-3.1416i.)
Check function or try again with a different starting value.

```

```

plot(xvals, yvals); % Plot of solution
xlabel('x');
ylabel('y');
title('Implicit solution of dy/dx = (-cosx + 3x^2)y');

```



Install iode

Objective: install iode

Details: visit <https://faculty.math.illinois.edu/iode/> and follow the instructions there to download and install iode.

Exercise 11

Objective: use iode to plot the direction field of a differential equation

Details: After starting iode, click the "direction fields" button from the main menu. The default is the direction field for

$$dy/dx = \sin(y-x)$$

Click any point in the x-y plane to see a (numerically computed) solution to the differential equation passing through that point.

Starting from the "Equation" menu, plot the direction field of

$$dy/dx = xy^2$$

Describe, in words, the behaviour of the solutions. What happens as x approaches infinity? Explain why solutions are symmetric about the y-axis, i.e. $y(x) = y(-x)$ for any solution.

```
%{
As x approaches infinity, the solution curves approach a semistable
equilibrium point of type 1. As x approaches infinity, the solution curves
begin to approach  $y = 0$  from the bottom. In general, the solution curves
```

above the equilibrium resemble an upward opening parabola, while solution curves below the equilibrium resemble a parabola near $x=0$ and approach $y=0$ from below as x approaches infinity. The solutions are symmetric about the y -axis because the explicit solution to the differential equation is $y = -1/(0.5x^2 + C)$ which when graphed out is always symmetric about the y -axis. Even if we solve for different particular solutions with varying initial conditions, the only thing changing in the solution curve equation is the value of C . This will never cause a shift in the horizontal direction, this causing the solutions to always be symmetric about the y -axis.

```
%}
```

Exercise 12

Objective: study the long-run behaviour of a differential equation from its direction field

Details: Using iode, plot the direction field of

$$dy/dx = y^4 - y^3 - 3y^2 + y + 2$$

By clicking on various initial conditions $y(0) = y_0$ (iode plots the solution), determine the long-run behaviour of solutions as a function of y_0 . In other words, list the constant solutions that are approached as x goes to infinity and how y_0 determines which constant solution is approached.

If your numerically computed solutions ever appear to cross then change the solution method from Euler to the, much better, Runge-Kutta method. Think about why solutions are not permitted to cross. If they do then this indicates a problem with the numerical solver.

```
%{
Description of solutions in direction field for  $dy/dx = y^4 - y^3 - 3y^2 + y + 2$ 
When  $y_0$  is less than -1, the solutions approach a constant solution of -1
as  $x$  approaches infinity. When  $y_0$  is between -1 and 1 or between 1 and 2, the solutions
approach a constant solution of 1 as  $x$  approaches infinity. Finally, when
 $y_0$  is greater than 3, the solutions approach infinity. The solutions are
not permitted to cross because of the uniqueness property of differential
equations.

For  $x$  approaches negative infinity:
When  $y_0$  is between 1 and 2, as  $x$  approaches infinity,  $y$  approaches a value
of 2. When  $y_0$  is between 1 and -1,  $y$  approaches a value of -1 as  $x$ 
approaches negative infinity. When  $y_0$  is greater than 2,  $y$  approaches 2
when  $x$  approaches negative infinity. Finally, when  $y_0$  is less than -1,  $y$ 
approaches negative infinity as  $x$  approaches negative infinity.
%}
```

Exercise 13 (NOT TO BE HANDED IN)

Objective: Solve a differential equation and plot the largest interval of existence for this solution.

Details: Find the particular implicit solution of the differential equation

$$dy/dx = -x/y, \quad y(0) = -2$$

Determine the largest interval of validity and plot the solution with 50 grid points in this interval.

In the comments before your code, explain why fzero has an error.

Your submission should show the particular solution, in implicit form, in the comments, the definition of the appropriate inline functions, arrays, loops, and the figure.

Label your axes.

Exercise 14 (NOT TO BE HANDED IN)

Objective: Solve a differential equation and plot the solution on the specified interval

Details: Find the particular implicit solution of the differential equation

$$du/dt = -(u^4 - 1), \quad u(0) = .1$$

and plot it for t from 0 to 1.

Determine a good starting guess that works throughout the interval and plot the solution with 50 grid points in this interval.

Your submission should show the particular solution, in implicit form, in the comments, the definition of the appropriate inline functions, arrays, loops, and the figure.

Label your axes.