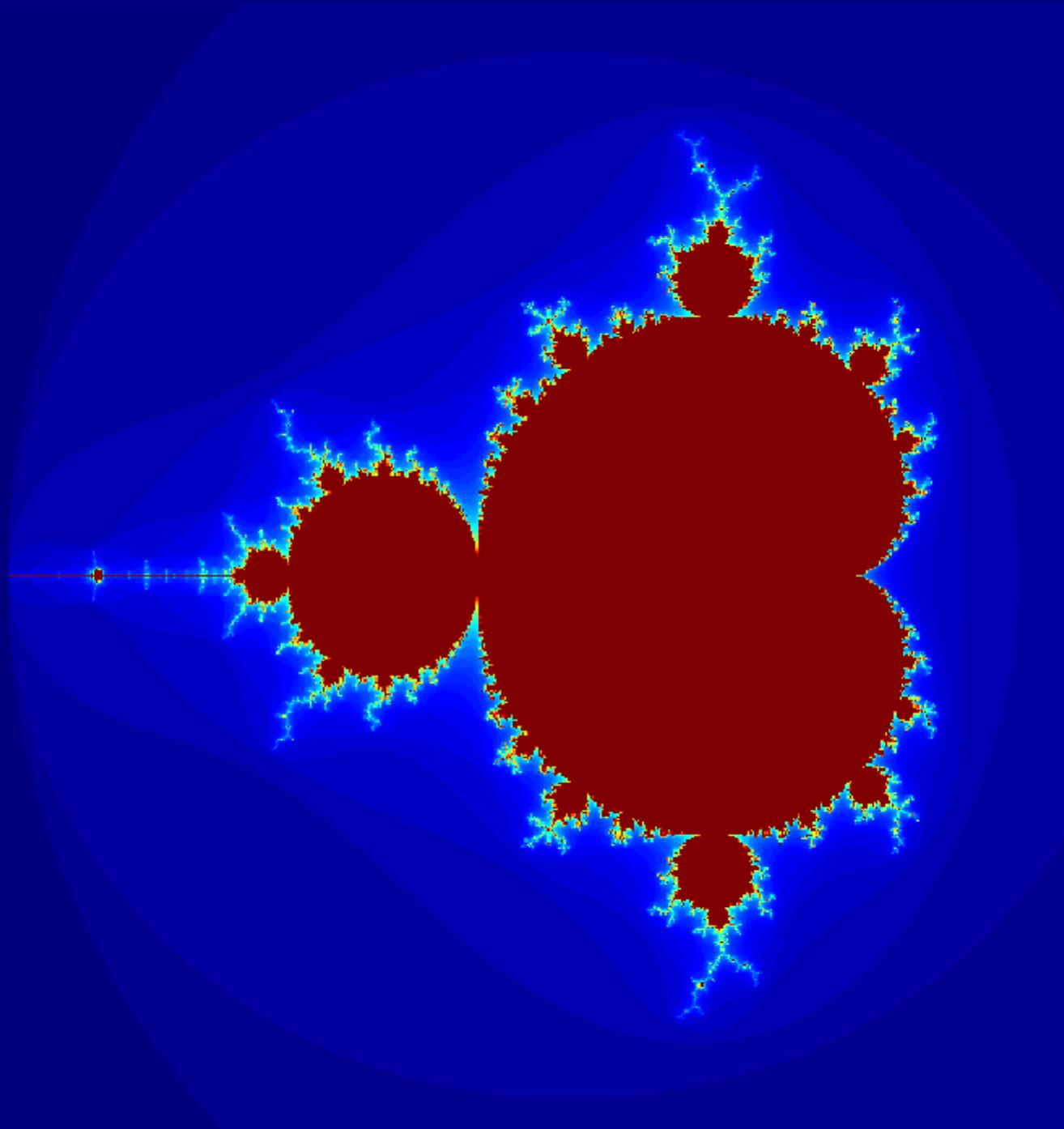


# Introduction to GNU Octave

## Second Edition



A brief tutorial for linear algebra and calculus students  
by Jason Lachniet



# Introduction to GNU Octave

A brief tutorial for linear algebra and calculus students

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SECOND EDITION



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<https://www.wcc.vccs.edu/sites/default/files/Introduction-to-GNU-Octave.pdf>.



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# Preface

These notes are not intended as a comprehensive manual. Instead, what follows is a tutorial that puts Octave to work solving a selection of applied problems in linear algebra and calculus. The goal is to learn enough of the basics to begin solving problems with minimum frustration. Note that minimum frustration does not mean no frustration. Be patient!

## Features of the text

To get the most out of this book, you should read it alongside an open Octave window where you can follow along with the computations (you will want paper and pencil, too, as well as your math books). Blocks of Octave commands are indented and printed with special formatting as follows.

```
>> % example Octave commands:  
>> x = [-3 : 0.1 : 3];  
>> plot(x, x.^2);  
>> title('Example plot')
```

Comments used to explain the code are preceded by a “%” sign and shown in green. Key words are highlighted in magenta. Strings (text variables) are highlighted in purple. The same formatting is used for commands that appear inline in the text. The Octave prompt is shown as “>>”.

Octave scripts (.m-files) are shown between horizontal rules and are labeled with a title, as in the following example. These are short programs in the Octave language.

---

### Octave Script 1: Example

---

```
1 % This is an example Octave script (.m-file)  
2 t = linspace(0, 2*pi, 50);  
3 x = cos(t);  
4 y = sin(t);  
5  
6 % plot the graph of a unit circle  
7 plot(x, y);  
8  
9 % Line numbers are for reference purposes only and are not part of the code
```

---

The color coding is not essential to understand the text. Thus the text can be printed in black and white to save on printing costs.

If you are reading the electronic PDF version, there are numerous hyperlinks throughout the text that link back to other parts of the text, or to external urls. There is a set of bookmarks to each chapter and section that can be used to easily navigate from section to section. Open the bookmark link in your PDF viewer to use this feature (not always visible in a web browser view; use a full PDF reader, like <https://get.adobe.com/reader/>).

Solutions to the many example problems are offset with a bar along the left side of the page, as shown here. A box signifies the end of the example. □

## MATLAB

The majority of the code shown in this book will work in MATLAB. This guide can therefore also be used an introduction to that software package. Refer to Appendix A for some notes on MATLAB compatibility.

## Scope and purpose

The overarching objective of this book is to enhance our understanding of calculus and linear algebra using Octave as a tool for computations. This is not a computer programming book, but we will learn the basics of programming in the Octave scripting language as we work through the mathematical concepts. This is also not a numerical analysis book, but we will deal with plenty of useful numerical algorithms. However, we'll mostly gloss over issues of accuracy and round-off error in machine arithmetic. For more details about numerical issues, refer to [1], which also contains many useful Octave examples.

To get started, read Chapter 1, without worrying too much about any of the mathematics you don't yet understand. After grasping the basics, you should be able to move into any of the chapters or sections that interest you.

Every chapter concludes with a set of problems, some of which are routine practice, and some of which are more involved. Chapter 6 contains a series of applied projects.

Most examples assume the reader is familiar with the mathematics involved. In a few cases, more detailed explanation of relevant theorems is given by way of motivation, but there are no proofs. Refer to the linear algebra and calculus books listed in the references for background on the underlying mathematics. In the spirit of openness, all references listed are available for free under GNU or Creative Commons licenses and can be accessed using the links provided.

## What's new

The second edition has been updated to reflect changes implemented in Octave through version 5.1, including the addition of a variable editor, migration of some statistical functions to the statistics package, and the addition of MATLAB-compatible ODE solvers to the Octave core.

New material has been added on implicit plots, complex variables, matrix transformations, and symbolic operations. There are several new exercises and a new chapter has been added containing a set of applied projects suitable for linear algebra and calculus students.



# Chapter 1

## Basic operation

### 1.1 Introduction

#### 1.1.1 What is GNU Octave?

GNU Octave is free software designed for scientific computing. It is intended primarily for solving numerical problems. In linear algebra, we will use Octave's capabilities to solve systems of linear equations and to work with matrices and vectors. Octave can also generate sophisticated plots. For example, we will use it in vector calculus to plot vector fields, space curves, and three dimensional surfaces. Octave is mostly compatible with the popular "industry standard" commercial software package MATLAB, so the skills you learn here can be applied to MATLAB programming as well. In fact, while this guide is written and intended as an introduction to Octave, it can serve equally well as a basic introduction to MATLAB.

What is *GNU*? A ‘gnu’ is a type of antelope, but ‘GNU’ is a free, UNIX-like computer operating system. GNU is a recursive acronym that stands for “GNU’s not Unix.” GNU Octave (and many other free programs) are licensed under the GNU General Public License: <http://www.gnu.org/licenses/gpl.html>.

From [www.gnu.org/software/octave](http://www.gnu.org/software/octave):

GNU Octave is a high-level interpreted language, primarily intended for numerical computations. It provides capabilities for the numerical solution of linear and non-linear problems, and for performing other numerical experiments. It also provides extensive graphics capabilities for data visualization and manipulation. Octave is normally used through its interactive command line interface, but it can also be used to write non-interactive programs. The Octave language is quite similar to MATLAB so that most programs are easily portable.

Octave is a fully functioning programming language, but it is not a general purpose programming language (like C++, Java, or Python). Octave is numerical, not symbolic; it is not a computer

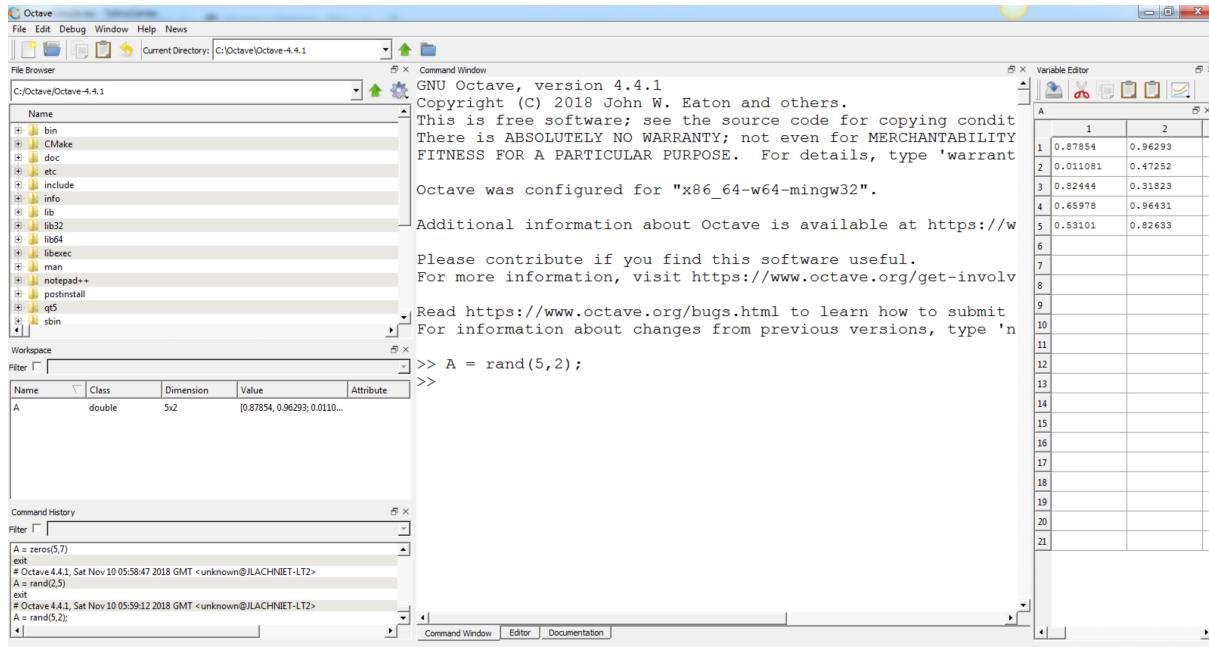


Figure 1.1: Windows Octave GUI

algebra system (like Maple, Mathematica, or Sage). However, Octave is ideally suited to all types of numeric calculations and simulations. Matrices are the basic variable type and the software is optimized for vectorized operations.

### 1.1.2 Installing Octave

It's free! Octave will work with Windows, Macs, or Linux. Go to <https://www.gnu.org/software/octave/download.html> and look for the download that matches your system. For example, Windows users can find an installer for the current Windows version at <https://ftp.gnu.org/gnu/octave/windows/>. Manual installation can be tricky, so look for the most recent .exe installer file and run that. Installation in most Linux systems is easy. For example, in Debian/Ubuntu, run the command `sudo apt-get install octave`. If you find Octave useful, consider making a donation to support the project at <https://www.gnu.org/software/octave/donate.html>.

Beginning with version 4.0, Octave uses a graphical user interface (GUI) by default. When you start Octave, you should see something like Figure 1.1.

The user can customize the arrangement of windows. By default, you will have a large command window, which is where commands are entered and run, a file browser, a workspace window displaying the variables in the current scope, a command history, and beginning with version 4.4, a variable editor.

### 1.1.3 Getting started

There are several good help resources on the web, and built-in help functions within Octave. The shell command `help` can be used at the Octave prompt. In particular, if you know the name of the command you want to use, `help NAME` will give the correct syntax.

Here are two good free, online resources:

- The Octave Manual [3]:  
<http://www.gnu.org/software/octave/octave.pdf>
- Wikibooks Tutorial:  
[https://en.wikibooks.org/wiki/Octave\\_Programming\\_Tutorial](https://en.wikibooks.org/wiki/Octave_Programming_Tutorial)

Additional help can be found with internet searches. Depending on what you are looking for, searches for Octave commands and searches for MATLAB commands can both be useful. Numerous commercial user's guides and textbooks for Octave and/or MATLAB are available. Linear algebra textbooks sometimes contain MATLAB code examples and these generally work in Octave as well.

The best way to get started is to try some simple problems. Use the following examples as a tutorial to learn your way around the program. Octave knows about basic arithmetic. Try something simple like:

```
>> 2*6 + (7 - 4)^2
ans = 21
```

Octave ignores white space, so `2*6` and `2 * 6` are interpreted the same way. You can't take shortcuts and leave out implied operations, though. For example, `2(5 - 1)` will give an error. Use `2*(5 - 1)`.

Vectors and matrices are basic variable types, so it is easier to learn Octave syntax if you already know a little linear algebra. Try this example to enter a row vector and name it `u`. You do not need to enter the comments (indicated by the % sign).

```
>> u = [1 -4 6]    % row vector
u =
              % variable name
1   -4   6           % output
```

The code `u = ...` assigns the result of the operation that follows to the variable `u`, which can then be recalled and used in further calculations.

To create a column vector instead, use semicolons:

```
>> u = [1; -4; 6]    % column vector
u =
              % variable name
1
-4
6           % output
```

Notice that the function of the semicolon is to begin a new row. The same basic syntax is used to enter matrices. For example, let's see how to enter a matrix:

```
>> A = [1 2 -3; 2 4 0; 1 1 1] % matrix
A =
1 2 -3
2 4 0
1 1 1 % output
```

## 1.2 Navigating the GUI

### 1.2.1 Command history

In Octave, you can save variables that you defined in your session, but this does not save the commands you used, or a whole worksheet. Octave does have a command history that persists between sessions, so past commands can be brought up using the up arrow key, or using the command history list in the GUI.

If you want to save a series of commands that can be reopened, edited, and run again, you can create an Octave script, also known as an .m-file. This will be described in more detail in Chapter 3.

### 1.2.2 File browser

Within the Octave graphical user interface, you should see your current directory listed near the top left. You can click the folder button to navigate to a different directory, such as the desktop, a flash drive, or a folder dedicated to Octave projects. The default start-up directory (and many other options) can be modified in the Octave start-up file `.octaverc`, or the MATLAB-compatible equivalent `startup.m`.

### 1.2.3 Workspace

Under the file menu, the option “save workspace as” will save all of your current variables in a file of your choosing. You can see a list of the variables currently defined listed in the workspace on the left side of the screen. You can use the “load workspace” option under the file menu to load previously saved variables.

Another approach is to use the manual `save` and `load` commands at the command line. If you type `save FILENAME var1 var2 ...`, Octave will save the specified variables in the file `FILENAME`. If you do not supply a list of variables, then all variables in the current scope will be saved. You can then reload the saved variable(s) at another time by navigating to the appropriate directory and using `load FILENAME`. You can also load a variable or workspace by double-clicking on its name in the file browser.

### 1.2.4 The variable editor

The variable editor allows displaying or editing a variable in a simple spreadsheet format. To use it, double click on the name of the variable in the workspace panel. You can undock the variable editor and maximize it as a standalone window to facilitate working with larger arrays. If you want to enter data in a variable that does not already exist, you will need to preallocate a matrix of the correct size, for example using the command `A = zeros(m, n)` to create an  $m \times n$  matrix of zeros. You can then open this in the variable editor and enter the data.

## 1.3 Matrices and vectors

Matrices are the basic variable type in Octave. In fact, a scalar is treated as a  $1 \times 1$  matrix. Similarly, a row vector is a  $1 \times n$  matrix and a column vector is an  $m \times 1$  matrix.

### 1.3.1 Vector operations

We'll start with some simple examples. First, enter the column vector **u** from above, if it is not already in memory.

```
>> u = [1; -4; 6]
u =
    1
   -4
    6
```

Now enter another column vector **v** and try the following vector operations which illustrate linear combinations, dot product, cross product, and norm.

```
>> v = [2; 1; -1]
v =
    2
    1
   -1

>> 2*v + 3*u
ans =
    7
   -10
    16

>> dot(u, v)          % dot product
ans = -8

>> cross(u, v)        % cross product
ans =
```

```

-2
13
 9

>> norm(u)           % length of vector u
ans = 7.2801

```

Try a few more operations:

- Find `cross(v, u)`. How does that compare to  $\mathbf{u} \times \mathbf{v}$ ?
- Calculate the length of  $\mathbf{v}$ ,  $\|\mathbf{v}\|$ , using `norm(v)`.
- Normalize  $\mathbf{v}$  by calculating  $\mathbf{v}/\|\mathbf{v}\|$ . This gives a unit vector that points in the same direction as  $\mathbf{v}$ .

Now let's try a more complicated vector geometry problem, to see some of Octave's potential.

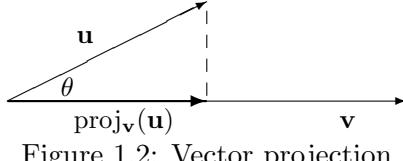


Figure 1.2: Vector projection

The *projection of  $\mathbf{u}$  onto  $\mathbf{v}$* , denoted  $\text{proj}_{\mathbf{v}}(\mathbf{u})$ , is the component of  $\mathbf{u}$  that points in the direction of  $\mathbf{v}$ . This can be thought of as the shadow  $\mathbf{u}$  casts onto  $\mathbf{v}$  from a direction orthogonal to  $\mathbf{v}$ , as shown in the figure. To find the magnitude of the projection, use basic right-triangle trigonometry:

$$\|\text{proj}_{\mathbf{v}}(\mathbf{u})\| = \|\mathbf{u}\| \cos(\theta)$$

Then, since  $\mathbf{u} \cdot \mathbf{v} = \|\mathbf{u}\| \|\mathbf{v}\| \cos(\theta)$ ,

$$\begin{aligned} \|\text{proj}_{\mathbf{v}}(\mathbf{u})\| &= \|\mathbf{u}\| \cos(\theta) \\ &= \|\mathbf{u}\| \frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{u}\| \|\mathbf{v}\|} \\ &= \frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|} \end{aligned}$$

This is known as the *scalar projection* of  $\mathbf{u}$  onto  $\mathbf{v}$ . The *vector projection* onto  $\mathbf{v}$  is obtained by multiplying the scalar projection by a unit vector that points in the direction of  $\mathbf{v}$ . Thus,

$$\begin{aligned} \text{proj}_{\mathbf{v}}(\mathbf{u}) &= \frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|} \frac{\mathbf{v}}{\|\mathbf{v}\|} \\ &= \frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|^2} (\mathbf{v}) \end{aligned}$$

Since  $\mathbf{v} \cdot \mathbf{v} = \|\mathbf{v}\|^2$ , this can also be written as:

$$\text{proj}_{\mathbf{v}}(\mathbf{u}) = \frac{\mathbf{u} \cdot \mathbf{v}}{\mathbf{v} \cdot \mathbf{v}} (\mathbf{v})$$

**Example 1.3.1.** Find the projection of  $\langle 3, 5 \rangle$  onto  $\langle 7, 2 \rangle$ .

**Solution.** The operations needed for vector projection are easily carried out in Octave.

```
>> u = [3 5]
u =
3 5

>> v = [7 2]
v =
7 2

>> proj = dot(u,v)/(norm(v))^2*v
proj =
4.0943 1.1698
```

Thus  $\text{proj}_v(u) = \langle 4.0943, 1.1698 \rangle$ . □

### 1.3.2 Matrix operations

Matrix operations are carried out very easily. We'll start with matrix multiplication.

**Example 1.3.2.** Let  $A = \begin{bmatrix} 1 & 2 & -3 \\ 2 & 4 & 0 \\ 1 & 1 & 1 \end{bmatrix}$  and  $B = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 0 & -2 & -4 & 6 \\ 1 & -1 & 0 & 0 \end{bmatrix}$ . Find  $AB$ .

**Solution.**

```
>> A = [1 2 -3; 2 4 0; 1 1 1]    % matrix
A =
1 2 -3
2 4 0
1 1 1

% output

>> B = [1 2 3 4; 0 -2 -4 6; 1 -1 0 0]
B =
1 2 3 4
0 -2 -4 6
1 -1 0 0

% multiply A and B
>> ans =                                % result stored as 'ans'
                                         % answer
                                         % ans =
                                         % -2 1 -5 16
                                         % 2 -4 -10 32
                                         % 2 -1 -1 10
```

Notice that the result is stored in the temporary variable `ans`. □

Arithmetic operations in Octave are always assumed to be matrix operations. Therefore, for  $A$  and  $B$  defined as above, we can compute things like  $4A$  or  $AB$  by entering  $4*A$  or  $A*B$ , but operations like  $B*A$  or  $A+B$  give errors (why?).

To get the transpose of a matrix, use the single quote<sup>1</sup>. For example, try calculating  $B^T A$ .

```
>> B' *A           % B' is the transpose of B
ans =
2      3      -2
-3     -5      -7
-5    -10      -9
16     32     -12
```

To perform basic matrix arithmetic, we also need the identity matrix. This is easy to do in Octave with the `eye(n)` command, where  $n$  is the dimension of the matrix. Let's find  $2A - 4I$ .

```
>> 2*A - 4*eye(3)        % eye(3) is a 3x3 identity matrix
ans =
-2      4      -6
 4      4       0
 2      2      -2
```

Octave can also find determinants, inverses, and eigenvalues. For example, try these commands.

```
>> det(A)                  % determinant
ans = 6

>> inv(A)                  % matrix inverse
ans =
0.66667  -0.83333  2.00000
0.33333   0.66667 -1.00000
0.33333   0.16667  0.00000

>> eig(A)                  % eigenvalues
ans =
4.52510 + 0.00000i
0.73745 + 0.88437i
0.73745 - 0.88437i
```

Notice that our matrix has one real and two complex eigenvalues. Octave handles complex numbers, of course! Eigenvalues will be discussed in more detail in Chapter 4. Octave can also compute many other matrix values, such as rank:

```
>> rank(A)      % matrix rank
ans = 3
```

---

<sup>1</sup>Technically this gives the *conjugate transpose*, but for a matrix with real entries, there is no difference between the conjugate transpose and the ordinary transpose.

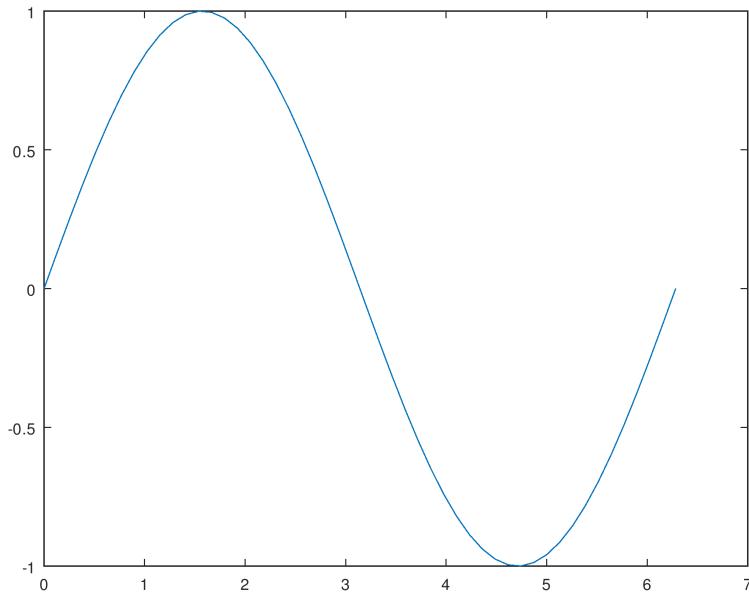


Figure 1.3: Default graph of  $y = \sin(x)$  on  $[0, 2\pi]$

## 1.4 Plotting

Basic two-dimensional plotting of functions in Octave is accomplished by creating a vector for the independent variable and a second vector for the range of the function. There are several forms for the syntax and we will attempt to outline the simplest methods here<sup>2</sup>.

Let's start by plotting the graph of the function  $\sin(x)$  on the interval  $[0, 2\pi]$  (Figure 1.3). Like a typical graphing calculator, Octave will simply plot a series of points and connect the dots to represent the curve. The process is less automated in Octave (but in the end, much more powerful). We begin by creating a vector of  $x$ -values.

```
>> x = linspace(0, 2*pi, 50);
```

Notice the format `linspace(start_val, end_val, n)`. This creates a row vector of 50 evenly spaced values beginning at 0 and going up to  $2\pi$ . The smaller the increment, the smoother the curve will look. In this case, 50 points should be suitable. The semicolon at the end of the line is to suppress the output to the screen, since we don't need to see all the values in the vector. Now, we want to create a vector of the corresponding  $y$ -values. Use this command:

```
>> y = sin(x);
```

Now, to plot the function, use the `plot` command:

```
>> plot(x, y);
```

---

<sup>2</sup>See also <http://www.gnu.org/software/octave/doc/interpreter/Plotting.html> and [http://en.wikibooks.org/wiki/Octave\\_Programming\\_Tutorial/Plotting](http://en.wikibooks.org/wiki/Octave_Programming_Tutorial/Plotting)

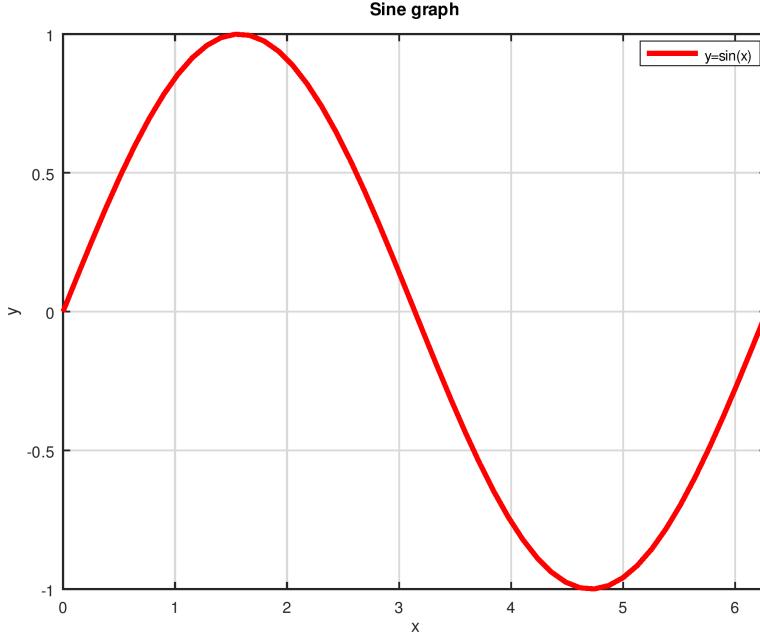


Figure 1.4: Improved graph of  $y = \sin(x)$  on  $[0, 2\pi]$

You should see the graph of  $f(x) = \sin(x)$  pop up in a new window.

Figure 1.3 shows the default graph. You may wish to customize it a little bit. For example, the  $x$ -axis extends too far. We can set the window with the `axis` command. The window is controlled by a vector of the form `[Xmin Xmax Ymin Ymax]`. Let's set the axes to match the domain and range of the function.

```
>> axis ([0 2*pi -1 1]);
```

We may want to change the color (to, say, red) or make the line thicker. We can add a grid to help guide our eye. In addition, a graph should usually be labeled with a title, axis labels, and legend. Try these options to get the improved graph shown in Figure 1.4.

```
>> plot (x, y, 'r', 'linewidth', 3)
>> grid on
>> xlabel ('x');
>> ylabel ('y');
>> title ('Sine graph');
>> legend ('y=sin(x)');
```

Note that some adjustments, like zooming in, or turning on the grid, can be done within the graph window using the controls provided. Some standard color options are red, green, blue, cyan, and magenta, which can be specified with their first letter in single quotes.

Now, let's try plotting points. The procedure is the same, but we use an option to specify the marker we want. Some marker options are `o`, `+`, or `*`. We will plot the set of points  $\{(1, 1), (2, 2), (3, 5), (4, 4)\}$  using circles as our marker. First, clear the variables from the workspace

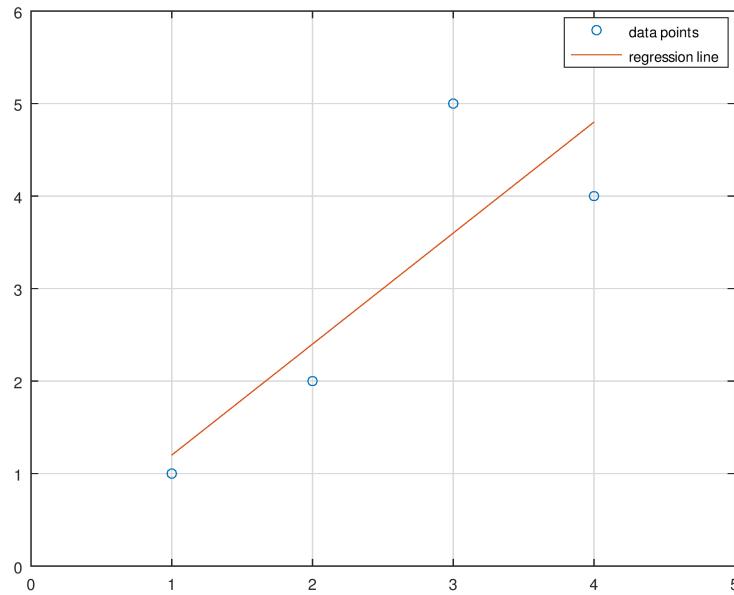


Figure 1.5: Scatter plot with regression line

and clear any existing graphs. Then define a vector of  $x$ -values and a vector of  $y$ -values and use the `plot` command.

```
>> clear; clf;
>> x = [1 2 3 4]
>> y = [1 2 5 4]
>> plot(x, y, 'o')
```

Now suppose we want to graph the line  $y = 1.2x$  on the same set of axes (this is the line of best fit for this data). To add to our current graph we need to use the command `hold on`. Then any new plots will be drawn onto the current axes. We can switch back later with `hold off`.

```
>> hold on
>> plot(x, 1.2*x)
```

Now we should see four points and the graph of the line. Alternately, we can create multiple plots within a single plot command. Try this, for example:

```
>> clear; clf;
>> x = [1 2 3 4];
>> y1 = [1 2 5 4];
>> y2 = 1.2*x;
>> plot(x, y1, 'o', x, y2)
>> axis([0 5 0 6]);
>> grid on;
>> legend('data points', 'regression line');
```

Notice that sets of input and output variables come in pairs, followed by any options that apply to that pair. The result is shown in Figure 1.5.

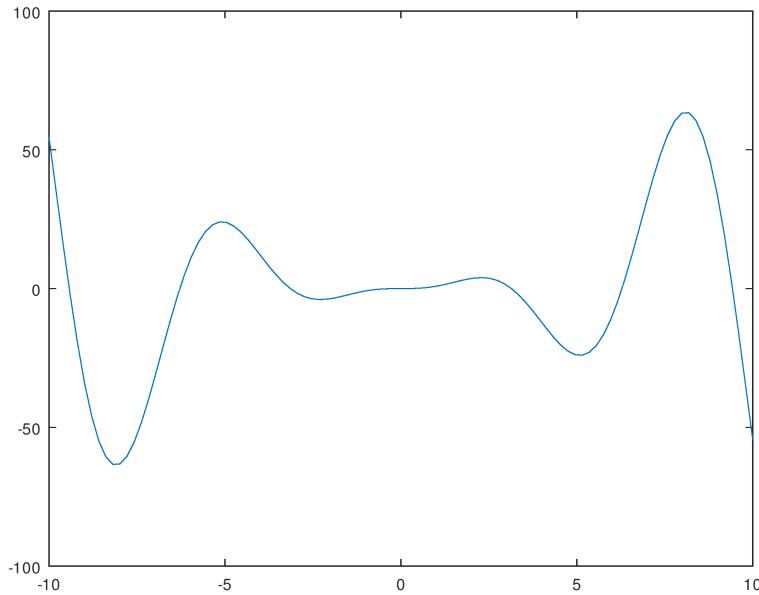


Figure 1.6: Graph of  $y = x^2 \sin(x)$

It would be good practice for you to try graphing some other functions. One thing to remember is that we are defining the independent variable  $x$  as a vector, so when we multiply, Octave will regard multiplication as matrix multiplication, unless we indicate otherwise. Likewise, division and exponentiation are interpreted as matrix operations. To graph a function such as  $y = x^2 \sin(x)$ , we need to use *elementwise* exponentiation and multiplication. This is done by preceding the operation with a period (as in,  $.^$  or  $.*$  or  $./$ ). For example, these commands will give an error:

```
>> x = linspace(-10, 10, 100);
>> plot(x, x^2*sin(x))
error: for A^b, A must be a square matrix. Use .^ for elementwise power.
error: evaluating argument list element number 2
```

But this will do the trick:

```
>> x = linspace(-10, 10, 100);
>> plot(x, x.^2.*sin(x))
```

The result is shown in Figure 1.6.

The point is that we are not calculating the matrix power  $x^2$ , instead we simply want to square each element of our input vector. Likewise when we multiply that result by  $\sin(x)$ , we want to multiply each squared  $x$ -value by its sine; we are not doing matrix multiplication.

So, for graphing functions, remember to use elementwise multiplication, division, and exponentiation! This is the source of many errors and frustration for beginning Octave users.

### 1.4.1 Plot options

The following table summarizes some standard plot options.

PLOT OPTIONS

			COLOR	
MARKER	'+'	crosshair	'k'	black
	'o'	circle	'r'	red
	'*'	star	'g'	green
	'.'	point	'b'	blue
	's'	square	'm'	magenta
	'^'	triangle	'c'	cyan
SIZE	'linewidth', n	(where n is a positive value)		
	'markersize', n	(where n is a positive value)		
LINE STYLE	'—'	solid line (default)		
	'--'	dashed line		
	':'	dotted line		

Several options may be combined. For example, `plot(x, y, 'ro:')` indicates red color with circle markers joined by dotted lines.

### 1.4.2 Saving plots

If we have created a good plot, we probably want to save it. The easiest option is to use copy and paste from the plot window. You can also use the “save as” option under the file menu to save the plot in various image formats.

An alternate method is to save the plot directly by “printing” it to a file. Octave supports several image formats. In the example below, the PNG format is used. To save the current graph as a PNG, use this syntax:

```
>> print filename.png -dpng
```

Here `filename.png` is whatever file name you want (include the extension). You can replace “png” with other image formats, such as “jpg” or “eps.” The file will be saved in your current working directory.

## Chapter 1 Exercises

Begin each problem with no variables stored. You can clear any previous results with the command `clear`.

1. For practice saving and loading variables, try the following.
  - (a) Create a new directory called “octave\_projects”.
  - (b) Change to the octave\_projects directory.
  - (c) Save the example matrices  $A$  and  $B$  from above in a text file named “matrices.mat”.
  - (d) Quit Octave.
  - (e) Restart Octave and reload the saved matrices.
2. Let  $\mathbf{u} = \langle 2, -4, 0 \rangle$  and  $\mathbf{v} = \langle 3, 1.5, -7 \rangle$ . Find each of the following.
  - (a)  $\mathbf{w} = 2\mathbf{u} + 5\mathbf{v}$
  - (b)  $d = \mathbf{u} \cdot \mathbf{v}$
  - (c)  $l = \|\mathbf{u}\|$
  - (d) Find a unit vector  $\mathbf{u}_1$  that points in the direction of  $\mathbf{u}$ .
  - (e) Find a vector  $\mathbf{n}$  orthogonal to both  $\mathbf{u}$  and  $\mathbf{v}$ .
  - (f) Find  $\text{proj}_{\mathbf{v}}(\mathbf{u})$ .

Be sure to use the variable names indicated to store your answers. Save your workspace including all of the required variables. What does the dot product reveal about  $\mathbf{u}$  and  $\mathbf{v}$ ? How did you produce a vector mutually orthogonal to  $\mathbf{u}$  and  $\mathbf{v}$ ?

3. Begin this problem with no variables stored. Enter the following matrices.

$$A = \begin{bmatrix} 1 & -3 & 5 \\ 2 & -4 & 3 \\ 0 & 1 & -1 \end{bmatrix}, B = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -3 & 0 & 7 & -6 \\ 2 & 1 & -2 & -1 \end{bmatrix}, \text{ and } I_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Use Octave to compute each of the following, if possible, or explain why the operation is undefined.

- (a)  $d = \det(A)$
- (b)  $C = 2A + 4I$
- (c)  $D = A^{-1}$
- (d)  $E = B^{-1}$
- (e)  $F = BA$
- (f)  $G = (AB)^T$
- (g)  $H = B^T A^T$

Use the variable names indicated to store your answers. Save your workspace including all of the required variables. Which of the operations were undefined and why? Did you notice anything about  $(AB)^T$  and  $B^T A^T$ ? If so, explain the relationship between these quantities.

4. Modify the plot of  $y = x^2 \sin(x)$  given in Figure 1.6 as follows:
- (a) Make the graph of  $y = x^2 \sin(x)$  a thick red line.
  - (b) Graph  $y = x^2$  and  $y = -x^2$  on the same axes, as thin black dotted lines.
  - (c) Use a legend to identify each curve.
  - (d) Add a title.
  - (e) Add a grid.
  - (f) Save the plot as a PNG or JPG image file.



# Chapter 2

## Matrices and linear systems

Octave is a powerful tool for many problems in linear algebra. We have already seen some of the basics in Section 1.3. In this chapter, we will consider systems of linear equations, polynomial curve fitting, and matrix transformations.

### 2.1 Linear systems

#### 2.1.1 Gaussian elimination

Octave has sophisticated algorithms built in for solving systems of linear equations, but it is useful to start with the more basic process of Gaussian elimination. Using Octave for Gaussian elimination lets us practice the procedure, without the inevitable arithmetic errors that come when doing elimination by hand. It also teaches useful Octave syntax and methods for manipulating matrices.

Row operations are easy to carry out. But first, we need to see how matrices and vectors are indexed in Octave. Consider the following augmented matrix.

```
>> B = [1 2 3 4; 0 -2 -4 6; 1 -1 0 0]
B =
1   2   3   4
0  -2  -4   6
1  -1   0   0
```

If we enter  $B(2, 3)$ , then the result given is  $-4$ . This is the scalar stored in row 2, column 3. We can also pull out an entire row vector or column vector using the colon operator. A colon can be used to specify a limited range, or if no starting or ending value is specified, it gives the full range. For example,  $B(1, :)$  will give every entry out of the first row.

```
>> B(1, :)
ans =
```

1	2	3	4
---	---	---	---

Now, let's use this notation to carry out basic row operations on  $B$  to reach row-echelon form.

**Example 2.1.1.** Let

$$B = \left[ \begin{array}{ccc|c} 1 & 2 & 3 & 4 \\ 0 & -2 & -4 & 6 \\ 1 & -1 & 0 & 0 \end{array} \right]$$

Use row operations to put  $B$  into row-echelon form, then solve by backward substitution. Compare to the row-reduced echelon form computed by Octave.

**Solution.** The first operation is to replace row 3 with  $-1$  times row 1, added to row 3.

```
>> B(3, :) = (-1)*B(1, :) + B(3, :)  
ans =
```

$$\begin{matrix} 1 & 2 & 3 & 4 \\ 0 & -2 & -4 & 6 \\ 0 & -3 & -3 & -4 \end{matrix}$$

Next, we will replace row 3 with  $-1.5$  times row 2, added to row 3.

```
>> B(3, :) = -1.5*B(2, :) + B(3, :)  
ans =
```

$$\begin{matrix} 1 & 2 & 3 & 4 \\ 0 & -2 & -4 & 6 \\ 0 & 0 & 3 & -13 \end{matrix}$$

The matrix is now in row echelon form. We could continue using row operations to reach row-reduced echelon form, but it is more efficient to simply write out the corresponding linear system on paper and solve by backward substitution. Do it! The solution vector is  $\langle \frac{17}{3}, \frac{17}{3}, -\frac{13}{3} \rangle$ . Of course, Octave also has a built-in command to find the row-reduced echelon form of the matrix directly. Try `rref(B)` to see the result.

```
>> rref(B)  
ans =  
  
1.00000 0.00000 0.00000 5.66667  
0.00000 1.00000 0.00000 5.66667  
0.00000 0.00000 1.00000 -4.33333
```

From here, the solution to the system is evident. Notice that everything is now expressed as floating point numbers (i.e., decimals). Five decimal places are displayed by default. The variables are actually stored with higher precision and it is possible to display more decimal places, if desired (type `format(long)`).  $\square$

### 2.1.2 Left division

The built-in operation for solving linear systems of the form  $A\mathbf{x} = \mathbf{b}$  in Octave is called *left division* and is entered as  $A\backslash b$ . This is conceptually equivalent to the product  $A^{-1}\mathbf{b}$ . For example, let's go back to the matrix  $B$  given previously, which represents an augmented matrix.

**Example 2.1.2.** Use left division to solve the system of equations with augmented matrix  $B$ .

$$B = \left[ \begin{array}{ccc|c} 1 & 2 & 3 & 4 \\ 0 & -2 & -4 & 6 \\ 1 & -1 & 0 & 0 \end{array} \right]$$

**Solution.** To use left division, we need to extract the coefficient matrix and vector of right-side constants. Let's call the coefficient matrix  $A$  and the right-side constants  $\mathbf{b}$ . (You have probably already noticed that Octave is case-sensitive.)

```
>> B = [1 2 3 4; 0 -2 -4 6; 1 -1 0 0]
B =
1 2 3 4
0 -2 -4 6
1 -1 0 0

>> A = B(:, 1:3) % extract coefficient matrix
A =
1 2 3
0 -2 -4
1 -1 0

>> b = B(:, 4)    % extract right side constants
b =
4
6
0

>> A\b           % solve system Ax = b
ans =
5.6667
5.6667
-4.3333
```

The solution vector matches what we found by Gaussian elimination.  $\square$

### 2.1.3 LU decomposition

*LU* decomposition is a matrix factorization that encodes the results of the Gaussian elimination algorithm. The goal is to write

$$A = LU$$

where  $L$  is a unit lower triangular matrix and  $U$  is an upper triangular matrix. We will see that this factored form can be used to easily solve  $A\mathbf{x} = \mathbf{b}$ .

The process is best explained with an example. We will not attempt to justify why the algorithm works; refer to [6] for the underlying theory.

**Example 2.1.3.** Find an  $LU$  decomposition for

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 1 & -1 & 0 \end{bmatrix}$$

**Solution.** This is the same coefficient matrix we row-reduced in Example 2.1.1. We proceed the same way, carefully noting the multiplier used to obtain each 0. The lower triangular  $L$  starts as an identity matrix, then the negative of each multiplier used in the elimination process is placed into the corresponding entry of  $L$ .

The first zero in position  $(2, 1)$  is already there, so we put 0 for that multiplier in the corresponding position of  $L$ . Then we replace row 3 with  $-1$  times row 1 plus row 3. The negative of this multiplier is  $-(-1) = 1$ , which is entered in  $L$  at the point where the 0 was obtained.

At this point, we have two entries for  $L$  along with a partly reduced  $A$ :

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 1 & -1 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & -3 & -3 \end{bmatrix}; L = \begin{bmatrix} 1 & 0 & 0 \\ \textcolor{red}{0} & 1 & 0 \\ \textcolor{red}{1} & 0 & 1 \end{bmatrix}$$

The next step is to replace row 3 using  $-1.5$  times row 2. Thus we put  $-(-1.5) = 1.5$  in the corresponding position of  $L$ . Once  $A$  has reached row echelon form, we have the desired upper triangular matrix  $U$ .

$$\begin{aligned} A &= \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 1 & -1 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & -3 & -3 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & 0 & 3 \end{bmatrix} = U \\ L &= \begin{bmatrix} 1 & 0 & 0 \\ \textcolor{red}{0} & 1 & 0 \\ \textcolor{red}{1} & \textcolor{red}{1.5} & 1 \end{bmatrix}, U = \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & 0 & 3 \end{bmatrix} \end{aligned}$$

So, to review,  $U$  is the row-echelon form of  $A$  and  $L$  is an identity matrix with the negatives of the Gaussian elimination multipliers placed into the corresponding positions where they were used to obtain zeros.

Let's check to see if it worked.

```
>> L = [1 0 0; 0 1 0; 1 1.5 1]
L =
```

1.00000	0.00000	0.00000
0.00000	1.00000	0.00000
1.00000	1.50000	1.00000

```
>> U = [1 2 3; 0 -2 -4; 0 0 3]
U =
```

$$\begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & 0 & 3 \end{bmatrix}$$

```
>> L*U
ans =
```

$$\begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 1 & -1 & 0 \end{bmatrix}$$

It worked! In fact, the procedure outlined in this example will work anytime Gaussian elimination can be performed *without row interchanges*.  $\square$

Now, let's see how the  $LU$  form can be used to solve linear systems  $A\mathbf{x} = \mathbf{b}$ . If  $A = LU$ , then the system  $A\mathbf{x} = \mathbf{b}$  can be written as  $LUX = \mathbf{b}$ . Let  $U\mathbf{x} = \mathbf{y}$ . Then we can proceed in two steps:

1. Solve  $L\mathbf{y} = \mathbf{b}$ .
2. Solve  $U\mathbf{x} = \mathbf{y}$ .

Since we are dealing with triangular matrices, each step is easy.

**Example 2.1.4.** Solve  $A\mathbf{x} = \mathbf{b}$ , where  $A = \begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 1 & -1 & 0 \end{bmatrix}$  and  $\mathbf{b} = \begin{bmatrix} 4 \\ 6 \\ 0 \end{bmatrix}$ , using  $LU$  decomposition.

**Solution.** We already have the  $LU$  decomposition. Since  $L = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1.5 & 1 \end{bmatrix}$ , the first step

is to solve:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1.5 & 1 \end{bmatrix} \cdot \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} 4 \\ 6 \\ 0 \end{bmatrix}$$

The corresponding system of equations is

$$\begin{aligned} y_1 &= 4 \\ y_2 &= 6 \\ y_1 + 1.5y_2 + y_3 &= 0 \end{aligned}$$

Starting with the first row and working down, this system is easily solved by *forward substitution*. We can see that  $y_1 = 4$  and  $y_2 = 6$ . Substituting these values into the third equation

and solving for  $y_3$  gives  $y_3 = -13$ . Thus the intermediate solution for  $\mathbf{y}$  is  $\begin{bmatrix} 4 \\ 6 \\ -13 \end{bmatrix}$ .

Step two is to solve  $U\mathbf{x} = \mathbf{y}$ , which looks like:

$$\begin{bmatrix} 1 & 2 & 3 \\ 0 & -2 & -4 \\ 0 & 0 & 3 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 4 \\ 6 \\ -13 \end{bmatrix}$$

This is easily solved by backward substitution to get  $\mathbf{x} = \begin{bmatrix} 17/3 \\ 17/3 \\ -13/3 \end{bmatrix}$ .  $\square$

If row interchanges are used, then  $A$  is multiplied by a *permutation matrix* and the decomposition takes the form  $PA = LU$ . This is the default form of the *LU* decomposition given by Octave using the command `[L U P] = lu(A)`.

**Example 2.1.5.** Find an *LU* decomposition (with permutation) for

$$A = \begin{bmatrix} -7 & -2 & 9 & 4 \\ -4 & -9 & 3 & 0 \\ -3 & 4 & 6 & -2 \\ 6 & 7 & -4 & -8 \end{bmatrix}$$

**Solution.** We will use Octave for this.

```
>> A = [-7 -2 9 4; -4 -9 3 0; -3 4 6 -2; 6 7 -4 -8]
A =
-7   -2    9    4
-4   -9    3    0
-3    4    6   -2
 6    7   -4   -8
```

```
>> [L U P] = lu(A)
L =
1.00000  0.00000  0.00000  0.00000
0.57143  1.00000  0.00000  0.00000
-0.85714 -0.67273  1.00000  0.00000
 0.42857 -0.61818  0.36000  1.00000
```

```
U =
-7.00000  -2.00000  9.00000  4.00000
 0.00000  -7.85714 -2.14286 -2.28571
 0.00000   0.00000  2.27273 -6.10909
 0.00000   0.00000  0.00000 -2.92800
```

P =

Permutation Matrix

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$\begin{array}{cccc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{array}$$

□

Refer to Exercise 4 to see how  $PA = LU$  can be used to solve a linear system, using a method almost identical to what we did in Example 2.1.4.

*LU* decomposition is widely used in numerical linear algebra. In fact, it is the basis of how Octave's left division operation works. It is especially efficient to use *LU* decomposition when one is solving several systems of equations that all have the same coefficient matrix, but different right side constants. The *LU* decomposition only needs to be done once for all of the systems with that coefficient matrix.

## 2.2 Polynomial curve fitting

In statistics, the problem of fitting a straight line to a set of data is often considered. We tackle the more general problem of fitting a polynomial to a set of points.

**Example 2.2.1.** Set-up and solve the normal equations to find the least-squares parabola for the set of points in the following  $6 \times 2$  data matrix  $D$ .

$$D = \begin{bmatrix} 1 & 1 \\ 2 & 2 \\ 3 & 5 \\ 4 & 4 \\ 5 & 2 \\ 6 & -3 \end{bmatrix}$$

The matrix shows  $x$ -values in column 1 and  $y$ -values in column 2.

**Solution.** Enter the data matrix in Octave and extract the  $x$ - and  $y$ -data to column vectors. Then plot the points to get a sense of what the data look like.

```
>> D = [1 1; 2 2; 3 5; 4 4; 5 2; 6 -3]
>> xdata = D(:, 1)
>> ydata = D(:, 2)
>> plot(xdata, ydata, 'o-') % plot line segments with circle markers
```

In this case, we are constructing a model of the form  $y = ax^2 + bx + c$ , but it is easy to see how our approach generalizes to polynomials of any degree (including linear functions). By plugging in the given data to the proposed equation, we obtain the following system of linear equations.

$$\begin{bmatrix} 1 & 1 & 1 \\ 4 & 2 & 1 \\ 9 & 3 & 1 \\ 16 & 4 & 1 \\ 25 & 5 & 1 \\ 36 & 6 & 1 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ 5 \\ 4 \\ 2 \\ -3 \end{bmatrix}$$

Notice the form of the coefficient matrix, which we'll call  $A$ . The third column is all ones, the second column is the  $x$ -values, and the first column is the square of the  $x$ -values (this column would not appear if we were using a linear model). The right-side constants are the  $y$ -values. There are several ways to construct the coefficient matrix in Octave. One approach is to use the `ones` command to create a matrix of ones of the appropriate size, and then overwrite the first and second columns with the correct data.

```
>> A = ones(6, 3);
>> A(:, 1) = xdata.^2;
>> A(:, 2) = xdata
A =
1   1   1
4   2   1
9   3   1
16  4   1
25  5   1
36  6   1
```

Note the use of elementwise exponentiation to square each value of the vector `xdata`. Our system is inconsistent. It can be shown that the least-squares solution comes from solving the *normal equations*,  $A^T A \mathbf{b} = A^T \mathbf{y}$ , where  $\mathbf{b}$  is the vector  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$  of polynomial coefficients.

We can use Octave to construct the normal equations.

```
>> A'*A
ans =
2275   441   91
  441    91   21
   91    21    6

>> A'*ydata
ans =
  60
  28
  11
```

The corresponding augmented matrix is:

$$\left[ \begin{array}{ccc|c} 2275 & 441 & 91 & 60 \\ 441 & 91 & 21 & 28 \\ 91 & 21 & 6 & 11 \end{array} \right]$$

We can then solve the problem using Gaussian elimination. Here is one way to create the augmented matrix and row-reduce it:

```
>> B = A'*A;
>> B(:, 4) = A'*ydata;
```

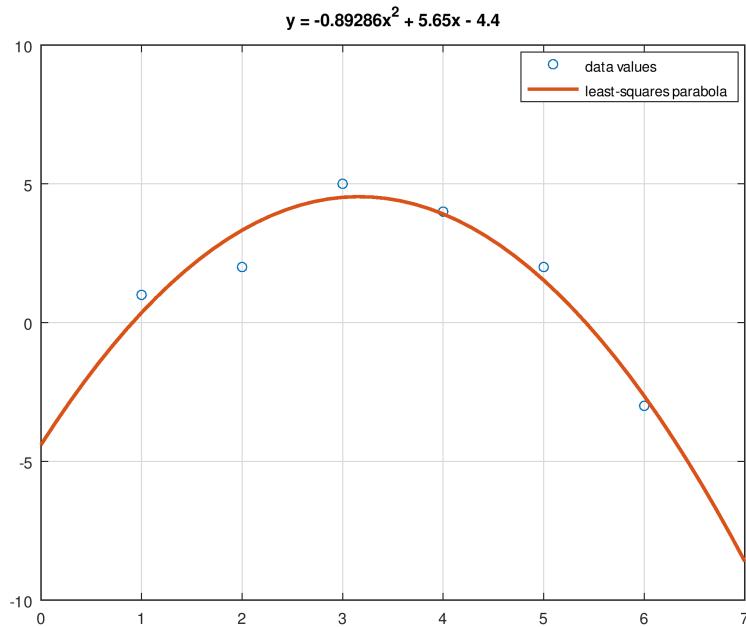


Figure 2.1: Least-squares parabola

```
>> rref(B)
ans =
1.00000 0.00000 0.00000 -0.89286
0.00000 1.00000 0.00000 5.65000
0.00000 0.00000 1.00000 -4.40000
```

Thus the correct quadratic equation is  $y = -0.89286x^2 + 5.65x - 4.4$ .

Figure 2.1 shows a graph of this parabola together with our original data points. These are the commands used to create the graph:

```
>> x = linspace(0, 7, 50);
>> y = -0.89286*x.^2 + 5.65*x - 4.4;
>> plot(xdata, ydata, 'o', x, y, 'linewidth', 2)
>> grid on;
>> legend('data values', 'least-squares parabola')
>> title('y = -0.89286x^2 + 5.65x - 4.4')
```

□

You may be wondering if any of this process can be “automated” by built-in Octave functions. Yes! If we want Octave to do all of the work for us, we can use the built-in function for polynomial fitting, `polyfit`. The syntax is `polyfit(x, y, order)`, where “order” is the degree of the polynomial desired.

Octave is configured to work with polynomials by associating their coefficients with a simple

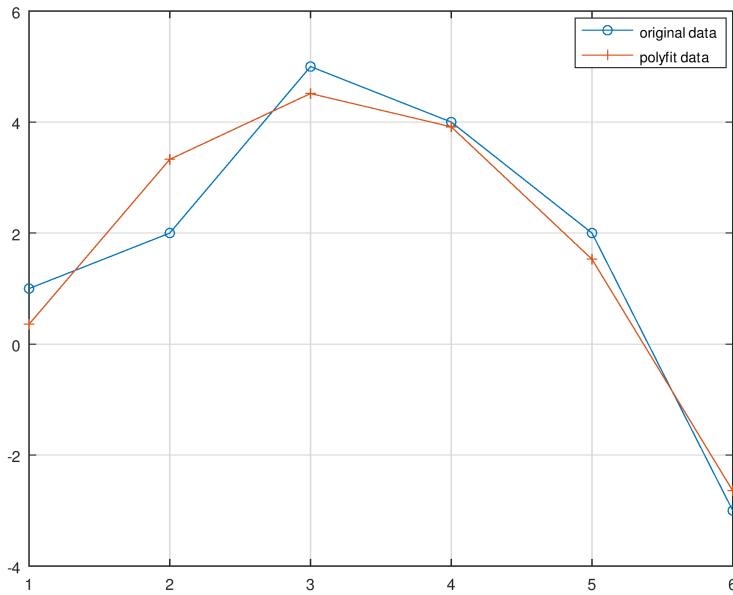


Figure 2.2: Plot of original data vs. polyfit data

row-vector. For example, the `polyval` function can be used to evaluate a polynomial using the syntax `polyval(P, x)`.

**Example 2.2.2.** Use `polyfit` to find the least-squares parabola for the following data:

$x$	1	2	3	4	5	6
$y$	1	2	5	4	2	-3

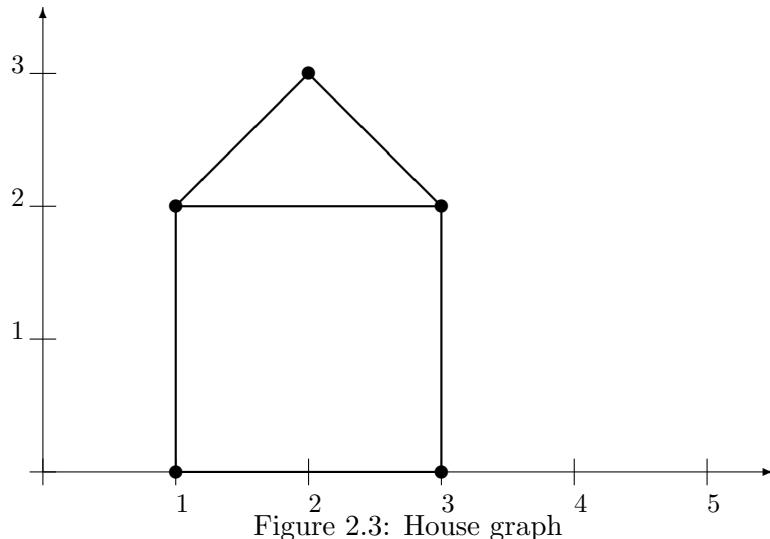
Graph the original data and `polyfit` data together on the same axes.

**Solution.** This is the same data as in Example 2.2. Re-enter the data values if necessary.

We use `polyfit` to determine the equation, then the `polyval` function to evaluate the polynomial at the given  $x$ -values.

```
>> P = polyfit(xdata, ydata, 2) % degree two polynomial fit
P =
    -0.89286   5.65000  -4.40000
>> y = polyval(P, xdata); % evaluate polynomial P at input xdata
>> plot(xdata, ydata, 'o-', xdata, y, '+');
>> grid on;
>> legend('original data', 'polyfit data');
```

The graph is shown in Figure 2.2. □



## 2.3 Matrix transformations

Matrices and matrix transformations play a key role in computer graphics. There are several ways to represent an image as a matrix. The approach we take here is to list a series of vertices that are connected sequentially to produce the edges of a simple graph. We write this as a  $2 \times n$  matrix where each column represents a point in the figure. As a simple example, let's try to encode a 'house graph.' First, we draw the figure on a grid and record the coordinates of the points, as in Figure 2.3.

There are many ways to encode this in a matrix. An efficient method is to choose a path that traverses each edge exactly once, if possible<sup>1</sup>. Here is one such matrix, starting from (1, 2) and traversing counterclockwise.

$$D = \begin{bmatrix} 1 & 1 & 3 & 3 & 2 & 1 & 3 \\ 2 & 0 & 0 & 2 & 3 & 2 & 2 \end{bmatrix}$$

Try plotting it in Octave and see if it worked.

```
>> D = [1 1 3 3 2 1 3; 2 0 0 2 3 2 2]
D =
    1    1    3    3    2    1    3
    2    0    0    2    3    2    2

>> x = D(1, :);
>> y = D(2, :);
>> plot(x, y);
```

You may want to zoom out to see the origin. Then the graph appears correct.

---

<sup>1</sup>This is called an *Eulerian path*. Such a path exists if the graph has exactly 0 or 2 vertices with odd degree.

### 2.3.1 Rotation

Now that we have a representation of a digital image, we consider various ways to transform it. Rotations can be obtained using multiplication by a special matrix.

A rotation of the point  $(x, y)$  about the origin is given by

$$R \cdot \begin{bmatrix} x \\ y \end{bmatrix}$$

where

$$R = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

and  $\theta$  is the angle of rotation (measured counterclockwise).

For example, what happens to the point  $(1, 0)$  under a  $90^\circ$  rotation?

$$\begin{bmatrix} \cos(90^\circ) & -\sin(90^\circ) \\ \sin(90^\circ) & \cos(90^\circ) \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

The rotation appears to work, at least in this case. Try a few more points to convince yourself. Notice that a rotation about the origin corresponds to moving along a circle, thus the trigonometry is fairly straightforward to work out.

Now, to produce rotations of a data matrix  $D$ , encoded as above, we only need to compute the matrix product  $RD$ .

**Example 2.3.1.** Rotate the house graph through  $90^\circ$  and  $225^\circ$ .

**Solution.** Note that  $\theta$  must be converted to radians. Here we go:

```
>> D = [1 1 3 3 2 1 3; 2 0 0 2 3 2 2];
>> x = D(1, :);
>> y = D(2, :);

>> theta1 = 90*pi/180;
>> R1 = [cos(theta1) -sin(theta1); sin(theta1) cos(theta1)];
>> RD1 = R1*D;
>> x1 = RD1(1, :);
>> y1 = RD1(2, :);

>> theta2 = 225*pi/180;
>> R2 = [cos(theta2) -sin(theta2); sin(theta2) cos(theta2)];
>> RD2 = R2*D;
>> x2 = RD2(1, :);
>> y2 = RD2(2, :);

>> plot(x, y, 'bo-', x1, y1, 'ro-', x2, y2, 'go-')
>> axis([-4 4 -4 4], 'equal');
>> grid on;
>> legend('original', 'rotated 90 deg', 'rotated 225 deg');
```

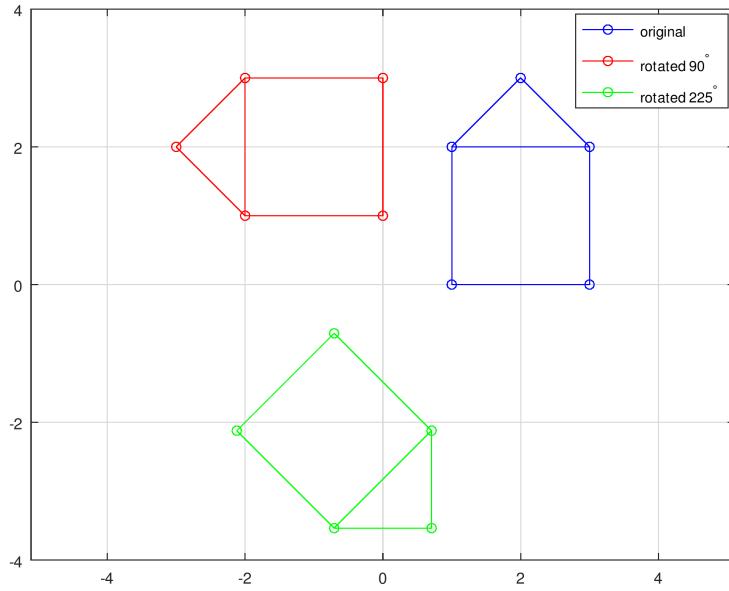


Figure 2.4: Rotations of the ‘house graph’

Note the combined plot options to set color, marker and line styles. The original and rotated graphs are shown in Figure 2.4. Notice that the rotation is about the origin. For rotations about an arbitrary point, see Exercise 12.  $\square$

### 2.3.2 Reflection

If  $\ell$  is a line through the origin, then a reflection of the point  $(x, y)$  in the line  $\ell$  is given by

$$R \cdot \begin{bmatrix} x \\ y \end{bmatrix}$$

where

$$R = \begin{bmatrix} \cos(2\theta) & \sin(2\theta) \\ \sin(2\theta) & -\cos(2\theta) \end{bmatrix}$$

and  $\theta$  is the angle  $\ell$  makes with the  $x$ -axis (measured counterclockwise).

For example, what matrix represents a reflection in the line  $y = x$ ? Here  $\theta = 45^\circ$ .

$$\begin{bmatrix} \cos(2 \cdot 45^\circ) & \sin(2 \cdot 45^\circ) \\ \sin(2 \cdot 45^\circ) & -\cos(2 \cdot 45^\circ) \end{bmatrix} = \begin{bmatrix} \cos(90^\circ) & \sin(90^\circ) \\ \sin(90^\circ) & -\cos(90^\circ) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

What is the effect of this matrix on a point  $(x, y)$ ?

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} y \\ x \end{bmatrix}$$

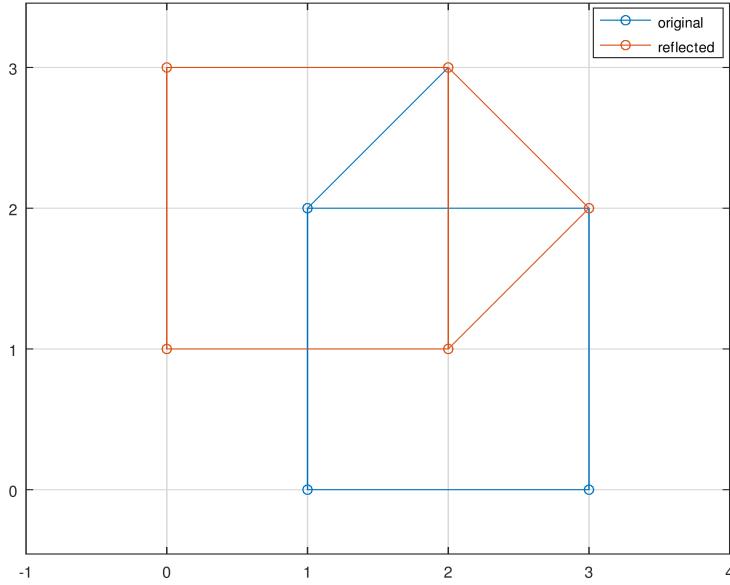


Figure 2.5: Reflection of the ‘house graph’

We see that the point is indeed reflected in the line  $y = x$ .

**Example 2.3.2.** Reflect the house graph in the line  $y = x$ .

**Solution.** With the data matrix  $D$  and the original  $x$  and  $y$  vectors already defined, and using  $R$  as determined above, we have:

```
>> R = [0 1; 1 0]
R =
    0    1
    1    0

>> RD = R*D;
>> x1 = RD(1, :);
>> y1 = RD(2, :);
>> plot(x, y, 'o-', x1, y1, 'o-')
>> axis([-1 4 -1 4], 'equal');
>> grid on;
>> legend('original', 'reflected')
```

The result is shown in Figure 2.5. □

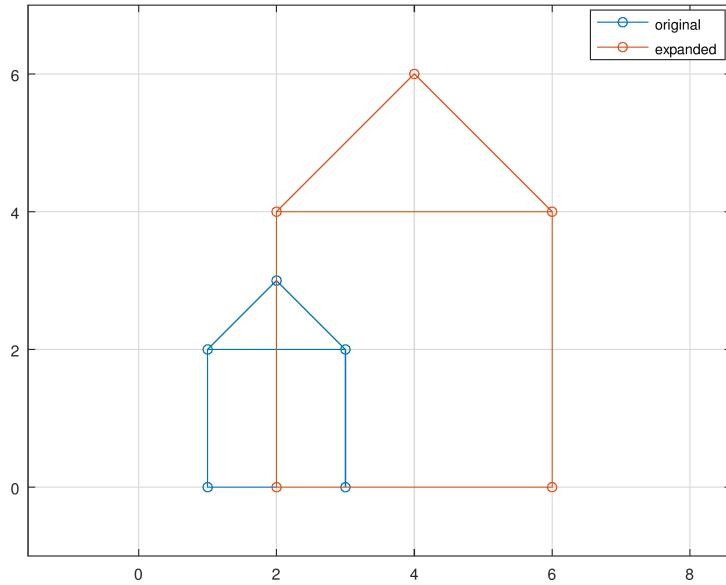


Figure 2.6: Dilation of the ‘house graph’

### 2.3.3 Dilation

*Dilation* (i.e., expansion or contraction) can also be accomplished by matrix multiplication. Let

$$T = \begin{bmatrix} k & 0 \\ 0 & k \end{bmatrix}$$

Then the matrix product  $TD$  will expand or contract  $D$  by a factor of  $k$ .

**Example 2.3.3.** Expand the house graph by a factor of 2.

**Solution.** To scale by a factor of 2, we only need to multiply  $D$  by the matrix  $\begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$ .

```
>> T = [2 0; 0 2]
T =
    2     0
    0     2

>> TD = T*D;
>> x1 = TD(1, :); y1 = TD(2, :);
>> plot(x, y, 'o-', x1, y1, 'o-')
>> axis([-1 7 -1 7], 'equal');
>> grid on;
>> legend('original', 'expanded')
```

The result is shown in Figure 2.6. □

### 2.3.4 Combining transformations

While some nonlinear transformations, such as translations, could be accomplished by addition, in practice even a translation can be completed using a special kind of matrix product. Refer to Exercises 11–12 for some of the details and an example. The advantage to using only multiplication is that the composition of several transformations can be handled with the relatively simple operation of composing matrix multiplications. Furthermore, inverse transformations are easily produced by inverting the original transformation matrix.

For example, if  $T$  is a translation,  $R$  is a rotation, and  $S$  is a stretch, the combined operations of first translating, then rotating, then stretching can be completed with the matrix  $SRT$  and a data matrix  $D$  can be transformed with the product  $(SRT)D$ . The inverse of these combined operations is  $(SRT)^{-1} = T^{-1}R^{-1}S^{-1}$ .

## Chapter 2 Exercises

1. Solve the system of equations using Gaussian elimination row operations

$$\begin{cases} -x_1 + x_2 - 2x_3 = 1 \\ x_1 + x_2 + 2x_3 = -1 \\ x_1 + 3x_2 + 2x_3 = -1 \end{cases}$$

To document your work in Octave, click “select all,” then “copy” under the edit menu, and paste your work into a Word or text document. After you have the row-echelon form, solve the system by hand on paper, using backward substitution.

2. Use the Gaussian elimination multipliers from Exercise 1 to write an *LU* decomposition

for  $A = \begin{bmatrix} -1 & 1 & -2 \\ 1 & 1 & 2 \\ 1 & 3 & 2 \end{bmatrix}$ . Use this factorization to solve the system from Exercise 1.

3. Let  $A = \begin{bmatrix} 1 & -3 & 5 \\ 2 & -4 & 3 \\ 0 & 1 & -1 \end{bmatrix}$  be the coefficient matrix for a system of linear equations  $A\mathbf{x} = \mathbf{b}$ , where  $\mathbf{b} = \langle 1, -1, 3 \rangle$ . Solve the system using left division. Then, construct an augmented matrix  $A_1$  and use `rref` to row-reduce it. Compare the results.

4. Use *LU* decomposition to solve the system from Exercise 3. Use Octave’s  $[L \ U \ P] = \text{lu}(A)$  command. To use  $PA = LU$  to solve  $A\mathbf{x} = \mathbf{b}$ , first multiply through by  $P$ , then replace  $PA$  with  $LU$ :

$$\begin{aligned} A\mathbf{x} &= \mathbf{b} \\ PA\mathbf{x} &= P\mathbf{b} \\ LU\mathbf{x} &= P\mathbf{b} \end{aligned}$$

First solve  $L\mathbf{y} = P\mathbf{b}$ , then solve  $U\mathbf{x} = \mathbf{y}$ .

5. So far we have only looked at consistent systems. How does Octave handle inconsistent systems? Let’s turn our previous system into an inconsistent one. Let  $A\mathbf{x} = \mathbf{b}$  be the system from Exercise 3. To make this into a inconsistent system, we will make one row of the coefficient matrix into a linear combination of some other rows, without making the corresponding adjustment to the right-side constants. Do the following:

```
>> A(1, :) = 3*A(2, :) - 4*A(3, :)
```

Now  $A\mathbf{x} = \mathbf{b}$  should be an inconsistent system. Try solving it and see what Octave does. Compare the results of left-division with the row-reduced echelon form. How can you see that the system is inconsistent?

6. Octave can easily solve large problems that we would never consider working by-hand. Let’s try constructing and solving a larger systems of equations. We can use the command `rand(m, n)` to generate an  $m \times n$  matrix with entries uniformly distributed from the interval  $(0, 1)$ . If we want integer entries, we can multiply by 10 and use the `floor` function to chop off the decimal. Use this command to generate an augmented matrix  $M$  for a system of 25 equations in 25 unknowns:

```
>> M = floor(10*rand(25, 26));
```

Note the semicolon. This suppresses the output to the screen, since the matrix is now too large to display conveniently. Solve the system of equations using `rref` and/or left division and save the solution as a column vector  $\mathbf{x}$ .

7. On July 4, 2006, during a launch of the space shuttle Discovery, NASA recorded the following altitude data<sup>2</sup>.

Time (s)	Altitude (ft)
0	7
10	938
20	4,160
30	9,872
40	17,635
50	26,969
60	37,746
70	50,548
80	66,033
90	83,966
100	103,911
110	125,512
120	147,411

- (a) Find the quadratic polynomial that best fits this data. Use Octave to set-up and solve the normal equations. After you have the equations set up, you may solve using either the `rref` command or the left-division operator. Do not use `polyfit`.
- (b) Plot the best-fitting parabola together with the given data points. Save or print the plot. Your plot should have labeled axes and include a legend.
- (c) Use the first and second derivatives of the quadratic altitude model from part (a) to determine models for the vertical component of the velocity and acceleration of the shuttle. Estimate the velocity two minutes into the flight.
8. There are many situations where the polynomial models we have considered so far are not appropriate. However, sometimes we can use a simple transformation to linearize the data. For example, if the points  $(x, y)$  lie on an exponential curve, then the points  $(x, \ln y)$  should lie on a straight line. To see this, assume that  $y = Ce^{kx}$  and take the logarithm of both sides of the equation:

$$\begin{aligned} y &= Ce^{kx} \\ \ln y &= \ln Ce^{kx} \\ &= \ln C + \ln e^{kx} \\ &= kx + \ln C \end{aligned}$$

Make the change of variables  $Y = \ln y$  and  $A = \ln C$ . Then we have a linear function of the form

$$Y = kx + A$$

---

<sup>2</sup>[https://www.nasa.gov/pdf/585034main\\_ALG\\_ED\\_SSA-Altitude.pdf](https://www.nasa.gov/pdf/585034main_ALG_ED_SSA-Altitude.pdf)

We can find the line that best fits the  $(x, Y)$ -data and then use inverse transformations to obtain the exponential model we need:

$$y = Ce^{kx}$$

where

$$C = e^A$$

Consider the following world population data<sup>3</sup>:

$x = \text{year}$	$y = \text{population (in millions)}$	$Y = \ln y$
1900	1650	7.4085
1910	1750	
1920	1860	
1930	2070	
1940	2300	
1950	2525	
1960	3018	
1970	3682	
1980	4440	
1990	5310	
2000	6127	
2010	6930	

- (a) Fill in the blanks in the table with the values for  $\ln y$ . Note that in Octave, the `log(x)` command is used for the natural logarithm. Make a scatter plot of  $x$  vs.  $Y$ . This is called a semi-log plot. Is the trend approximately linear?
- (b) Use the `polyfit` function to find the best-fitting line for the  $(x, Y)$ -data and add the graph of the line to your scatter plot from part (a). Save or print the plot. Your plot should have labeled axes and include a legend. Note that the vertical axis is the logarithm of the population. Give the plot the title “Semi-log plot.”
- (c) Use the data from part (b) to determine the exponential model  $y = Ce^{kx}$ . Plot the original data and the exponential function on the same set of axes. Save or print the plot. Your plot should have labeled axes and include a legend. Give the plot the title “Exponential plot.”
- (d) Use the model from part (c) to predict the date when the global population will (or did) reach 7 billion.
9. Create a data matrix that corresponds to a picture of your own design, containing six or more edges. Plot it, then plot two rotations of the same image.
10. Expand your figure from problem 9 by a factor of 2, then reflect the expanded figure in the  $x$ -axis.
11. Let the point  $(x, y)$  be represented by the column vector  $\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$ . These are known as

---

<sup>3</sup><https://esa.un.org/unpd/wpp/>

*homogeneous coordinates.* Then the translation matrix

$$T = \begin{bmatrix} 1 & 0 & h \\ 0 & 1 & k \\ 0 & 0 & 1 \end{bmatrix}$$

is used to move the point  $(x, y)$  to  $(x + h, y + k)$  as follows:

$$\begin{bmatrix} 1 & 0 & h \\ 0 & 1 & k \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x + h \\ y + k \\ 1 \end{bmatrix}$$

Use a translation matrix and homogeneous coordinates to shift the graph you created in problem 9 as follows: shift 3 units left and 2 units up.

12. The translation method described in problem 11 can be combined with a rotation matrix to give rotations around an arbitrary point. Suppose for example that we wished to rotate the house graph from Figure 2.3 about the center of the rectangular portion (coordinates  $(2, 1)$  in the original figure). This can be done by using homogeneous coordinates and a translation  $T$  to move the figure, then a rotation matrix  $R$  for the rotation. The form of  $R$  is now

$$R = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The shifted and rotated figure is then given by  $(RT)D$ . To shift back to the original position, an inverse transformation  $T^{-1}$  is used. Thus the rotated image can be found by computing  $(T^{-1}RT)D$ . Use this method to rotate the house graph  $90^\circ$  about the point  $(2, 1)$ . Show the combined transformation matrix  $T^{-1}RT$  and the results.

# Chapter 3

## Calculus

### 3.1 Limits, sequences, and series

Octave is an excellent tool for many types of numerical experiments. Octave is a full-fledged programming language supporting many types of loops and conditional statements. However, since it is a vector-based language, many things that would be done using loops in FORTRAN or other languages can be “vectorized.” As an example, let’s construct some numerical evidence to guess at the value of the following limit:

$$\lim_{n \rightarrow \infty} \left(1 + \frac{1}{n}\right)^n$$

We simply want to evaluate the expression for a series of larger and larger  $n$ -values. This is what we mean by vectorized code: instead of writing a loop to evaluate the function multiple times, we will generate a vector of input values, then evaluate the function using the vector input. This produces code that is easier to read and understand, and executes faster, due to Octave’s underlying efficient algorithms for matrix operations.

First, we need to define the function. There are a number of ways to do this. The method we use here is known as an *anonymous function*. This is a good way to quickly define a simple function.

```
>> f = @(n) (1 + 1./n).^ n; % anonymous function
```

Note the use of elementwise operations. We have named the function  $f$ . The input variable is designated by the @-sign followed by the variable in parentheses. The expression that follows gives the rule to be used when the function is evaluated. Now  $f$  can be used like any function in Octave.

Next we create an index variable, consisting of the integers from 0 to 9:

```
>> k = [0:1:9]'; % index variable  
k =
```

```
0
1
2
3
4
5
6
7
8
9
```

The syntax `[0:1:9]` produces a row vector that starts at 0 and increases by an increment of 1 up to 9 (`linspace` can also be used). Notice that we have used the transpose operation, simply because our results will be easier to read as column vectors. Now, we'll take increasing powers of 10, which will be the input values, then evaluate  $f(n)$ .

```
>> format long % display additional decimal places
>> n = 10.^k
n =
1
10
100
1000
10000
100000
1000000
10000000
100000000
1000000000

>> f(n)
ans =
2.00000000000000
2.59374246010000
2.70481382942153
2.71692393223552
2.71814592682436
2.71826823719753
2.71828046915643
2.71828169398037
2.71828178639580
2.71828203081451

>> format      % return to standard 5-digit display
```

This is good evidence that the limit converges to a finite value that is approximately 2.71828... You (hopefully!) recognize the number as  $e$ .

Similar methods can be used for numerical exploration of sequences and series, as we show in the following examples.

**Example 3.1.1.** Let  $\sum_{n=2}^{\infty} a_n$  be the series whose  $n$ th term is  $a_n = \frac{1}{n(n+2)}$ . Find the first ten terms, the first ten partial sums, and plot the sequence and partial sums.

**Solution.** To do this, we will define an index vector  $n$  from 2 to 11, then calculate the terms.

```
>> n = [2:1:11]'; % index
>> a = 1./(n.*(n + 2)) % terms of the sequence
a =
0.1250000
0.0666667
0.0416667
0.0285714
0.0208333
0.0158730
0.0125000
0.0101010
0.0083333
0.0069930
```

If we want to know the 10th partial sum, we need only type `sum(a)`. If we want to produce the sequence of partial sums, we need to make careful use of a loop. We will use a “for-loop” with index  $i$  from 1 to 10. For each  $i$ , we produce a partial sum of the sequence  $a_n$  from the first term to the  $i$ th term. The output is a 10-element vector of these partial sums.

```
>> for i = 1:10
    s(i) = sum(a(1:i));
end
>> s' % sequence of partial sums, displayed as a column
ans =
0.12500
0.19167
0.23333
0.26190
0.28274
0.29861
0.31111
0.32121
0.32955
0.33654
```

Finally, we will plot the terms and partial sums, for  $2 \leq n \leq 11$ .

```
>> plot(n, a, 'o', n, s, '+')
>> grid on
>> legend('terms', 'partial sums')
```

The result is shown in Figure 3.1. □

An advantage of using a language like Octave is that it is simple to determine the sum of many

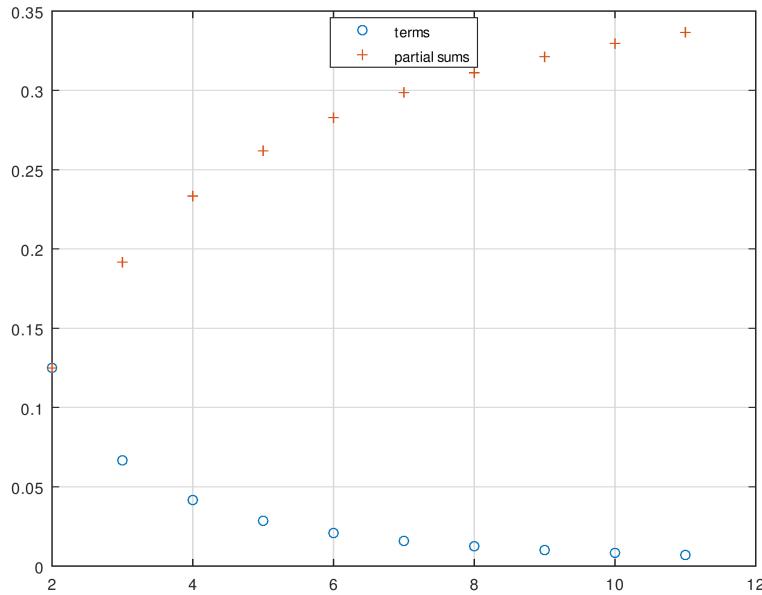


Figure 3.1: Plot of a sequence and its partial sums

terms of a series. If the series is known to converge, this can help give an estimate for the sum.

**Example 3.1.2.** Find the sum of the first 1000 terms of the harmonic series.

$$\sum_{n=1}^{1000} \frac{1}{n}$$

**Solution.** We only need to generate the terms as a vector, then take its sum.

```
>> n = [1:1:1000];
>> a = 1./n;
>> sum(a)
ans = 7.4855
```

Of course, Octave cannot tell us if this figure is a good estimate for the sum of the infinite series. In this case it is not, since, by the integral test, we know the series diverges. We can use Octave to easily document how slowly this particular series diverges. The first 1000 terms sum to only about 7.5. If we look at the 1,000,000th partial sum, it is still only about 14.4.  $\square$

## 3.2 Numerical integration

When it is not possible to find an explicit antiderivative, numerical methods are used to find definite integrals. We will use Octave's built-in numerical integration capability, then try writing

our own scripts to apply the midpoint rule, trapezoid rule, and Simpson's rule.

### 3.2.1 Quadrature

Octave has several built in functions to calculate definite integrals. We will use the `quad` command. 'Quad' is short for *quadrature*, which refers to the process of numeric integration.

**Example 3.2.1.** Estimate  $\int_0^{\pi/2} e^{x^2} \cos(x) dx$  using Octave's `quad` algorithm.

**Solution.** The correct syntax is `quad('f', a, b)`. We need to first define the function.

```
>> function y = f(x)
    y = exp(x.^2).*cos(x);
end
>> quad('f', 0, pi/2)
ans = 1.8757
```

Note that the function `exp(x)` is used for  $e^x$ . In this example, we used the `function ... end` construction to define  $f$ . This is a versatile format that allows for multiple operations and outputs. We could have also used an anonymous function. Note that no quotes are used around the name  $f$  if using an anonymous function with `quad`.  $\square$

### 3.2.2 Approximating sums

The midpoint rule, trapezoid rule, and Simpson's rule are common algorithms used for numerical integration. Ideally these are implemented in a computer program and Octave is well suited for this purpose.

Let  $\{a = x_0, x_1, x_2, \dots, x_n = b\}$  be a partition of  $[a, b]$  into  $n$  subintervals, each of width  $\Delta x = \frac{b-a}{n}$ . Then  $\int_a^b f(x) dx$  can be approximated as follows.

MIDPOINT RULE:

$$\Delta x [f(m_1) + f(m_2) + \cdots + f(m_n)]$$

where  $m_i$  is the midpoint of the  $i$ th subinterval.

TRAPEZOID RULE:

$$\frac{\Delta x}{2} [f(x_0) + 2f(x_1) + 2f(x_2) + \cdots + 2f(x_{n-1}) + 2f(x_n)]$$

where  $x_i = a + i\Delta x$ .

SIMPSON'S RULE:

$$\frac{\Delta x}{3} [f(x_0) + 4f(x_1) + 2f(x_2) + 4f(x_3) + \cdots + 2f(x_{n-2}) + 4f(x_{n-1}) + f(x_n)]$$

where  $x_i = a + i\Delta x$ .

Notice that the sum in the midpoint formula has  $n$  terms, while the trapezoid and Simpson's rules have  $n+1$  (the index  $i$  goes from 0 to  $n$ ). To implement these rules in Octave, we will write *script* files, which are plain text files containing a series of Octave commands. Use a text editor, such as Notepad, Notepad++, or Emacs. A script file needs to have a “.m” extension (not the .txt used by default in Windows for text files) and cannot begin with the keyword **function**. The Octave GUI has its own built in text editor which can be accessed by changing to the “Editor” tab option displayed below the main command window. This editor is ideal for creating, editing, and running .m files and will automatically color code comments and key words.

**Example 3.2.2.** Write an Octave script to calculate a midpoint rule approximation of

$$\int_0^{\pi/2} e^{x^2} \cos(x) dx$$

using  $n = 100$ .

**Solution.** The basic strategy is to use a loop that adds an additional function value to a running total with each iteration. Then the final answer is found by multiplying the sum by  $\Delta x$ .

The following code can be used. Enter the code in a plain text file and name it “midpoint.m”. It must be placed in your working directory, then it can be run by typing ‘midpoint’ at the command prompt.

Octave Script 3.1: Midpoint rule approximation

---

```

1 % file 'midpoint.m'
2 % calculates a midpoint rule approximation of
3 %   the integral from 0 to pi/2 of f(x) = exp(x^2) cos(x)
4 %   —traditional looped code
5
6 % set limits of integration , number of terms and delta x
7 a = 0
8 b = pi/2
9 n = 100
10 dx = (b - a)/n
11
12 % define function to integrate
13 function y = f(x)
14   y = exp(x.^2).*cos(x);
15 end
16
17 msum = 0;          % initialize sum
18 m1 = a + dx/2;    % first midpoint
19
20 % loop to create sum of function values
21 for i = 1:n
22   m = m1 + (i - 1)*dx; % calculate midpoint
23   msum = msum + f(m);  % add to midpoint sum
24 end
25
26 % midpoint approximation to the integral
27 approx = msum*dx

```

---

Now run midpoint.m.

```
>> midpoint
a = 0
b = 1.5708
n = 100
dx = 0.015708
approx = 1.8758
```

□

The traditional code works fine, but because Octave is a vector-based language, it is also possible to write vectorized code that does not require any loops.

**Example 3.2.3.** Write a vectorized Octave script to calculate a midpoint rule approximation of

$$\int_0^{\pi/2} e^{x^2} \cos(x) dx$$

using  $n = 100$ .

**Solution.** Now our strategy is to create a vector of the  $x$ -coordinates of the midpoints. Then we evaluate  $f$  over this midpoint vector to obtain a vector of function values. The midpoint approximation is the sum of the components of the vector, multiplied by  $\Delta x$ .

Octave Script 3.2: Midpoint rule approximation - vectorized

---

```

1 % file 'midpoint2.m'
2 % calculates a midpoint rule approximation of
3 % the integral from 0 to pi/2 of f(x) = exp(x^2)cos(x)
4 % --vectorized code
5
6 % set limits of integration , number of terms and delta x
7 a = 0
8 b = pi/2
9 n = 100
10 dx = (b - a)/n
11
12 % define function to integrate
13 function y = f(x)
14 y = exp(x.^2).*cos(x);
15 end
16
17 % create vector of midpoints
18 m = [a + dx/2 : dx : b - dx/2];
19
20 % create vector of function values at midpoints
21 M = f(m);
22
23 % midpoint approximation to the integral
24 approx = dx*sum(M)
```

---

This code will give the same results as the traditional looped code, but it executes much faster.

□

### 3.3 Parametric, polar, and implicit functions

#### 3.3.1 Parametric and polar plots

Curves defined by parametric and polar equations are usually studied in Calculus II. Such curves can be difficult to graph by hand! The plotting methods we used in Section 1.4 carry over easily to these new settings. For example, parametric equations for a *cycloid* are given by

$$\begin{aligned}x &= r(t - \sin(t)) \\y &= r(1 - \cos(t))\end{aligned}$$

**Example 3.3.1.** Graph three periods of a radius 2 cycloid.

**Solution.** The functions have period  $2\pi$ , so we need  $0 \leq t \leq 6\pi$  to see three full cycles. We need to define the parameter  $t$  as a vector over this range, then we calculate  $x$  and  $y$ , and plot  $x$  vs.  $y$ .

```
>> t = linspace(0, 6*pi, 50);
>> r = 2;
>> x = r*(t - sin(t));
>> y = r*(1 - cos(t));
>> plot(x, y)
>> axis('equal')
>> axis([0 12*pi 0 4])
```

The command `axis('equal')` is used to force an equal aspect ratio between the  $x$ - and  $y$ -axes. The result is shown in Figure 3.2.  $\square$

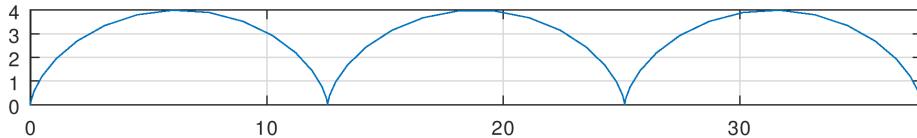


Figure 3.2: Graph of a cycloid

Polar graphs are handled in a similar way. For a function  $r = f(\theta)$ , we start by defining the independent variable  $\theta$ , then we calculate  $r$ . To plot the graph, we calculate  $x$  and  $y$  using the standard polar identities  $x = r \cos(\theta)$ ,  $y = r \sin(\theta)$ , then plot  $x$  vs.  $y$ .

**Example 3.3.2.** Plot the *limaçon*  $r = 1 - 2 \sin(\theta)$ .

**Solution.** The needed commands are shown below and the graph is shown in Figure 3.3.

```
>> theta = linspace(0, 2*pi, 100);
>> r = 1 - 2*sin(theta);
>> x = r.*cos(theta);
>> y = r.*sin(theta);
>> plot(x, y)
```

$\square$

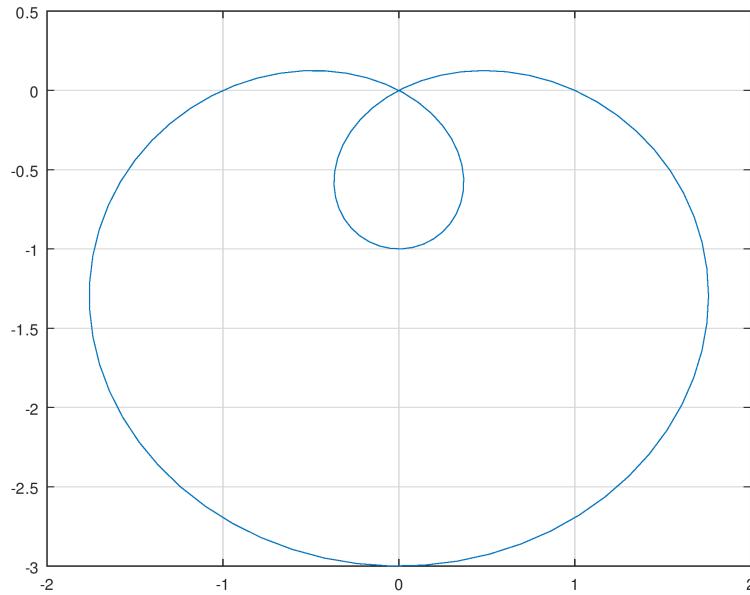


Figure 3.3: Graph of a limaçon

It is also possible to plot a function  $r = f(\theta)$  on a set of polar axes using the `polar` command. For example, the following commands will produce a graph of the limaçon shown above on a polar grid. Try it!

```
>> theta = linspace(0, 2*pi, 50);
>> r = 1 - 2*sin(theta);
>> polar(theta, r)
```

### 3.3.2 Implicit plots

Sometimes we need to plot a function defined implicitly by an equation of the form  $f(x, y) = 0$ . The easiest way to do this in Octave is with the `ezplot` command.

**Example 3.3.3.** Plot the curve defined by the equation

$$-x^2 - xy + x + y^2 - y = 1$$

**Solution.** To define the function as  $f(x, y) = 0$ , we subtract 1 from both sides of the equation.

```
>> f = @(x,y) -x.^2 - x.*y + x + y.^2 - y - 1
f =
@(x, y) -x .^ 2 - x .* y + x + y .^ 2 - y - 1
>> ezplot(f)
```

Run the `ezplot` command to see the results. Do you recognize the curve? □

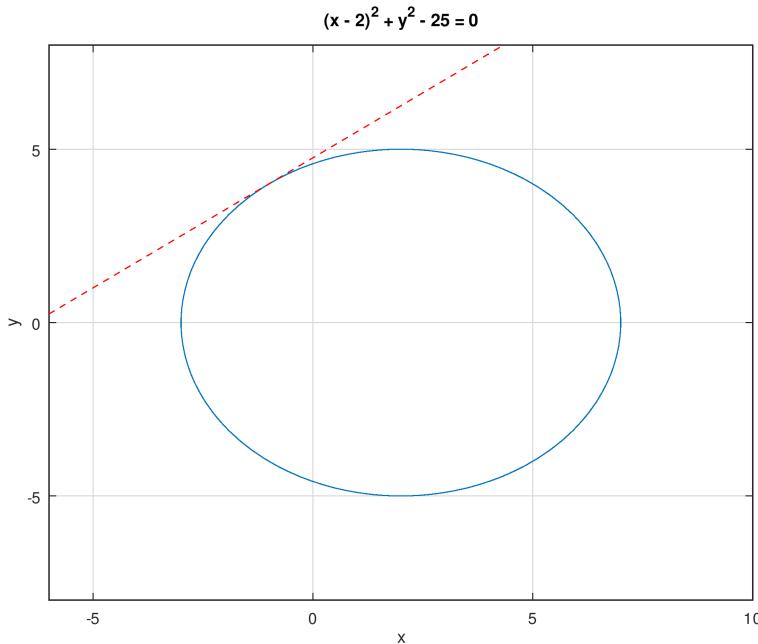


Figure 3.4: Implicit plot

**Example 3.3.4.** Find the equation of the line tangent to the graph of the circle  $(x-2)^2+y^2=25$ , at the point  $(-1, 4)$ . Plot a graph of the circle and the tangent line on the same axes.

**Solution.** To plot the circle, we'll first define it as a function of the form  $f(x, y) = 0$ .

```
>> f = @(x, y) (x - 2).^2 + y.^2 - 25;
```

The center of the circle is at  $(2, 0)$  and the radius is 5. We will set the axes of our plot to extend a few units beyond the circumference of the circle.

```
>> % implicit plot of f(x,y) = 0 over domain [-6, 10]x[-8, 8]
>> ezplot(f, [-6 10 -8 8])
```

Using implicit differentiation, the derivative is

$$y' = \frac{2-x}{y}$$

At the point  $(-1, 4)$ , we have

$$y' = \frac{2 - (-1)}{4} = \frac{3}{4}$$

The equation of the tangent line is thus

$$\begin{aligned} y - 4 &= \frac{3}{4}(x - (-1)) \\ y &= \frac{3}{4}x + \frac{19}{4} \end{aligned}$$

Finally we add the tangent line to the graph.

```
>> x = [-6 : 10];
>> y = 3/4*x + 19/4;
>> hold on
>> plot(x, y, 'r—')
```

The result is shown in Figure 3.4. □

## 3.4 Complex variables

Complex variables are ubiquitous in some engineering fields. Even if we attempt to limit our attention to real variables, some mathematical subjects cannot be fully understood without extending into the field of complex numbers. Examples include the eigenvalues and eigenvectors of matrices and the roots of polynomial equations.

The study of complex numbers begins with one basic definition:

$$i = \sqrt{-1}$$

The number  $i$  is called an *imaginary number*. A *complex number*  $z = a + bi$  has real part  $a$  and imaginary part  $b$ . We will illustrate complex number arithmetic in Octave using some simple examples.

**Example 3.4.1.** Let  $z_1 = 1 + 2i$  and  $z_2 = 2 - 3i$ . Find each of the following:

- (a)  $z_1 + z_2$
- (b)  $z_2 - z_1$
- (c)  $z_1 \cdot z_2$
- (d)  $\frac{z_1}{z_2}$

**Solution.** Octave has no difficulty dealing with complex arithmetic. The variables  $i$  and  $j$  (not case-sensitive) are both by default recognized as the imaginary unit  $\sqrt{-1}$ .

```
>> % define complex variables
>> z1 = 1 + 2*i;
>> z2 = 2 - 3*i;

>> % addition
>> z1 + z2
ans = 3 - 1i

>> % subtraction
>> z1 - z2
ans = -1 + 5i
```

```
>> % multiplication
>> z1*z2
ans = 8 + 1i

>> % division
>> z1/z2
ans = -0.30769 + 0.53846i
```

Each result is expressed in the standard  $a + bi$  format. The commands `real(z)` and `imag(z)` can be used to extract the real part  $a$  and complex part  $b$ , if needed.  $\square$

We can plot numbers in the complex plane using the `compass` command.

**Example 3.4.2.** Let  $z_1 = 1 + 2i$  and  $z_2 = 2 - 3i$ . Plot  $z_1$ ,  $z_2$ , and the sum  $z_1 + z_2$  in the complex plane.

**Solution.** We will show both variables and their sum on one set of axes.

```
>> z1 = 1 + 2*i;
>> z2 = 2 - 3*i;
>> compass(z1, 'b')
>> hold on
>> compass(z2, 'r')
>> compass(z1 + z2, 'k—')
>> legend('z_1', 'z_2', 'z_1+z_2')
```

The plot is shown in Figure 3.5. The horizontal axis is real and the vertical axis is imaginary.

It is interesting to note that the sum of the two variables in the complex plane is equivalent to the sum of two vectors in  $\mathbf{R}^2$ . Thus the `compass` command can also be used to illustrate vector arithmetic. The only difference is how we interpret the axes.  $\square$

Sometimes Octave may return complex results unexpectedly. For example, suppose we want to evaluate  $\sqrt[3]{-8}$ :

```
>> (-8)^(1/3)
ans = 1.0000 + 1.7321i
```

While we probably expected the answer  $-2$ , we can also easily verify that the cube of the given answer is indeed  $-8$  (at least up to some minor round-off error):

```
>> ans^3
ans = -8.0000e+00 + 2.2204e-15i
```

There are actually three cube roots of  $-8$ , and by default, Octave will return the one with the smallest argument (angle). See Exercise 8. If we simply want the real root, we can use the `nthroot` command.

```
>> % real cube root of -8
>> nthroot(-8, 3)
ans = -2
```

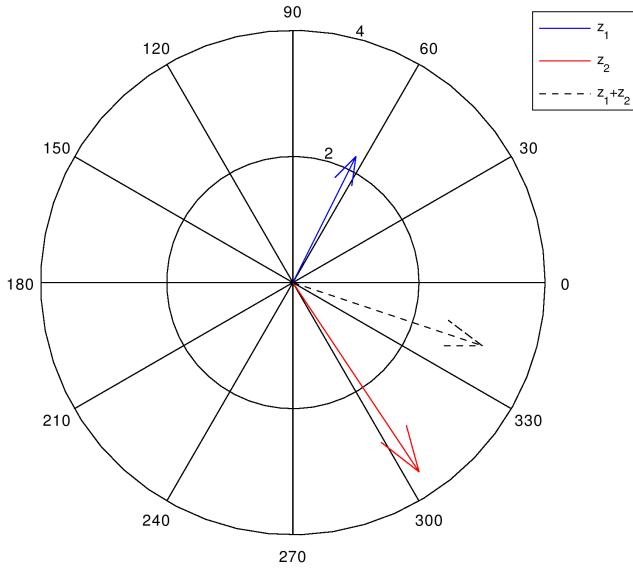


Figure 3.5: Addition in the complex plane

### 3.5 Special functions

Octave has many common *special functions* available, such as Bessel functions (`bessel`), the error function (`erf`), and the gamma function (`gamma`), to name a few.

For example, the *gamma function* is defined by

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt$$

This is an extension of the factorial function, since for positive integers  $n$ , the gamma function satisfies

$$\Gamma(n) = (n - 1)!$$

**Example 3.5.1.** Graph  $\Gamma(x + 1)$  together on the same set of axes with the factorial function  $n!$ .

**Solution.** Both the gamma function and factorial function grow quite large very quickly, so we need to take care in selecting the domain. The gamma function is defined for positive and negative real numbers, while the factorial function is of course defined only for nonnegative integers. We will try the graph for  $x \in [-5, 5]$  for the gamma function and  $n = 0, 1, 2, 3, 4, 5$  for the factorial.

Trial and error shows that a fine increment is needed for a smooth graph of the gamma function.

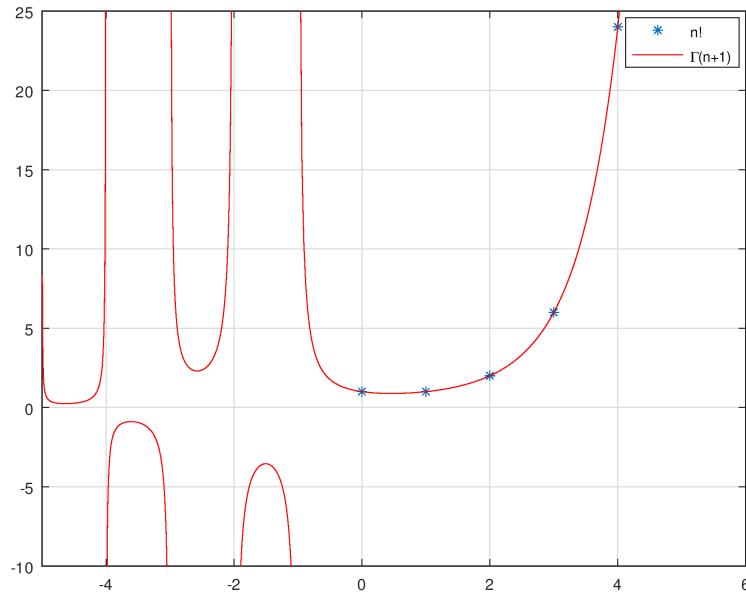


Figure 3.6: Improved graph of gamma function and factorial function

These are the basic commands needed:

```
>> n = [0 : 1 : 5];
>> x = linspace(-5, 5, 500);
>> plot(n, factorial(n), '*', x, gamma(x + 1))
>> axis([-5 6 -10 25]);
>> grid on;
>> legend('n!', 'gamma(n+1)')
```

Notice the vertical asymptotes at each negative integer. If you run the plot commands as shown above, you will see vertical line segments that are not a true part of the graph. If we don't want to see these, we can divide the domain into separate intervals with breaks at the discontinuities. This is somewhat tedious, but produces a more accurate graph, as shown in Figure 3.6.

Define the  $x$ -values as follows:

```
x1 = linspace(-5, -4, 200);
x2 = linspace(-4, -3, 200);
x3 = linspace(-3, -2, 200);
x4 = linspace(-2, -1, 200);
x5 = linspace(-1, 5, 200);
```

Then, plot  $x_1$  vs.  $\Gamma(x_1 + 1)$ ,  $x_2$  vs.  $\Gamma(x_2 + 1)$ , etc., on the same set of axes.  $\square$

## 3.6 Symbolic operations

While Octave is primarily numeric software, the Octave Forge *Symbolic* package allows Octave to function as a computer algebra system.

### 3.6.1 Installation

The package relies on the Python ‘SymPy’ library. If you already have a Python interpreter and SymPy, installation of the package in Octave only requires the command `pkg install --forge symbolic`.

If you don’t want to do a separate installation of Python, a standalone installer for Windows users is available from the package developers that includes all dependencies. To install the package using the standalone Windows installer, download the file `symbolic-win-py-bundle-2.7.1.zip` (or more recent version) from <https://github.com/cbm755/octsympy/releases>. Then in Octave, type:

```
>> pkg install symbolic-win-py-bundle-2.7.1.zip
>> pkg load symbolic
```

To see if it is working, try declaring a symbolic variable. You should get a message indicating a Python communication link.

```
>> syms x
Symbolic pkg v2.7.1: Python communication link active, SymPy v1.3.
```

Once installed and operating, the package works much like MATLAB’s Symbolic Toolbox.

### 3.6.2 Using symbolic functions

A few basic examples showing the use of Octave as a computer algebra system are included below.

**Example 3.6.1.** Let  $f(x) = x^3 + 3x^2 - 10x$ .

- (a) Find an exact value for  $f(\frac{1}{2})$ .
- (b) Factor the expression.
- (c) Solve  $f(x) = 0$ .

**Solution.** The first step is to define  $x$  as a symbolic variable with the command `syms`.

```
>> syms x
```

Now we define the expression. Notice that we do not need to worry about using elementwise operations here.

```
>> f = x^3 + 3*x^2 - 10*x
f = (sym)
```

$$\begin{matrix} 3 & 2 \\ x & + 3*x & - 10*x \end{matrix}$$

The command to evaluate a symbolic expression is `subs(expr, val)`. But, if we enter `subs(f, 1/2)`, we will receive a warning that floating-point values should not be passed to symbolic functions. To avoid this, we should enter  $\frac{1}{2}$  as a symbolic variable by using `sym(1)/2`. This will keep the fraction as an exact symbolic expression.

```
>> subs(f, sym(1)/2)
ans = (sym) -33/8
```

Factoring is straightforward:

```
>> factor(f)
ans = (sym) x*(x - 2)*(x + 5)
```

To solve, we use the `solve` command with the equality comparison, ‘`==`’.

```
>> solve(f == 0)
ans = (sym 3x1 matrix)
```

$$\begin{bmatrix} -5 \\ 0 \\ 2 \end{bmatrix}$$

The solutions are easily seen to correspond to the factors in the factored form above.  $\square$

We can also find exact answers for derivatives, antiderivatives, and definite integrals.

**Example 3.6.2.** Let  $f(x) = x^2 \sin x$ . Find each of the following:

(a)  $f'(x)$

(b)  $\int f(x) dx$

(c)  $\int_0^{\pi/4} f(x) dx$

**Solution.** The commands we need are `diff` and `int`.

```
>> % define the function
>> f = x^2*sin(x)
f = (sym)
```

$$\begin{matrix} 2 \\ x * \sin(x) \end{matrix}$$

```

>> % differentiate with respect to x
>> diff(f, x)
ans = (sym)


$$x^2 \cos(x) + 2x \sin(x)$$


>> % indefinite integral with respect to x
>> int(f, x)
ans = (sym)


$$-x^2 \cos(x) + 2x \sin(x) + 2 \cos(x)$$


>> % definite integral from 0 to pi/4
>> int(f, x, 0, sym(pi)/4)
ans = (sym)


$$-2 - \frac{\sqrt{2} \pi^2}{32} + \frac{\sqrt{2} \pi}{4} + \sqrt{2}$$


```

If you want to see the answer converted to a decimal (double-precision floating point) approximation, type `double(ans)`:

```

>> double(ans)
ans = 0.088755

```

□

### 3.6.3 Plotting

The `ezplot` method we used in Section 3.3.2 for plotting implicit functions is also the easiest way to plot a symbolic function.

**Example 3.6.3.** Let  $f(x) = x^3 + 3x^2 - 10x$ . Graph  $f$ ,  $f'$ , and  $f''$  on the same axes.

**Solution.** Once we've defined  $f$ , plotting the function is as simple as typing `ezplot(f)`.

```

>> syms x
>> f = x^3 + 3*x^2 - 10*x
f = (sym)


$$x^3 + 3x^2 - 10x$$


>> ezplot(f)

```

The default plot is over  $[-2\pi, 2\pi]$ . If we want to see the function over a wider range, we can use `ezplot(f, [a b])` to set the domain. In this case, the default domain covers the region of

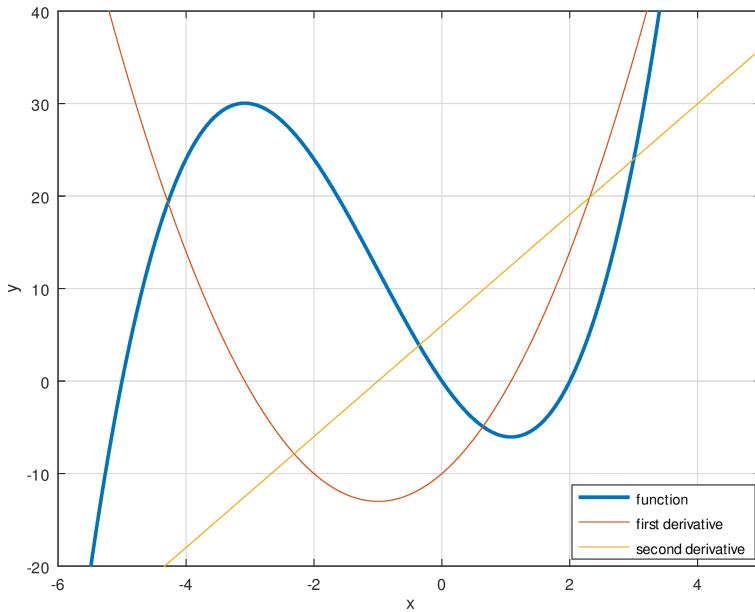


Figure 3.7: Graph of a polynomial and its derivatives

interest, but it will be helpful to adjust the viewpoint using the `axis` function. We would also like to change the line width. To do that, we will name the plot, then use that handle as a reference to the `set` function. Similar syntax can be used to adjust line width, color, and line style options.

```
>> h = ezplot(f);
>> axis([-6 5 -20 40])
>> set(h, 'linewidth', 2);
```

Now we just need to add the graphs of the first two derivatives.

```
>> hold on
>> ezplot(diff(f, x))
>> ezplot(diff(f, x, 2))
>> axis([-6 5 -20 40])
>> grid on
>> xlabel('x')
>> ylabel('y')
>> title('') % remove default ezplot title
>> legend('function', 'first derivative', 'second derivative')
>> legend('location', 'southeast') % move legend to lower right
```

The graph is shown in Figure 3.7. □

### 3.6.4 Assumptions

Sometime it is necessary to set assumptions on symbolic variables, as we show in the next example.

**Example 3.6.4.** Show that

$$\int_{-r}^r 2\sqrt{r^2 - x^2} dx = \pi r^2$$

**Solution.** The integral represents the area of circle of radius  $r$ , expressed in rectangular coordinates. Of course, polar form would be easier to evaluate, but Octave should be able to handle this symbolic integral as written.

```
>> syms x r
>> f = 2*sqrt(r^2 - x^2)
f = (sym)

          / 2      2
2* \ / r  - x

>> int(f, -r, r)
```

If you run these commands as shown, you will get a rather complicated and unexpected answer. The problem is that we have implicitly assumed  $r > 0$ , but Octave does not know this. We can fix the problem by setting an assumption on  $r$ .

```
>> assume(r, 'positive')
>> int(f, -r, r)
ans = (sym)

          2
pi * r
```

Now the result is as expected. Various other assumptions on symbolic variables are also possible (e.g., integer, nonzero, real, etc).  $\square$

### 3.6.5 Options

Notice that the output of symbolic operations in this section is displayed in a plain text approximation of standard mathematical notation. There are multiple display options available. The ASCII format is shown above. To change to a ‘prettier’ format, you can change to a unicode pretty print format using the command `sympref display unicode`. But, this option does not work on all systems. For plain text without special formatting, use `sympref display flat`.

It is important to note that when the symbolic package is loaded, some commands shadow (override) a core library function of the same name. For help on the symbolic functions, type `help @sym/diff`, `help @sym/int`, etc. For a complete list of available functions and options, refer to the documentation for the package<sup>1</sup>.

---

<sup>1</sup><https://octave.sourceforge.io/symbolic/overview.html>

## Chapter 3 Exercises

1. Show (numerically) that  $\lim_{\theta \rightarrow 0} \frac{\sin \theta}{\theta} = 1$ .
2. Let  $\sum a_n$  be the series whose  $n$ th term is  $a_n = \frac{1}{2^n} - \frac{1}{3^n}$ ,  $n \geq 1$ . Find the first ten terms, the first ten partial sums, and plot the sequence and partial sums. Do you think the series converges? If so, what is the sum?
3. How many terms need to be included in the harmonic series to reach a partial sum that exceeds 10?
4. Write an Octave script based on a for-loop to calculate  $\int_0^{\pi/2} e^{x^2} \cos(x) dx$  using the trapezoid rule with  $n = 100$ . Compare your answer to the midpoint approximation given above. (Use the command `format long` to see more decimal places.)
5. Write a vectorized Octave script to calculate  $\int_{-2}^2 \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} dx$  using Simpson's rule with  $n = 100$ . Compare your answer to the midpoint approximation using the script from Example 3.2.3. Which approximation seems to be most accurate, judged against Octave's `quad` algorithm?
6. Graph each equation.
  - (a)  $x = t^3, y = t^2$
  - (b)  $x = \sin(t), y = 1 - \cos(t)$
  - (c)  $r = \theta$
  - (d)  $r = \sin(2\theta)$
  - (e)  $r = \cos(7\theta/3)$
  - (f)  $x^2 = y^3 - 10y$
7. The polar form of a complex number is:

$$z = re^{i\theta}$$

where

$$re^{i\theta} = r(\cos(\theta) + i \sin(\theta))$$

Octave can determine the magnitude (modulus)  $r$  and angle (argument)  $\theta$  of a complex number  $z$  using the commands `abs(z)` and `angle(z)`, respectively.

- (a) Write the polar form of  $z_1 = 3 - 7i$  and  $z_2 = 1 + 5i$ .
- (b) Find  $z_1 z_2$  in both polar and  $a + bi$  form. How are the magnitudes and angles of each number related to the magnitudes and angles of the product?
- (c) Find  $z_1/z_2$  in both polar and  $a + bi$  form. How are the magnitudes and angles of each number related to the magnitudes and angles of the quotient?

8. A nonzero number (real or complex)  $x$  has  $n$  distinct  $n$ th roots. These are evenly spaced on a circle about the origin with radius equal to  $\sqrt[n]{r}$ , where  $r$  is the absolute value (or modulus) of  $x$ . Find the three complex cube roots of  $-8$  and show them on a complex plane compass plot.
9. Graph the Bessel functions of the first kind  $J_0(x)$ ,  $J_1(x)$ , and  $J_2(x)$  on  $[0, 20]$ .
10. The gamma function can be used to calculate the “volume” (or “hypervolume”) of an  $n$ -dimensional sphere. The volume formula is

$$V_n(a) = \frac{\pi^{n/2}}{\Gamma(\frac{n}{2} + 1)} \cdot a^n$$

where  $a$  is the radius,  $n$  is the dimension, and  $\Gamma(n)$  is the gamma function.

- (a) Write a user-defined Octave function  $V_n = f(n, a)$  that gives the volume of an  $n$ -dimensional sphere of radius  $a$ . Test it by computing the volumes of 2- and 3-dimensional spheres of radius 1. The answers should be  $\pi$  and  $4\pi/3$ , respectively.
- (b) Use the function to calculate the volume of a 4-dimensional sphere of radius 2 and a 12-dimensional sphere of radius  $1/2$ .
- (c) For a fixed radius  $a$ , the “volume” is a function of the dimension  $n$ . For  $n = 1, 2, \dots, 20$ , graph the volume functions for  $a = 1$ ,  $a = 1.1$ , and  $a = 1.2$  on the same axes. Your graph should show only points for integer values of  $n$  and should have axis labels and a legend. Use the graph to determine the following limit:

$$\lim_{n \rightarrow \infty} V_n$$

Does the answer surprise you?

11. Octave scripts can be used for many problems in numerical analysis. Newton’s method for root finding is a good example. Newton’s method is an iterative process based on the formula

$$x_{i+1} = x_i - \frac{f(x_i)}{f'(x_i)}$$

Starting from an initial guess of  $x_1$ , a sequence of approximations  $x_i$  is generated (refer to [1, §2.4] and [5, §4.1]).

- (a) The function  $f(x) = x^3 + 5x^2 + x - 1$  has one positive root. Write an Octave script to find it using Newton’s method.

- (b) Compare your answer to the result obtained with Octave’s `fsolve` command.

```
>> fsolve('f', x1) % solve f(x) = 0 numerically using initial
guess x1
```

- (c) How many iterations of Newton’s method were needed to obtain agreement with the `fsolve` result to five decimal places (using the same initial guess)?
- (d) Plot the function and its tangent lines at  $x_1$ ,  $x_2$ , and  $x_3$ .

12. Recall that for  $y = f(x)$ , the arc length from  $x = a$  to  $x = b$  is given by

$$s = \int_a^b \sqrt{1 + \left(\frac{dy}{dx}\right)^2} dx$$

([5, §7.4]).

Let  $f(x) = x^2$ . Use symbolic functions to find an exact value for the arc length from  $x = 0$  to  $x = 1$ .

13. The Taylor series for an infinitely differentiable function  $f$  at  $x = a$  is given by

$$T(x) = \sum_{k=0}^{\infty} \frac{f^{(k)}(a)}{k!} (x - a)^k$$

where  $f^{(k)}$  is the  $k$ th derivative of  $f$  ([5, §8.8]).

Let  $f(x) = e^{x^2}$ .

- (a) Find (by-hand) the first three nonzero terms of the Taylor series for  $f$  at  $x = 0$ .
- (b) Check your answer to part (a) by defining  $f$  as a symbolic function and using the `taylor` function:

```
>> syms x
>> f = exp(x^2)
>> T5 = taylor(f, x, 'order', 5)
```

- (c) Plot the function and the Taylor polynomial on the same axes.
- (d) Use the Taylor polynomial to approximate  $\int_0^1 e^{x^2} dx$ .

# Chapter 4

## Eigenvalue problems

### 4.1 Eigenvalues and eigenvectors

Let  $A = \begin{bmatrix} 1 & 2 & -3 \\ 2 & 4 & 0 \\ 1 & 1 & 1 \end{bmatrix}$ . We showed in Section 1.3.2 the use of `eig(A)` to find the eigenvalues of a matrix  $A$ . You might be wondering about the eigenvectors for this matrix. To find those, we use the `eig` command with two output arguments. The correct syntax is `[v lambda] = eig(A)`. The first output will be a matrix whose columns represent the eigenvectors and the second output value will be a diagonal matrix with the eigenvalues on the diagonal.

```
>> [v lambda] = eig(A) % 2-output form of eig command
v =
-0.23995+0.00000i  -0.79195+0.00000i  -0.79195-0.00000i
-0.91393+0.00000i  0.45225+0.12259i   0.45225-0.12259i
-0.32733+0.00000i  0.23219+0.31519i   0.23219-0.31519i

lambda =
Diagonal Matrix
4.52510+0.00000i           0           0
      0  0.73745+0.88437i           0
      0           0  0.73745-0.88437i
```

Notice that the output  $\Lambda$  (lambda) is classified as a diagonal matrix. That means the computer only stores the diagonal entries, which can be an important savings for large matrices.

Perhaps we would like to see a matrix with real eigenvalues. We can make a symmetric matrix (which must have real eigenvalues, as will be explained in Section 4.3.1) by multiplying a matrix and its transpose. For example:

```
>> C = A'*A
C =
```

```

6   11   -2
11   21   -5
-2   -5   10

>> [v lambda] = eig(C)
v =
0.876137   0.188733   -0.443581
-0.477715   0.216620   -0.851390
-0.064597   0.957839   0.279949

lambda =
Diagonal Matrix
0.14970      0      0
0    8.47515      0
0      0    28.37516

```

Here we can see that the diagonal entries of  $\Lambda$  are the eigenvalues and the corresponding columns of  $V$  are the associated eigenvectors. We know that each eigenvalue corresponds to an infinite family of eigenvectors. The representative eigenvectors given by Octave are normalized to unit length. Moreover, the collection of eigenvectors given will be linearly independent when possible.

## 4.2 Markov chains

Consider a sequence of random events, subject to the following conditions.

- A finite number of states are possible.
- At regular intervals an observation is made and the state of the system is recorded.
- For each state, we assign a probability of moving to each of the other states, or staying the same. The essential assumption is that these probabilities depend only on the current state.

Such a system is known as a *Markov chain*. Our problem is to predict the probability of future states of the system.

### 4.2.1 A random walk

Suppose we walk randomly along a four-block stretch of road in the following manner<sup>1</sup>. At intersections 2, 3, or 4 we either move to the left or to the right at random. Upon reaching the end of the road (intersections 1 or 5) we stop.

---

<sup>1</sup>The idea for this example comes from [4], which is an excellent open reference for more details about Markov chains and probability.

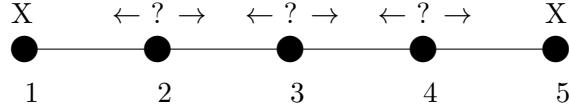


Figure 4.1: Random walk

Our goal is to predict where we will end up. We begin with a *probability vector*. For example, suppose we could start at any point with equal probability. Then the initial vector is  $\langle 0.2, 0.2, 0.2, 0.2, 0.2 \rangle$ . On the other hand, we may know the initial state. Suppose we begin at intersection 3. Then the initial vector is  $\langle 0, 0, 1, 0, 0 \rangle$ . In any case, we want to predict our location after  $k$  moves.

This is done by forming a *transition matrix*. Form an  $n \times n$  array whose  $ij$ th entry is the probability of moving from state  $i$  to  $j$ . Let  $T$  (for transition matrix) be the transpose of this matrix. The matrix product  $T\mathbf{x}$  gives the new probability distribution after one time period. Continued left-multiplication by  $T$  gives the probabilities for future states. Thus for any initial probability vector  $\mathbf{x}$  and any positive integer  $k$ , the probability vector after  $k$  time periods is  $\mathbf{y} = T^k \mathbf{x}$ .

**Example 4.2.1.** For our random walk example, find the probability vector after 5 steps for each of these initial probability vectors:

$$\mathbf{a} = \langle 0.2, 0.2, 0.2, 0.2, 0.2 \rangle$$

$$\mathbf{b} = \langle 0.5, 0, 0, 0, 0.5 \rangle$$

$$\mathbf{c} = \langle 0, 1, 0, 0, 0 \rangle$$

$$\mathbf{d} = \langle 0, 0, 1, 0, 0 \rangle$$

**Solution.** We form an array that records the probability of moving from each row to column.

		To				
		1	2	3	4	5
From	1	1	0	0	0	0
	2	0.5	0	0.5	0	0
3	0	0.5	0	0.5	0	
4	0	0	0.5	0	0.5	
5	0	0	0	0	1	

The transition matrix is the transpose.

$$T = \begin{bmatrix} 1 & 0.5 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0 & 0 \\ 0 & 0.5 & 0 & 0.5 & 0 \\ 0 & 0 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0.5 & 1 \end{bmatrix}$$

Notice that the sum of each column is 1. Now, the future state probabilities are easily computed as  $T^k \mathbf{x}$ , where  $\mathbf{x}$  is the initial probability vector (as a column vector).

```

>> T = [1 0.5 0 0 0; 0 0 0.5 0 0; 0 0.5 0 0.5 0; 0 0 0.5 0 0; 0 0 0
      0.5 1];
>> a = [0.2; 0.2; 0.2; 0.2; 0.2];
>> b = [0.5; 0; 0; 0; 0.5];
>> c = [0; 1; 0; 0; 0];
>> d = [0; 0; 1; 0; 0];
>> T^5*a
ans =
0.450000
0.025000
0.050000
0.025000
0.450000

>> T^5*b
ans =
0.50000
0.00000
0.00000
0.00000
0.50000

>> T^5*c
ans =
0.68750
0.00000
0.12500
0.00000
0.18750

>> T^5*d
ans =
0.37500
0.12500
0.00000
0.12500
0.37500

```

We notice that **b** results in no change from the initial probability.  $\square$

A probability vector  $\mathbf{x}$  is an *equilibrium vector* if  $\mathbf{x} = T\mathbf{x}$  where  $T$  is the transition matrix for the Markov chain. An equilibrium vector is one which results in no change moving to future states. Every Markov chain has at least one equilibrium vector and the eigenvalues of the transition matrix are the key to finding it.

**Theorem 4.2.2.** *Let  $T$  be the transition matrix for a Markov chain. Then  $\lambda = 1$  is an eigenvalue of  $T$ . If  $\mathbf{x}$  is an eigenvector for  $\lambda = 1$  with nonnegative components that sum to 1, then  $\mathbf{x}$  is an equilibrium vector for  $T$ .*

**Example 4.2.3.** Find an equilibrium vector for the Markov chain with transition matrix

$$T = \begin{bmatrix} 0.48 & 0.51 & 0.14 \\ 0.29 & 0.04 & 0.52 \\ 0.23 & 0.45 & 0.34 \end{bmatrix}$$

**Solution.**

```
>> T = [0.48 0.51 0.14; 0.29 0.04 0.52; 0.23 0.45 0.34]
T =
0.480000    0.510000    0.140000
0.290000    0.040000    0.520000
0.230000    0.450000    0.340000

>> [v lambda] = eig(T)
v =
-0.64840   -0.80111   0.43249
-0.50463   0.26394   -0.81601
-0.57002   0.53717   0.38351

lambda =
Diagonal Matrix
1.00000      0          0
0      0.21810      0
0          0      -0.35810

>> x = v(:, 1)/sum(v(:, 1))
x =
0.37631
0.29287
0.33082
```

Thus  $\mathbf{x} = \langle 0.37631, 0.29287, 0.33082 \rangle$  is an equilibrium vector. Let's test it.

```
>> T^10*x
ans =
0.37631
0.29287
0.33082

>> T^50*x
ans =
0.37631
0.29287
0.33082
```

There is no change evident, so it seems to work! □

### 4.3 Diagonalization

Diagonal matrices have important properties. Some matrices can be transformed into a special diagonal matrix that shares some properties with the original matrix, in particular, its eigenvalues. The diagonalization problem is to find a matrix  $S$  such that

$$S^{-1}AS = \Lambda$$

where  $\Lambda$  is a diagonal matrix.

**Theorem 4.3.1.** *Let  $A$  be an  $n \times n$  matrix with  $n$  linearly independent eigenvectors. Form an  $n \times n$  matrix  $S$  whose columns are the eigenvectors of  $A$ . Then  $S$  is invertible and  $S^{-1}AS = \Lambda$ , where*

$$\Lambda = \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{bmatrix}$$

and  $\lambda_i$  is the eigenvalue associated with the  $i$ th column of  $S$ . It follows that  $A$  can be written as  $A = S\Lambda S^{-1}$ .

Theorem 4.3.1 tells us how to diagonalize a square matrix. Notice that this can be done only for matrices that have enough independent eigenvectors. We need one more result.

**Theorem 4.3.2.** *If  $A$  is an  $n \times n$  diagonalizable matrix and  $A = S\Lambda S^{-1}$  and  $k$  is a positive integer, then*

$$A^k = S\Lambda^k S^{-1} = S \begin{bmatrix} \lambda_1^k & & & \\ & \lambda_2^k & & \\ & & \ddots & \\ & & & \lambda_n^k \end{bmatrix} S^{-1}$$

Theorem 4.3.2 shows how the diagonalized form can be used to simplify certain computational problems, such as raising a matrix to a high power.

**Example 4.3.3.** Let  $A = \begin{bmatrix} 7 & 8 \\ -4 & -5 \end{bmatrix}$ . Find  $A^{100}$ .

**Solution.** Octave can solve such a problem easily.

```
>> A = [7 8; -4 -5]
A =
    7   8
   -4  -5

>> A^100
ans =
    1.0308e+048   1.0308e+048
   -5.1538e+047  -5.1538e+047
```

But how does Octave do this? Not by brute force, but by using Theorem 4.3.2. Here's how. First we need to calculate the eigenvalues and associated eigenvectors. Verify that the eigenvalues and eigenvectors are

$$\lambda_1 = 3, \mathbf{v}_1 = \begin{bmatrix} -2 \\ 1 \end{bmatrix}$$

$$\lambda_2 = -1, \mathbf{v}_2 = \begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

Then  $\Lambda = \begin{bmatrix} 3 & 0 \\ 0 & -1 \end{bmatrix}$ . We form the matrix  $S$  using the eigenvectors:

$$S = \begin{bmatrix} -2 & -1 \\ 1 & 1 \end{bmatrix}$$

Now we need to calculate the inverse matrix. It is

$$S^{-1} = \begin{bmatrix} -1 & -1 \\ 1 & 2 \end{bmatrix}$$

Therefore the diagonalized form is

$$\begin{aligned} A &= S\Lambda S^{-1} \\ &= \begin{bmatrix} -2 & -1 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 3 & 0 \\ 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} -1 & -1 \\ 1 & 2 \end{bmatrix} \end{aligned}$$

So,

$$\begin{aligned} A^{100} &= S\Lambda^{100}S^{-1} \\ &= \begin{bmatrix} -2 & -1 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 3 & 0 \\ 0 & -1 \end{bmatrix}^{100} \cdot \begin{bmatrix} -1 & -1 \\ 1 & 2 \end{bmatrix} \\ &= \begin{bmatrix} -2 & -1 \\ 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} 3^{100} & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} -1 & -1 \\ 1 & 2 \end{bmatrix} \\ &= \begin{bmatrix} 2 \cdot 3^{100} - 1 & 2 \cdot 3^{100} - 2 \\ -3^{100} + 1 & -3^{100} + 2 \end{bmatrix} \end{aligned}$$

Compare to the earlier Octave result:

```
>> [2*3^100-1 2*3^100-2; -3^100+1 -3^100+2]
ans =
```

```
1.0308e+048    1.0308e+048
-5.1538e+047   -5.1538e+047
```

This example shows the power of diagonalization. □

### 4.3.1 Orthogonal diagonalization

We have already observed that not all square matrices can be diagonalized. However, a certain class of square matrices always has a diagonalization, and this diagonalization has special properties. First, we need to recall a few definitions.

- A *symmetric matrix* is a square matrix  $A$  such that  $A^T = A$ . Recall that a matrix with real entries may have complex eigenvalues. That cannot happen with symmetric matrices. A real symmetric matrix has all real eigenvalues.
- An *orthogonal matrix* is a square matrix whose columns are *orthonormal* (orthogonal and length 1). An important property of orthogonal matrices is that their inverse is equal to their transpose: If  $A$  is orthogonal, then  $A^{-1} = A^T$ .

All symmetric matrices are diagonalizable. Moreover, we can say the following:

**Theorem 4.3.4.** *Let  $A$  be a symmetric matrix. Then  $A$  can be diagonalized as*

$$A = Q\Lambda Q^T$$

where  $Q$  is an orthogonal matrix whose columns are eigenvectors of  $A$  and  $\Lambda$  is a diagonal matrix with the associated eigenvalues on the diagonal.

**Example 4.3.5.** Find an orthogonal diagonalization for  $A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$ .

**Solution.**  $A$  has eigenvalues 3 and 1. The eigenvectors are  $\begin{bmatrix} 1 \\ -1 \end{bmatrix}$  and  $\begin{bmatrix} 1 \\ 1 \end{bmatrix}$ . Notice that these are orthogonal. They are normalized by dividing by their length (both have length  $\sqrt{2}$ ). Then  $A$  can be diagonalized as

$$\begin{aligned} A &= Q\Lambda Q^T \\ &= \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \cdot \begin{bmatrix} 3 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \end{aligned}$$

The eigenvectors in this example were orthogonal since the eigenvalues were distinct. If the matrix  $A$  is symmetric, but has repeated eigenvalues, then the problem is a bit more difficult and finding a set of orthonormal eigenvectors requires the Gram-Schmidt process (see Section 4.5.1). We won't show the details here, but note that even in those cases, an orthonormal set of eigenvectors can still be found.  $\square$

Now, with these ideas in mind, let's take another look at the output of Octave's `eig` command.

```
>> A = [2 -1; -1 2]
A =
```

```
2 -1
```

```

-1      2
>> [v lambda] = eig(A)
v =
-0.70711 -0.70711
-0.70711  0.70711

lambda =
Diagonal Matrix

1      0
0      3

```

While the matrices are arranged slightly differently (the diagonalization is not unique), you should see that results given by Octave are precisely what is needed for the orthogonal diagonalization problem.

**Example 4.3.6.** Use Octave to diagonalize  $A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$ .

**Solution.** If an orthogonal diagonalization is possible, Octave will return the output of `eig(A)` in that format. This explains why Octave chooses normalized vectors that form an orthogonal set, when possible.

```

>> A = [2 -1; -1 2]
A =
2   -1
-1   2

>> [Q L] = eig(A)
Q =
-0.70711 -0.70711
-0.70711  0.70711

L =
Diagonal Matrix

1      0
0      3

>> Q*L*Q'    % check the factorization by multiplying
ans =
2.00000 -1.00000
-1.00000  2.00000

```

□

## 4.4 Singular value decomposition

We are now prepared to tackle the singular value decomposition (SVD). This factorization is something of a generalized version of what we just did for symmetric matrices in Section 4.3.1. But, the singular value decomposition exists for any matrix; the matrix need not even be square! The key is to consider the matrices  $A^T A$  and  $AA^T$ . These are always square symmetric matrices, and so, can be orthogonally diagonalized.

There are many applications associated with the SVD. For example, Netflix recently sponsored a competition with a one million dollar prize to improve their movie recommendation algorithm. The team that won used a method based in part on the SVD<sup>2</sup>, which can be used to discover hidden relationships among variables. We will consider applications to least-squares problems (Section 4.4.1) and image compression (Section 6.1).

**Theorem 4.4.1.** *Let  $A$  be an  $m \times n$  matrix. The square roots of the nonzero eigenvalues of  $A^T A$  and  $AA^T$  (they are the same) are called the singular values of  $A$ , denoted  $\sigma_1, \sigma_2, \dots, \sigma_r$ . Then  $A$  can be factored as*

$$A = U\Sigma V^T$$

where the columns of  $U$  are eigenvectors of  $AA^T$ , the columns of  $V$  are eigenvectors of  $A^T A$ , and the  $r$  singular values of  $A$  are on the diagonal of  $\Sigma$ . This factorization is called the singular value decomposition of  $A$ .

- $U$  is  $m \times m$  and orthogonal
- $V$  is  $n \times n$  and orthogonal
- $\Sigma$  is  $m \times n$  and diagonal of the special form

$$\Sigma = \begin{bmatrix} \sigma_1 & & & & \vdots \\ & \sigma_2 & & & 0 \\ & & \ddots & & \vdots \\ & & & \sigma_r & \\ \cdots & 0 & \cdots & & 0 \end{bmatrix}$$

If all the eigenvalues of  $A^T A$  are distinct, then the associated eigenvectors are “automatically” orthogonal. We only need to make them unit vectors. If there are repeated eigenvalues, it is still possible to choose orthogonal eigenvectors, but more advanced methods are needed (see Section 4.5.1). Our procedure starts with eigenvectors of  $A^T A$ , then appropriate orthogonal unit eigenvectors for  $AA^T$  are calculated using a simple formula. The number of singular values (nonzero eigenvalues) corresponds to the rank of the original matrix  $A$ . We will only consider examples where the number of singular values  $r$  is equal to  $m$ , the number of rows of  $A$ , otherwise, again, more advanced methods are required. We will consider a simple example using a  $2 \times 2$

---

<sup>2</sup><http://buzzard.ups.edu/courses/2014spring/420projects/math420-UPS-spring-2014-gower-netflix-SVD.pdf>

matrix, then see how Octave commands can be used to find the SVD for larger or more difficult matrices.

Here is the simplified procedure we will use:

1. Find  $A^T A$ .
2. Find the eigenvalues of  $A^T A$ . The square roots of these are the singular values  $\sigma_1, \sigma_2, \dots, \sigma_r$ , arranged in decreasing order.
3. Find the corresponding eigenvectors and make them unit vectors  $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n$ .
4. Find the vectors  $\mathbf{u}_i$  by computing  $\mathbf{u}_i = \frac{1}{\sigma_i} A \mathbf{v}_i$ .
5. Then  $A = U \Sigma V^T$ , where  $\sigma_1, \sigma_2, \dots, \sigma_r$  are on the diagonal of  $\Sigma$  and

$$U = [ \mathbf{u}_1 \mid \mathbf{u}_2 \mid \cdots \mid \mathbf{u}_m ]$$

$$V = [ \mathbf{v}_1 \mid \mathbf{v}_2 \mid \cdots \mid \mathbf{v}_n ]$$

- Remember to transpose  $V$  when you write the factorization.
- Remember to keep the eigenvalues and eigenvectors in their correct order.
- This simplified procedure only works if  $A^T A$  has no repeated eigenvalues and  $r = m$ .

**Example 4.4.2.** Let  $A = \begin{bmatrix} 4 & 4 \\ -3 & 3 \end{bmatrix}$ . Find the SVD via the simplified procedure outlined above, then compare to the results obtained using the Octave function `svd`.

**Solution.** We can readily verify that  $\text{rank}(A) = 2$ , so the matrix should have two singular values.

```
>> A = [4 4; -3 3]
A =
    4    4
   -3    3

>> ATA = A'*A
ATA =
    25      7
      7    25

>> [v lambda] = eig(ATA)
v =
    -0.70711    0.70711
    0.70711    0.70711

lambda =
```

Diagonal Matrix

$$\begin{matrix} 18 & 0 \\ 0 & 32 \end{matrix}$$

Notice that the given eigenvectors are orthogonal unit vectors. However, the eigenvalues are not in decreasing order. So, we need to switch the order of both eigenvectors and singular values (they must be in decreasing order) as we build  $V$  and  $\Sigma$ .

```
>> Sigma = zeros(2, 2);
>> Sigma(1, 1) = sqrt(lambda(2, 2))
Sigma =
      5.65685    0.00000
      0.00000    0.00000

>> Sigma(2, 2) = sqrt(lambda(1, 1))
Sigma =
      5.65685    0.00000
      0.00000    4.24264

>> V(:, 1) = v(:, 2)
V =
      0.70711
      0.70711

>> V(:, 2) = v(:, 1)
V =
      0.70711   -0.70711
      0.70711    0.70711
```

Now we build  $U$  to complete the factorization.

```
>> U(:, 1) = 1/Sigma(1, 1)*A*v(:, 1)
U =
      1.00000
      0.00000

>> U(:, 2) = 1/Sigma(2, 2)*A*v(:, 2)
U =
      1.00000    0.00000
      0.00000    1.00000
```

Now, let's verify that  $U\Sigma V^T = A$ .

```
>> U*Sigma*V'
ans =
```

4.0000	4.0000
-3.0000	3.0000

Now that we have a rough sense of how an SVD is determined, let's try the built-in Octave function. The command  $[U, S, V] = \text{svd}(A)$  computes the SVD of a matrix  $A$  and stores the result in matrices  $U$ ,  $S$ , and  $V$ . Let's use this command to find the SVD of the matrix  $A$  and verify that  $U*S*V'$  returns  $A$ .

```
>> [U S V] = svd(A) % 3-output format of svd command
U =
-1 0
0 1

S =
Diagonal Matrix
5.6569 0
0 4.2426

V =
-0.70711 -0.70711
-0.70711 0.70711

>> U*S*V'
ans =
4.0000 4.0000
-3.0000 3.0000
```

Notice that the factorization returned by `svd` is slightly different than we obtained above. This is normal: the SVD is not unique due to variations in how representative eigenvectors are chosen.  $\square$

#### 4.4.1 The pseudoinverse

In Section 2.2, we used the normal equations,  $A^T A \mathbf{x} = A^T \mathbf{b}$ , to solve least-squares problems. One potential problem with this approach is that the normal equations are typically *ill-conditioned*. This means that a small change in the data can lead to a large change in the numeric solution. This is bad! One way to avoid this computational problem is to use a generalized inverse known as the *pseudoinverse*, based on the SVD.

**Theorem 4.4.3.** *For an  $m \times n$  matrix  $A$  with singular value decomposition  $A = U\Sigma V^T$ , the least-squares solution to the system  $A\mathbf{x} = \mathbf{b}$  is given by*

$$\bar{\mathbf{x}} = A^+ \mathbf{b}$$

where

$$A^+ = V\Sigma^+U^T$$

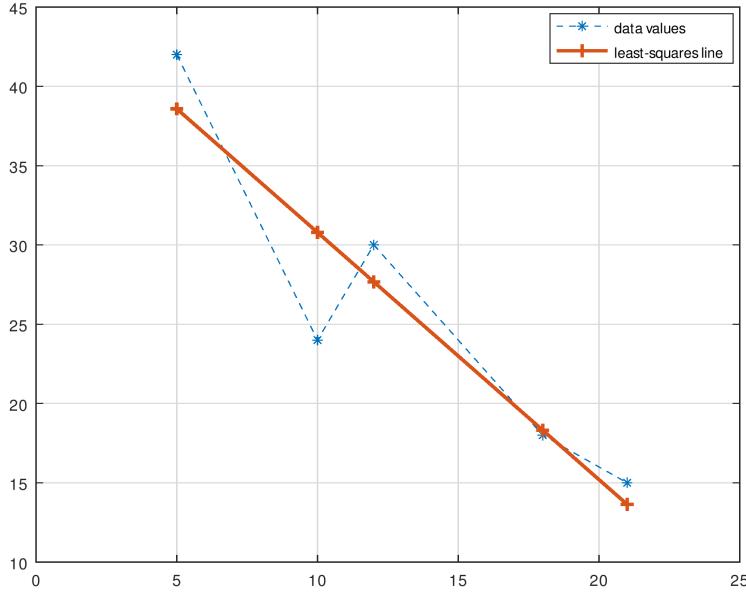


Figure 4.2: Regression line and original data

and  $\Sigma^+$  is the  $n \times m$  matrix found by transposing  $\Sigma$  and taking the reciprocals of the singular values:

$$\Sigma^+ = \begin{bmatrix} 1/\sigma_1 & & & & \vdots \\ & 1/\sigma_2 & & & 0 \\ & & \ddots & & \vdots \\ & & & 1/\sigma_r & \\ \dots & 0 & \dots & & 0 \end{bmatrix}$$

The matrix  $A^+$  is called the pseudoinverse or Moore-Penrose inverse of  $A$ .

**Example 4.4.4.** Consider the following sample data.

$x$	5	10	12	18	21
$y$	42	24	30	18	15

Find a linear equation of the form  $y = a + bx$  to model this data.

**Solution.** The given points give us a system  $A\mathbf{x} = \mathbf{b}$ , with

$$A = \begin{bmatrix} 1 & 5 \\ 1 & 10 \\ 1 & 12 \\ 1 & 18 \\ 1 & 21 \end{bmatrix}, \mathbf{x} = \begin{bmatrix} a \\ b \end{bmatrix}, \text{ and } \mathbf{b} = \begin{bmatrix} 42 \\ 24 \\ 30 \\ 18 \\ 15 \end{bmatrix}$$

First we need to find the SVD of  $A$ . From Octave,

```

>> [U S V] = svd(A)
U =

```

0.156839	0.767088	-0.427793	-0.340442	-0.296766
0.311700	0.407114	-0.027649	0.469589	0.718208
0.373645	0.263125	0.857417	-0.162313	-0.172178
0.559478	-0.168843	-0.189306	0.580804	-0.534141
0.652394	-0.384827	-0.212668	-0.547638	0.284878

```

S =

```

Diagonal Matrix

32.22136	0
0	0.88546
0	0
0	0
0	0

```

V =

```

0.063748	0.997966
0.997966	-0.063748

Next, we construct  $\Sigma^+$  by taking the transpose of  $\Sigma$  (called S in our Octave code) and the reciprocal of the nonzero entries:

$$\begin{aligned}\Sigma^+ &= \begin{bmatrix} 1/32.22136 & 0 & 0 & 0 & 0 \\ 0 & 1/0.88546 & 0 & 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} 0.031035 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.885459 & 0.000000 & 0.000000 & 0.000000 \end{bmatrix}\end{aligned}$$

After saving  $\Sigma^+$  as SP, the pseudoinverse,  $A^+$ , can be calculated as:

```

>> Aplus = V*SP*U'
Aplus =

```

0.864865	0.459460	0.297297	-0.189189	-0.432432
-0.050369	-0.019656	-0.007371	0.029484	0.047912

Thus the pseudoinverse is:

$$A^+ \approx \begin{bmatrix} 0.864865 & 0.459460 & 0.297297 & -0.189189 & -0.432432 \\ -0.050369 & -0.019656 & -0.007371 & 0.029484 & 0.047912 \end{bmatrix}$$

Finally, we are prepared to solve the original system of equations. The least-squares solution is simply  $A^+\mathbf{b}$ , easily computed in Octave. The (approximate) solution vector is  $\begin{bmatrix} 46.3784 \\ -1.5590 \end{bmatrix}$ . So, the correct linear equation is  $y = 46.3784 - 1.5590x$ . The original data and best-fitting line are shown in Figure 4.2.  $\square$

## 4.5 Gram-Schmidt and the QR algorithm

### 4.5.1 The Gram-Schmidt process

Let  $\mathbf{u}$  and  $\mathbf{v}$  be two linearly independent vectors. Then the vector  $\mathbf{u} - \text{proj}_{\mathbf{v}}(\mathbf{u})$  will be orthogonal to  $\mathbf{v}$ .

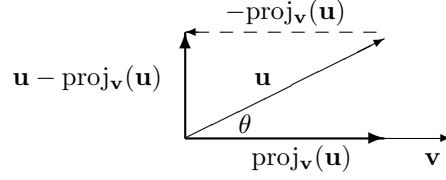


Figure 4.3: Orthogonal projection

Notice that the set  $\{\mathbf{v}, \mathbf{u} - \text{proj}_{\mathbf{v}}(\mathbf{u})\}$  is now an orthogonal set which has the same span as the original set  $\{\mathbf{v}, \mathbf{u}\}$ . This use of orthogonal projections to make a linearly independent set into an orthogonal set is the basis of the famous *Gram-Schmidt process*.

#### Theorem 4.5.1. THE GRAM-SCHMIDT PROCESS

Let  $\{\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_n\}$  be a linearly independent set. Then the following procedure will produce an orthogonal set  $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n\}$  with the same span.

$$\begin{aligned}\mathbf{v}_1 &= \mathbf{u}_1 \\ \mathbf{v}_2 &= \mathbf{u}_2 - \text{proj}_{\mathbf{v}_1}(\mathbf{u}_2) \\ \mathbf{v}_3 &= \mathbf{u}_3 - \text{proj}_{\mathbf{v}_1}(\mathbf{u}_3) - \text{proj}_{\mathbf{v}_2}(\mathbf{u}_3) \\ &\vdots \\ \mathbf{v}_n &= \mathbf{u}_n - \text{proj}_{\mathbf{v}_1}(\mathbf{u}_n) - \text{proj}_{\mathbf{v}_2}(\mathbf{u}_n) - \cdots - \text{proj}_{\mathbf{v}_{n-1}}(\mathbf{u}_n)\end{aligned}$$

To normalize, set

$$\mathbf{w}_i = \frac{\mathbf{v}_i}{\|\mathbf{v}_i\|}$$

Then the set  $\{\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_n\}$  is an orthonormal set with the same span as  $\{\mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_n\}$  and  $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n\}$ .

**Example 4.5.2.** Find an orthonormal set with the same span as

$$\{\langle 10, 9, -3, 0 \rangle, \langle -7, 7, -3, 4 \rangle, \langle 9, 1, -8, -1 \rangle\}$$

**Solution.** Since we are going to make extensive use of vector projections, it would be a good idea to write a function that handles that part of the computation. This can be entered at the command line, or better yet, it can be saved in a function file ‘proj.m’ and reused in future problems.

```
>> function vect = proj(u, v)
    vect = dot(u, v)/dot(v, v)*v;
end
```

As defined,  $\text{proj}(\mathbf{u}, \mathbf{v})$  now computes the projection of  $\mathbf{u}$  onto  $\mathbf{v}$ .

Now, we will enter the original set of vectors as columns in a matrix  $U$ .

```
>> U = [10 -7 9; 9 7 1; -3 -3 -8; 0 4 -1]
U =
10   -7    9
 9    7    1
-3   -3   -8
 0    4   -1
```

Next, we go through the steps of the Gram-Schmidt process to create a matrix  $V$  whose columns are an orthogonal set with the same span as the original set.

```
>> V = zeros(4, 3);
>> V(:, 1) = U(:, 1);
>> V(:, 2) = U(:, 2) - proj(U(:, 2), V(:, 1));
>> V(:, 3) = U(:, 3) - proj(U(:, 3), V(:, 1)) - proj(U(:, 3), V(:, 2))
V =
10.00000   -7.10526    0.37157
 9.00000    6.90526   -2.73222
-3.00000   -2.96842   -6.95810
 0.00000    4.00000    0.21304
```

These vectors are orthogonal, but not yet unit vectors, so we normalize. The final output matrix  $W$  should have columns that are orthogonal unit vectors with the same span as the original set.

```
>> W = zeros(4, 3);
>> W(:, 1) = V(:, 1)/norm(V(:, 1));
>> W(:, 2) = V(:, 2)/norm(V(:, 2));
>> W(:, 3) = V(:, 3)/norm(V(:, 3))
W =
 0.72548   -0.64071    0.04962
 0.65293    0.62268   -0.36490
-0.21764   -0.26768   -0.92929
 0.00000    0.36070    0.02845
```

The columns of  $W$  are the desired orthonormal set.  $\square$

We might want to verify that the process worked. As a spot check, we can look at the dot product of any two columns and we should get 0. Also, each column should have norm 1.

```
>> dot(W(:, 1), W(:, 3))
ans = 2.2204e-016
>> norm(W(:, 3))
ans = 1
```

Notice that the dot product is not quite zero due to rounding error, but the results are adequate for our purposes.

### 4.5.2 QR decomposition

We have already seen several important matrix factorizations. The Gram-Schmidt process is the key to another, one that turns out to provide a good means for finding eigenvalues numerically. This is known as the *QR decomposition*.

**Theorem 4.5.3.** *Let  $A$  be a nonsingular square matrix. Then there exists an orthogonal matrix  $Q$  and an upper triangular matrix  $R$  such that  $A = QR$ .*

Here's how to find  $Q$  and  $R$ .

1. Apply the Gram-Schmidt process to the columns of  $A$ . Use the resulting orthonormal vectors as columns of  $Q$ .

2. Let  $R = \begin{bmatrix} \mathbf{q}_1 \cdot \mathbf{a}_1 & \mathbf{q}_1 \cdot \mathbf{a}_2 & \mathbf{q}_1 \cdot \mathbf{a}_3 & \cdots & \mathbf{q}_1 \cdot \mathbf{a}_n \\ 0 & \mathbf{q}_2 \cdot \mathbf{a}_2 & \mathbf{q}_2 \cdot \mathbf{a}_3 & \cdots & \mathbf{q}_2 \cdot \mathbf{a}_n \\ 0 & 0 & \mathbf{q}_3 \cdot \mathbf{a}_3 & \cdots & \mathbf{q}_3 \cdot \mathbf{a}_n \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & \mathbf{q}_n \cdot \mathbf{a}_n \end{bmatrix}$ , where  $\mathbf{q}_i$  is the  $i$ th column of  $Q$  and  $\mathbf{a}_j$  is the  $j$ th column of  $A$ .

**Example 4.5.4.** Find the  $QR$  decomposition of the matrix  $A = \begin{bmatrix} 5 & 7 & 0 \\ 10 & 8 & 0 \\ 5 & 6 & -5 \end{bmatrix}$ .

**Solution.** First we apply the Gram-Schmidt process to  $A$ .

```
>> A = [5 7 0; 10 8 0; 5 6 -5]
A =
5    7    0
10   8    0
5    6   -5

>> Q = zeros(3, 3);
>> Q(:, 1) = A(:, 1)/norm(A(:, 1));
>> Q(:, 2) = A(:, 2) - proj(A(:, 2), Q(:, 1));
>> Q(:, 2) = Q(:, 2)/norm(Q(:, 2));
>> Q(:, 3) = A(:, 3) - proj(A(:, 3), Q(:, 1)) - proj(A(:, 3), Q(:, 2));
>> Q(:, 3) = Q(:, 3)/norm(Q(:, 3))
Q =
0.40825    0.72900    0.54944
0.81650   -0.56077    0.13736
0.40825    0.39254   -0.82416
```

Notice that we normalized each vector as we went through the process to find  $Q$ . Now, let's verify that  $Q$  is orthogonal. For an orthogonal matrix,  $Q^{-1} = Q^T$ , so a good way to check for orthogonality is to compute  $Q^T Q$ , which should be an identity matrix.

```
>> Q' *Q
ans =
1.00000 -0.00000 0.00000
-0.00000 1.00000 -0.00000
0.00000 -0.00000 1.00000
```

This looks correct (some round-off error can be seen if we check more digits than displayed here). Now, we build  $R$  using the appropriate dot products of columns of  $Q$  and  $A$ .

```
>> R = zeros(3, 3);
>> R(1, 1) = dot(Q(:, 1), A(:, 1));
>> R(1, 2) = dot(Q(:, 1), A(:, 2));
>> R(1, 3) = dot(Q(:, 1), A(:, 3));
>> R(2, 2) = dot(Q(:, 2), A(:, 2));
>> R(2, 3) = dot(Q(:, 2), A(:, 3));
>> R(3, 3) = dot(Q(:, 3), A(:, 3))
R =
12.24745 11.83920 -2.04124
0.00000 2.97209 -1.96270
0.00000 0.00000 4.12082
```

Of course, for a larger problem, we would use loops to compute the entries in  $R$ . Finally we check to see that  $QR = A$ .

```
>> Q*R
ans =
5.00000 7.00000 0.00000
10.00000 8.00000 0.00000
5.00000 6.00000 -5.00000
```

It works as expected. □

### 4.5.3 The QR algorithm

The  $QR$  decomposition is the basis of a numerical method for finding eigenvalues.

**Theorem 4.5.5. THE QR ALGORITHM**

Let  $A$  be an  $n \times n$  matrix with  $n$  real eigenvalues.

Set  $A_1 = A$ .

For each  $k = 1, 2, 3, \dots$  do the following:

- (i) Find the  $QR$  decomposition of  $A_k$ ,  $A_k = Q_k R_k$ .
- (ii) Set  $A_{k+1} = R_k Q_k$ .

Repeat steps (i) and (ii).

As  $k$  increases, the matrices  $A_k$  approach an upper triangular form with the eigenvalues of  $A$  on the diagonal.

**Example 4.5.6.** Apply three iterations of the QR algorithm to the matrix  $A = \begin{bmatrix} 5 & 7 & 0 \\ 10 & 8 & 0 \\ 5 & 6 & -5 \end{bmatrix}$ .

**Solution.** We will use the built-in QR-decomposition function,  $[Q R] = \text{qr}(A)$ .

```
>> A1 = A
A1 =
      5    7    0
     10   8    0
      5    6   -5

>> [Q1 R1] = qr(A1);
>> A2 = R1*Q1
A2 =
      13.8333   -1.4881   10.0378
     -1.6254   -2.4371   -2.0258
      1.6823   -1.6176   -3.3962

>> [Q2 R2] = qr(A2);
>> A3 = R2*Q2
A3 =
      15.159187   4.145301   -6.805968
     -0.013431   -4.054621   1.168669
      0.430485   1.750645   -3.104566

>> [Q3 R3] = qr(A3);
>> A4 = R3*Q3
A4 =
      14.959822   6.640881   5.216123
      0.065351   -4.860028   -0.375929
      0.064287   -0.846029   -2.099794
```

It turns out that the correct eigenvalues of  $A$  are 15, -5, and -2. These values are already evident on the diagonal after only three iterations.  $\square$

It is a simple matter to codify the algorithm into a loop, which allows easily running a large number of iterations. This is left as an exercise for the reader (see Exercise 10).

## Chapter 4 Exercises

1. Let  $A = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & 2 & 4 \end{bmatrix}$ ,  $B = \begin{bmatrix} 2 & -2 & 1 \\ 1 & -1 & 1 \\ -3 & 2 & -2 \end{bmatrix}$ , and  $C = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 2 \end{bmatrix}$ .

For each matrix, do the following:

- (a) Find the eigenvalues and eigenvectors by-hand. First give the infinite set of eigenvectors for each eigenvalue, then choose representative eigenvectors with integer (or Gaussian integer) components for each eigenvalue.
  - (b) Use Octave to find the eigenvalues and eigenvectors. Compare the Octave solution to your by-hand solution.
  - (c) How many linearly independent eigenvectors does the matrix have?
2. Suppose a hypothetical state is divided into four regions, A, B, C, and D. Each year, a certain number of people will move from one region to another, changing the population distribution. The initial populations are given below:

Region	Population
A	719
B	910
C	772
D	807

The following table records how the population moved in one year.

		To			
		A	B	C	D
From	A	624	79	2	14
	B	79	670	70	91
C	52	6	623	91	
D	77	20	58	652	

For example, we see that A began with  $624 + 79 + 2 + 14 = 719$  residents. Of these, 624 stayed in A, 79 moved to B, 2 moved to C, and 14 moved to D. From this empirical data, we can give approximate probabilities for moving from A. Of the 719 residents, 624 stayed in A, so the probability of ‘moving’ from A to A is  $624/719 = 0.8678720$ . The probability of moving from A to B is  $79/719 = 0.1098748$ , and so on.

- (a) Find the transition matrix  $T$  for this Markov chain. This is done by converting each entry in the table above to a probability, then transposing.
- (b) Express the initial population distribution as a probability vector  $\mathbf{x}$ . Remember, the components must add to 1.
- (c) Find the population distribution (expressed as percentages) in 5 years and in 10 years.
- (d) Compute the eigenvalues and eigenvectors for  $T$  and use the eigenvector for  $\lambda = 1$  to construct an equilibrium vector  $\mathbf{q}$  for this Markov chain. This represents a population distribution for which there is no further change from year to year. Verify that the distribution is in equilibrium by computing several future states, such as  $T^{25}\mathbf{q}$  and  $T^{50}\mathbf{q}$ . Is there any change in the distribution?

3. Which of the matrices in Exercise 1 can be diagonalized? For each matrix, give a diagonalization if possible, or explain why no diagonalization is possible.
4. Diagonalize the matrix  $A = \begin{bmatrix} 1 & 4 \\ 1 & -2 \end{bmatrix}$  as  $A = S\Lambda S^{-1}$  and use this to calculate  $A^{50}$ . Show all the steps needed to find the eigenvalues, eigenvectors, etc.
5. Orthogonally diagonalize the symmetric matrix  $A = \begin{bmatrix} 1 & 1 & 3 \\ 1 & 1 & 3 \\ 3 & 3 & 9 \end{bmatrix}$ . Verify that  $A = Q\Lambda Q^T$  and show that  $Q$  is orthogonal by verifying that  $QQ^T = Q^TQ = I$ . (Note: solving this problem by-hand requires the Gram-Schmidt process.)
6. Find the SVD of the matrix  $\begin{bmatrix} 2 & 3 \\ 0 & 2 \end{bmatrix}$  without using the `svd` command. Show all the steps needed to find the eigenvalues, eigenvectors, etc. Verify that  $A = U\Sigma V^T$ .
7. Use the pseudoinverse to find the least-squares line  $y = a + bx$  through the given set of points.

$$\{(-1, 5), (1, 4), (2, 2.5), (3, 0)\}$$

You may use the `svd` command, but show all the rest of the details, including construction of the pseudoinverse. Include a plot of the data values and the least-squares line.

8. Write an Octave script that takes a matrix  $U$  with linearly independent columns and outputs a matrix  $V$  with orthonormal columns. The core loop could look like this (or use your own formulation):

```

V(:, 1) = U(:, 1)/norm(U(:, 1));
for i = 2:n
    V(:, i) = U(:, i);
    for j = 1:i-1
        V(:, i) = V(:, i) - proj(U(:, i), V(:, j));
    end
    V(:, i) = V(:, i)/norm(V(:, i));
end

```

You will need to determine  $m$  and  $n$  and from the dimensions of  $U$  and the function `proj(u,v)` must be defined. Test your code on the vectors from Example 4.5.2.

9. Use your code from Exercise 8 as the starting point of a script file that computes the  $QR$  decomposition of an  $n \times n$  matrix  $A$ . Test your script on a randomly generated  $4 \times 4$  matrix,  $A = \text{rand}(4,4)$ . Check  $Q$  for orthogonality by computing  $Q^TQ$ , which should be an identity matrix, and verify that  $A = QR$ .
10. Using Octave's built-in  $[Q R] = \text{qr}(A)$  function for the  $QR$  decomposition, write a loop (at the command line or in a script file) that will approximate the eigenvalues of the matrix  $A = \begin{bmatrix} 1 & -1 & 2 \\ -1 & 1 & -2 \\ 2 & -2 & 0 \end{bmatrix}$ . Run your loop through ten iterations. The actual eigenvalues are integers. Were you able to determine the correct values from the  $QR$  algorithm?

# Chapter 5

## Additional topics

### 5.1 Three dimensional graphs

#### 5.1.1 Space curves

Plotting a curve in 3-dimensions is similar to the 2-dimensional plotting explained in Section 1.4. To plot space curves, we use the command `plot3(x, y, z)`, where  $x$ ,  $y$ , and  $z$  correspond to the parametric equations for the function. For example, let's plot a simple helix, with vector equation  $\mathbf{r}(t) = \sin(t)\mathbf{i} + \cos(t)\mathbf{j} + t\mathbf{k}$ . First we generate a row vector for the parameter  $t$ , then we calculate the range for  $x$ ,  $y$ , and  $z$ .

```
>> t = linspace(0, 2*pi, 30);
>> x = sin(t);
>> y = cos(t);
>> z = t;
>> plot3(x, y, z)
```

The graph is shown in Figure 5.1.

Now consider a more complicated curve, like

$$x = (5 + \sin 25t) \cos t, \quad y = (5 + \sin 25t) \sin t, \quad z = \cos 25t$$

This is a ‘toroidal spiral.’ We will need to use a much finer increment for  $t$  to get a smooth picture.

```
>> t = linspace(0, 2*pi, 500);
>> x = (5 + sin(25*t)).*cos(t);
>> y = (5 + sin(25*t)).*sin(t);
>> z = cos(25*t);
>> plot3(x, y, z)
```

These types of graphs are not easy to draw without a computer! See Figure 5.2.

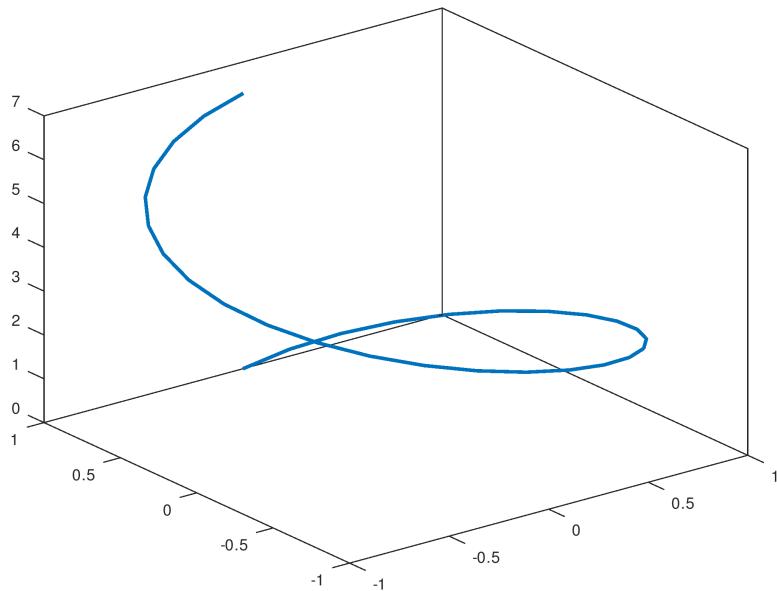


Figure 5.1: Helix

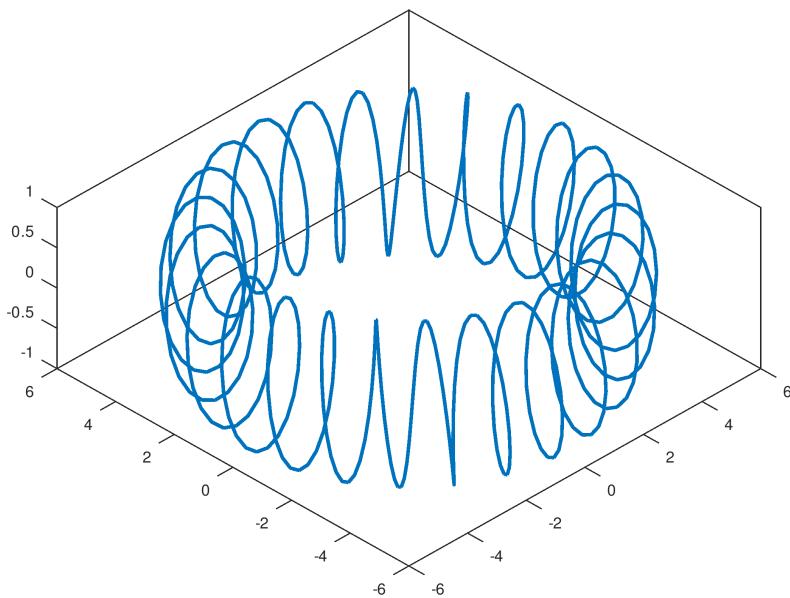


Figure 5.2: Toroidal spiral

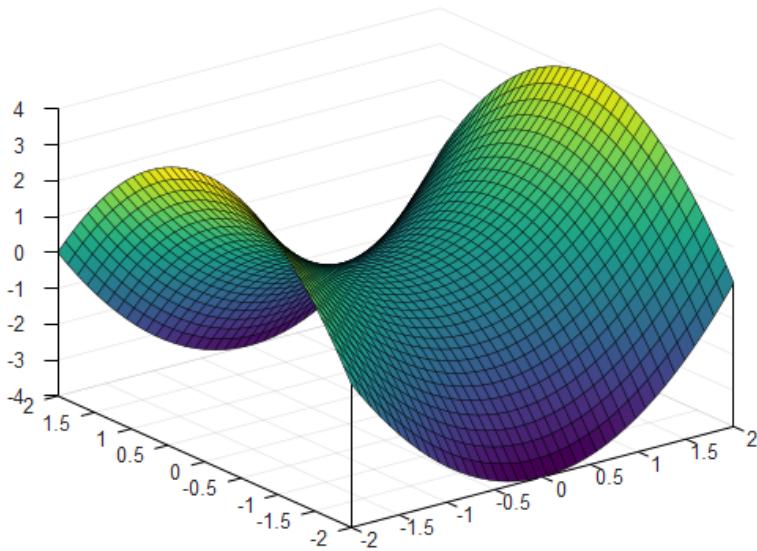


Figure 5.3: Saddle surface

### 5.1.2 Surfaces

How about plotting surfaces rather than curves? In this case, we use a two-dimensional ‘mesh’ of input values and calculate the range using a function of two variables. For example, let’s graph the familiar saddle surface shown in Figure 5.3, defined by:

$$f(x, y) = x^2 - y^2$$

First we define the domain.

```
>> x = linspace(-2, 2, 40);
>> y = linspace(-2, 2, 40);
```

Then, we use the `meshgrid` command to create a mesh of all possible combinations of  $x$  and  $y$  in the domain.

```
>> [X Y] = meshgrid(x, y);
```

Now calculate the range using these `meshgrid` variables.

```
>> Z = X.^2 - Y.^2;
```

Finally, we can plot the surface with the `surf` command.

```
>> surf(X, Y, Z)
```

Notice that the graph is color coded by elevation. The color map and many other settings can be modified as needed. The graph can be rotated in space by clicking and dragging with the

mouse. To see the graph of the mesh without the surface filled in, use `mesh(X, Y, Z)`. Also try `contour(X, Y, Z)` to see a contour plot of the surface.

We can use similar steps to plot surfaces defined parametrically, or surfaces defined in terms of polar/cylindrical or spherical coordinates.

**Example 5.1.1.** The function

$$\rho = 1 + \frac{1}{4} \sin(5\phi) \cos(6\theta), 0 \leq \theta \leq 2\pi, 0 \leq \phi \leq \pi$$

in spherical coordinates is known as a bumpy sphere. Graph this function.

**Solution.** We use a  $(\theta, \phi)$ -meshgrid to calculate  $\rho$ . Then we can calculate  $X$ ,  $Y$ , and  $Z$  using the standard spherical to rectangular coordinate identities.

```
>> % define phi (P) and theta (T)
>> theta = linspace(0, 2*pi, 30);
>> phi = linspace(0, pi, 30);
>> [T P] = meshgrid(theta, phi);

>> % calculate rho (R)
>> R = 1 + 1/4 * sin(5*P) .* cos(6*T);

>> % use spherical identities for X, Y, Z
>> X = R.*sin(P).*cos(T);
>> Y = R.*sin(P).*sin(T);
>> Z = R.*cos(P);

>> % plot the surface
>> surf(X, Y, Z)
```

The graph is shown in Figure 5.4. □

### 5.1.3 Solids of revolution

Solids of revolution can be graphed as parametrically defined surfaces. For example, parametric equations for the surface formed by rotating the graph of  $y = f(x)$  about the  $x$ -axis,  $a \leq x \leq b$  are:

$$x = x \tag{5.1}$$

$$y = f(x) \cos(t) \tag{5.2}$$

$$z = f(x) \sin(t) \tag{5.3}$$

where  $0 \leq t \leq 2\pi$  and  $a \leq x \leq b$ .

Equations 5.1–5.3 can be modified as needed to produce rotations around the other axes.

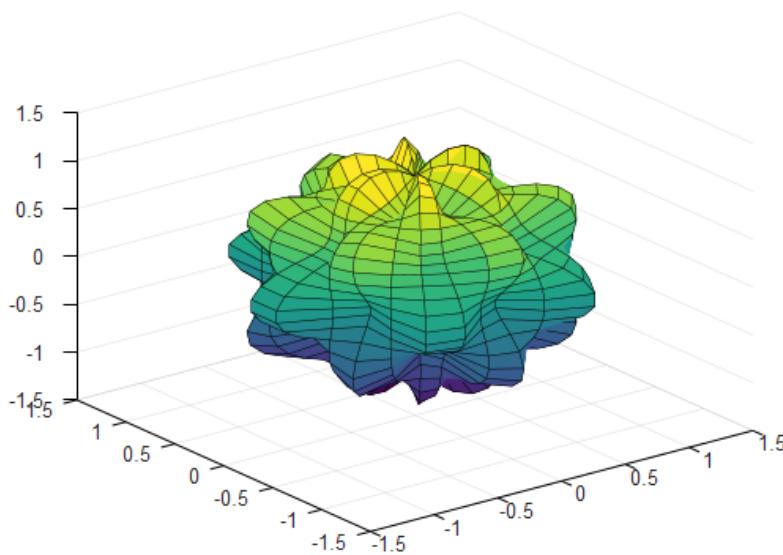


Figure 5.4: Bumpy sphere

**Example 5.1.2.** Graph the solid obtained by rotating  $f(x) = x^2 - 4x + 5$ , for  $1 \leq x \leq 4$ , about the  $x$ -axis.

**Solution.** These commands will graph the surface.

```
>> x = linspace(1, 4, 25);      % define the domain
>> f = @(x) x.^2 - 4*x + 5;    % define the function
>> t = linspace(0, 2*pi, 25);   % define the parameter
>> [X T] = meshgrid(x, t);     % (x, t)-mesh
>> Y = f(X).*cos(T);          % calculate Y
>> Z = f(X).*sin(T);          % calculate Z
>> surf(X, Y, Z)              % graph surface
```

The result is in Figure 5.5. □

## 5.2 Multiple integrals

We showed methods for evaluating single integrals numerically in Chapter 3. We now consider multiple integrals. The commands `dblquad` and `triplequad` can be used to evaluate double and triple integrals over a rectangle or rectangular box.

For example, let's evaluate:

$$\int_{-1}^3 \int_0^2 (x^2y + 2y) \, dx \, dy$$

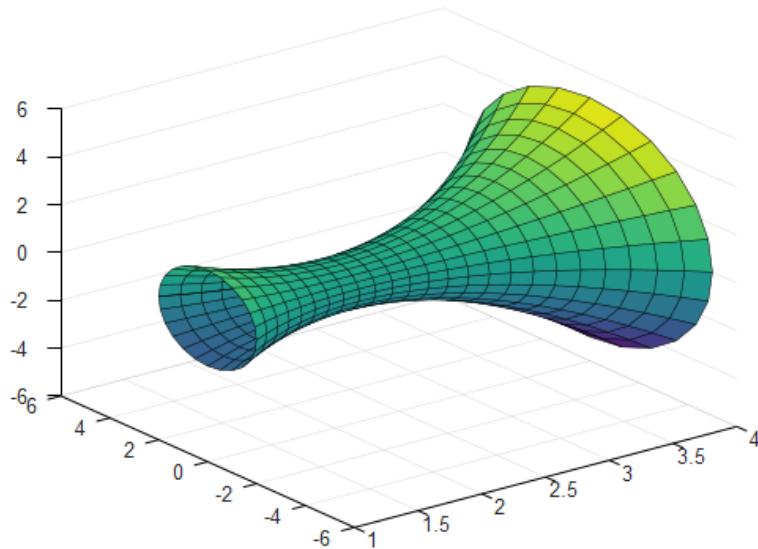


Figure 5.5: Solid of revolution

```

>> % double integral using dblquad
>> function z = f(x, y)
    z = x.^2.*y + 2*y;
end
>> dblquad('f', 0, 2, -1, 3)
ans = 26.667

```

Evaluating over a nonrectangular domain is a trickier problem. Let's give it a try.

**Example 5.2.1.** Evaluate

$$\iint_R (x^2y + y^2x) \, dA$$

over the region  $R$  bounded by the graphs of  $y = x^2$  and  $y = \sqrt{x}$ .

**Solution.** An analysis of the region of integration (Figure 5.6) shows that we need to evaluate the following integral:

$$\int_0^1 \int_{x^2}^{\sqrt{x}} (x^2y + y^2x) \, dy \, dx$$

We need to evaluate over only part of the rectangle  $[0, 1] \times [0, 1]$ . One approach is to define the integrand to be 0 for values outside of the region of integration. We do this using *logical functions*. Logical functions simply test whether a statement is true and return a value of 1 if true or 0 if false. For example  $2 + 3 < 4$  returns 0, since the inequality is false. We can also use Boolean operators, like `and` and `or`. Our region demands that we meet two conditions:

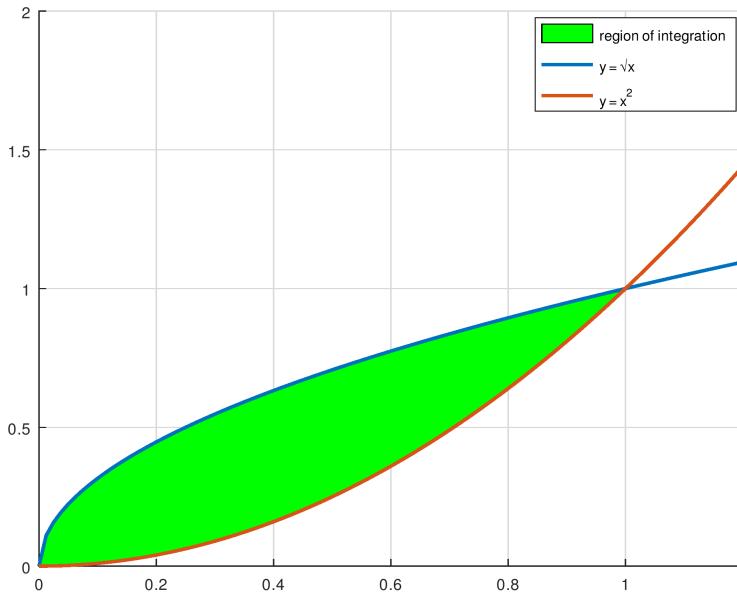


Figure 5.6: Region of integration for Example 5.2.1

$y > x^2$  and  $y < \sqrt{x}$ , so we use these conditions to define the function. By multiplying the integrand by the correct logical operator, it is set to 0 outside the region of interest.

```
>> % double integral over a nonrectangular domain
>> function z = f(x, y)
    z = (x.^2.*y + y.^2.*x) .* ((y > x.^2) & (y < sqrt(x)));
end
>> dblquad('f', 0, 1, 0, 1)
ans = 0.10701
```

Thus  $\int_0^1 \int_{x^2}^{\sqrt{x}} (x^2y + y^2x) dx dy \approx 0.10701$ . This is reasonably close to the exact value of  $3/28$ , but not in perfect agreement. The problem is that we have defined  $f$  as a discontinuous function (see Figure 5.7), but the quadrature algorithm works best on a smooth integrand.  $\square$

The approach in Example 5.2.1 is nice for two reasons: it illustrates the formal definition of a double Riemann integral over a nonrectangular domain (see [7, §5.2]), and it also allows us to plot the surface over the region of interest (Figure 5.7).

```
>> x = linspace(0, 1, 30);
>> y = x;
>> [X Y] = meshgrid(x, y);
>> Z = f(X, Y);
>> surf(X, Y, Z)
```

If we are unsatisfied with the numerical accuracy of this method for the double integral, another

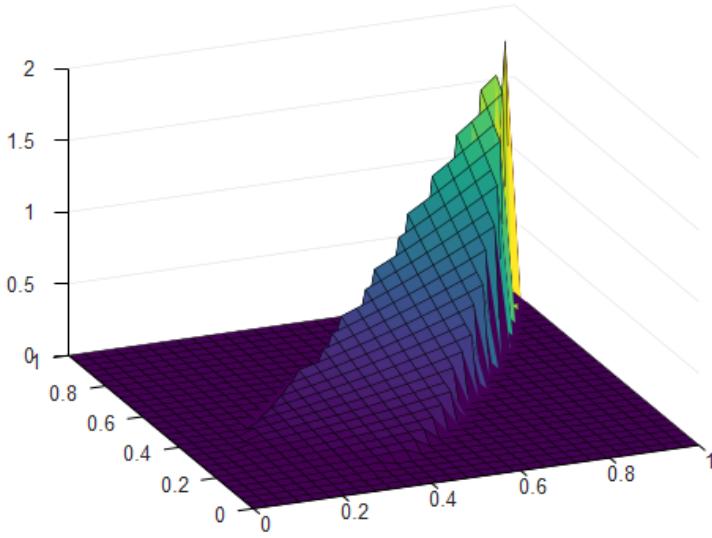


Figure 5.7: Solid volume for Example 5.2.1

approach is to use a change of variables to transform to a rectangular region of integration as follows:

$$y = y_1 + u(y_2 - y_1) \quad (5.4)$$

$$dy = (y_2 - y_1) du \quad (5.5)$$

Then as  $y$  ranges from  $y_1$  to  $y_2$ ,  $u$  ranges from 0 to 1 and the integrand becomes:

$$\int_{x_1}^{x_2} \int_{y_1}^{y_2} f(x, y) dy dx = \int_{x_1}^{x_2} \int_0^1 f(x, y_1 + u(y_2 - y_1))(y_2 - y_1) du dx \quad (5.6)$$

This is a bit cumbersome to enter in Octave. We'll use a series of *anonymous functions* (see page 37) to define the integrand, then try `dblquad` again.

**Example 5.2.2.** Use the change of variable formulas in Equations 5.4–5.6 to evaluate

$$\int_0^1 \int_{x^2}^{\sqrt{x}} (x^2 y + y^2 x) dy dx$$

### Solution.

```
>> f1 = @(x, y) x.^2.*y + y.^2.*x;
>> y1 = @(x) x.^2;
>> y2 = @(x) sqrt(x);
>> f2 = @(x, u) f1(x, y1(x) + u.* (y2(x) - y1(x))) .* (y2(x) - y1(x));
```

```

>> format long
>> dblquad(f2, 0, 1, 0, 1) % no quotes around anonymous function name
ans = 0.107142857143983
>> 3/28 % compare result to known exact answer
ans = 0.107142857142857

```

This approach gives a more satisfactory result.  $\square$

If one wishes to evaluate many integrals of this form, writing a *function file* to automate the above steps would be a good idea.

**Example 5.2.3.** Write an Octave function file that computes

$$\iint_R f(x, y) dA$$

over the region  $R$  bounded by the graphs of  $y = y_1(x)$ ,  $y = y_2(x)$ ,  $x = a$ , and  $x = b$ , using the change of variables in Equations 5.4–5.6.

**Solution.** A function file is similar to script: it is a plain text .m-file containing a series of Octave commands. To be recognized as a function file, the first line of code (excluding comments and white space) must be **function**. With the file placed in the load path, it can be run from the command line like any other Octave function. The function name should match the file name. A well written function file will include details like help text and provisions for error checking. Refer to [3]. We will give a minimal example that accomplishes our change of variables procedure.

---

#### Octave Script 5.1: Double integral function file

---

```

1 % function file 'dblint.m'
2 % evaluates dblquad(f, x1, x2, y1, y2)
3 % where f is an anonymous function of x and y
4 % y1 and y2 are anonymous functions of x
5 % x1 and x2 are real numbers
6
7 function val = dblint(f, x1, x2, y1, y2)
8     f2 = @(x, u) f(x, y1(x) + u.* (y2(x) - y1(x))) .* (y2(x) - y1(x));
9     val = dblquad(f2, x1, x2, 0, 1);
10 end

```

---

Note that the comment lines at the top of our function file will be displayed if we type **help dblint**. Thus we should strive to put a good description of the syntax in those lines. Now, to use this function, saved in our working directory as ‘dblint.m,’ we need to define the integrand, and the functions representing the limits of integration on  $y$ . Then we pass these to our function dblint. Let’s try it on the integral from Example 5.2.1.

```

>> f = @(x, y) x.^2.*y + y.^2.*x;
>> y1 = @(x) x.^2;
>> y2 = @(x) sqrt(x);
>> dblint(f, 0, 1, y1, y2)
ans = 0.10714

```

It works!  $\square$

### 5.2.1 Double Riemann sums

Suppose we want to write our own algorithms for double integration. It is straightforward to write an Octave script that will estimate a double integral over a rectangle using a double Riemann sum, taking sample points to be the upper right hand corners of the subrectangles in the partition. For our example, we'll use the function  $f(x, y) = x + 2y^2$ , defined on  $R = [0, 2] \times [0, 4]$ , using  $m = n = 1000$ . Use the following code.

Octave Script 5.2: Nested loop double integral

---

```

1 % approximates a double integral using upper right hand corners of
2 % subrectangles as sample points
3 % —nested loop version
4
5 clear
6
7 % define function
8 function z = f(x, y)
9     z = x + 2*y.^2;
10 end
11
12 % define region of integration
13 a = 0;
14 b = 2;
15 c = 0;
16 d = 4;
17
18 % define partition
19 m = 1000
20 n = 1000
21
22 % calculate dA and initialize Riemann sum total
23 dx = (b - a)/m
24 dy = (d - c)/n
25 dA = dx*dy;
26 rsum = 0;
27
28 % compute double Riemann sum
29 for i = 1:m
30     for j = 1:n
31         rsum = rsum + dA *f(a + dx*i, c + dy*j);
32     end
33 end
34
35 % display result
36 rsum

```

---

This gives an estimate of 93.469, reasonably close to the correct value of 93.333. However, the script is very slow, due to the inefficiency of running the calculation via nested loops. Notice that the program needs to compute one million function values in this example! The routine can be sped up dramatically by using vectorized code, which takes advantage of Octave's fast algorithms for executing matrix and vector calculations. The new strategy is to generate a

meshgrid array of the sample points, then that can be used to define an  $m \times n$  matrix containing the function values at the sample points. Then the Riemann sum is simply  $dA$  times the sum of all entries in the matrix. This runs MUCH faster!

---

Octave Script 5.3: Vectorized double integral

---

```

1 % approximates a double integral using upper right hand corners of
2 % subrectangles as sample points
3 % --vectorized version
4
5 clear
6
7 % define function
8 function z = f(x, y)
9     z = x + 2*y.^2;
10 end
11
12 % define region of integration
13 a = 0;
14 b = 2;
15 c = 0;
16 d = 4;
17
18 % define partition
19 m = 1000
20 n = 1000
21
22 % calculate dA
23 dx = (b - a)/m
24 dy = (d - c)/n
25 dA = dx*dy;
26
27 % calculate x and y values in partition
28 x = [a + dx : dx : b];
29 y = [c + dy : dy : d];
30
31 % create matrix of function values
32 [X Y] = meshgrid(x, y);
33 A = f(X, Y);
34
35 % calculate Riemann sum
36 rsum = dA*sum(sum(A))

```

---

While this executes significantly faster, it is still not particularly accurate, considering the rather large values for  $m$  and  $n$ . The problem is that taking the upper right hand corners as sample points generally does not give the best estimate. The code can easily be improved by taking sample points at the midpoints of each rectangle. This minor adjustment is left as an exercise for the reader (see Exercise 7).

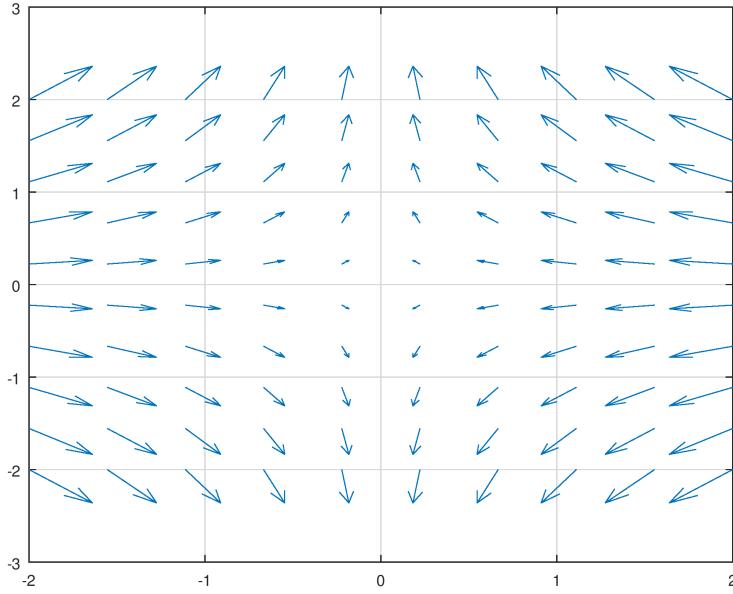


Figure 5.8: Vector field plot

### 5.3 Vector fields

A *vector field* assigns vectors to points in space. Vector fields are used to describe things like wind speed, fluid flow, electric charge, or gravitational force. A vector field is conveniently visualized by drawing a directed line segment for a series of representative points in the space. As any archer knows, a collection of arrows is called a *quiver*. Thus the command for plotting a vector field is `quiver`. The simplest form of the command is `quiver(X, Y, U, V)`, where  $X$  and  $Y$  are meshgrid variables over which the field is plotted and  $U$  and  $V$  are the  $x$ - and  $y$ -components, respectively.

**Example 5.3.1.** Graph the vector field  $\mathbf{F}(x, y) = \langle -x, y \rangle$ .

**Solution.**

```
>> x = linspace(-2, 2, 10);
>> y = x;
>> [X Y] = meshgrid(x, y);
>> quiver(X, Y, -X, Y);
>> grid on
```

See Figure 5.8. Some experimentation may be needed to determine the correct grid spacing. Too many points will result in an array of vectors too dense to interpret.  $\square$

We can also plot vector fields in three dimensions with `quiver3` or add a vector field plot to the contour graph of a surface. We will illustrate these ideas with two more examples.

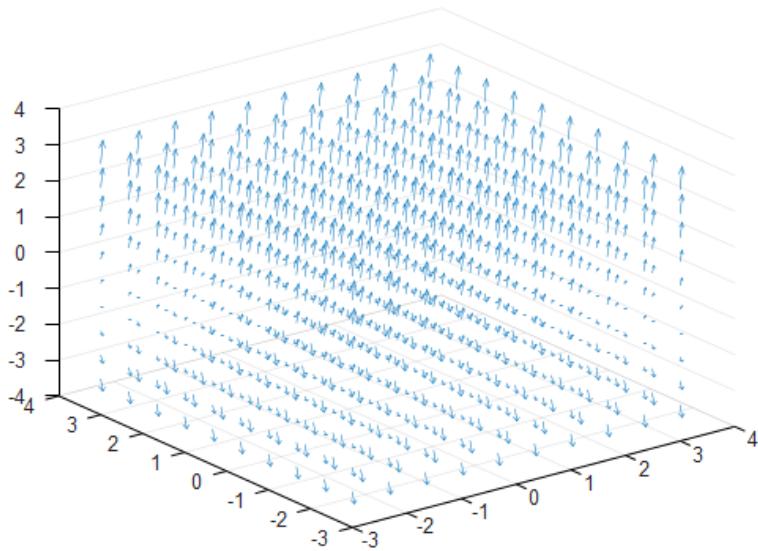


Figure 5.9: Three dimensional vector field

**Example 5.3.2.** Plot the vector field  $\mathbf{F}(x, y, z) = \langle 1, 1, z \rangle$ .

**Solution.**

```
>> x = linspace(-3, 3, 10);
>> y = x;
>> z = x;
>> [X Y Z] = meshgrid(x, y, z);
>> quiver3(X, Y, Z, ones(size(X)), ones(size(Y)), Z)
```

Note the use of the `ones` command to produce the constant terms. The result is in Figure 5.9. □

**Example 5.3.3.** Graph a contour plot of the Octave function “peaks” and its gradient field.

**Solution.** The command `peaks` plots an example graph of a surface with a number of maximums and minimums. Type `help peaks` for details, or just `peaks` to see the graph. It will be instructive to see its contours plotted together with its gradient field. We can use the built-in `gradient` function.

```
>> [X Y Z] = peaks;
>> [DX DY] = gradient(Z);
>> contour(X, Y, Z)
>> hold on
>> quiver(X, Y, DX, DY)
>> axis([-2 2 -2 2])
>> hold off
```

See the results in Figure 5.10. □

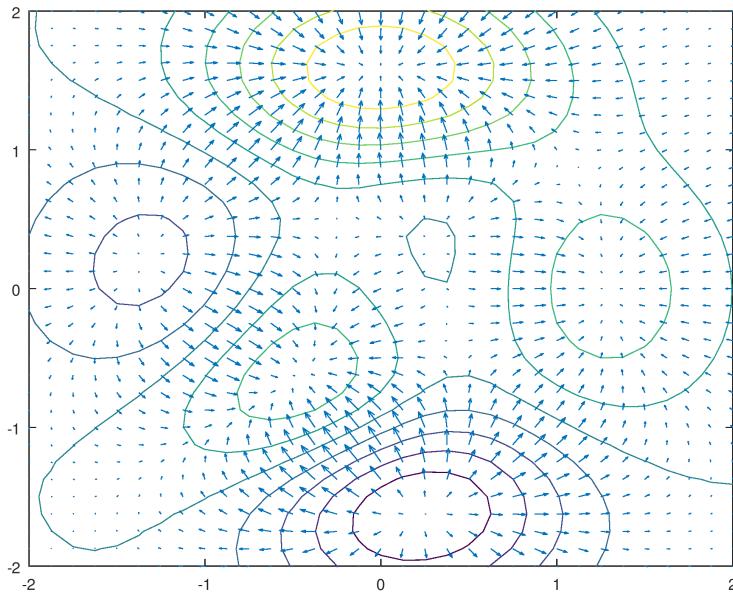


Figure 5.10: Gradient field

## 5.4 Statistics

Octave has good capabilities for statistical analysis. We'll start with something simple. Let's try rolling a six-sided die:

```
>> floor(6*rand + 1)
ans = 6 % the answer is random – your results will vary!
```

Now let's try repeating the experiment 100 times, storing the results in a column vector. We can analyze the results by looking at the sample mean, variance, and a histogram.

```
>> A = floor(6*rand(100, 1) + 1);
>> mean(A)
ans = 3.4100
>> var(A)
ans = 2.9514
>> hist(A, [1 2 3 4 5 6])
```

Your results will vary, but you should see something that looks close to a uniform distribution, such as in Figure 5.11. The vector [1 2 3 4 5 6] specifies the midpoints of the bins.

Now, let's use a loop to generate a distribution of 100 sample means.

```
>> for i = 1:100
    A = floor(6*rand(100, 1) + 1);
    d(i) = mean(A);
end
>> hist(d)
```

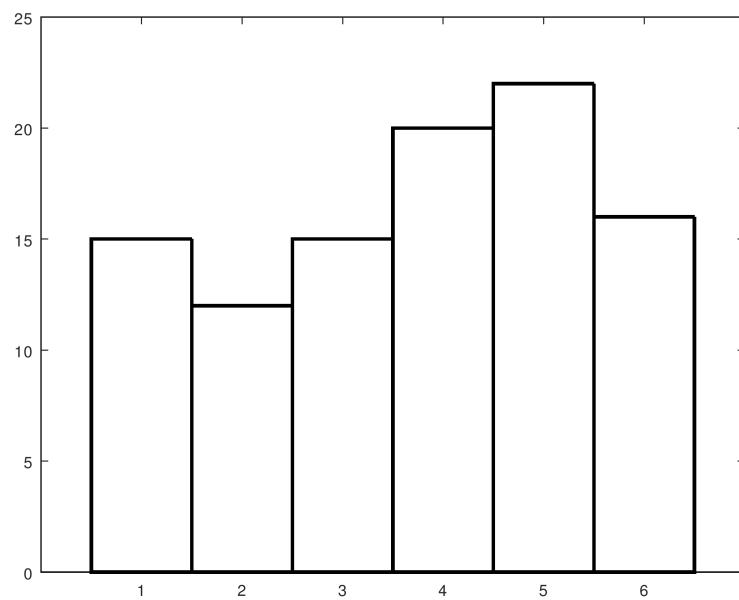


Figure 5.11: Results from 100 6-sided die trials

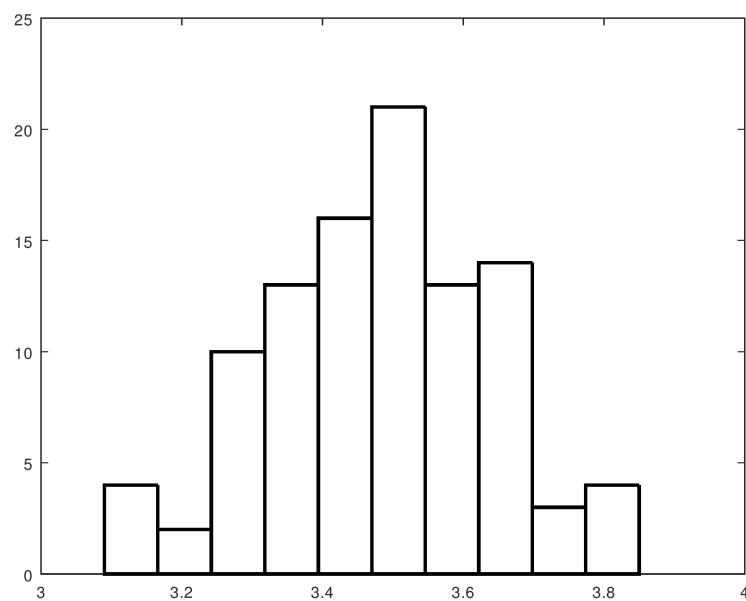


Figure 5.12: Distribution of sample means

Notice that the distribution of the sample means is approximately normal (Figure 5.12), even though the underlying distribution is not. We have just demonstrated the Central Limit Theorem!

We have seen that the `rand` function corresponds to a uniform distribution. Octave has other distributions built-in. For example, the function `randn` returns a matrix with normally distributed elements with mean 0 and standard deviation 1.

**Example 5.4.1.** Create a vector  $Z$  of 1000 elements from the standard normal distribution. Use the transformation  $X = Z\sigma + \mu$  to generate a vector  $X$  of elements from a normal distribution with mean 400 and standard deviation 50. Compare the means and variances of  $X$  and  $Z$ . Plot histograms of  $Z$  and  $X$ .

**Solution.** Here are the commands we need:

```
>> Z = randn(1000, 1);
>> mu = 400;
>> sigma = 50;
>> X = Z*sigma + mu;
>> format free;
>> means = mean([Z X])
means =
-0.00116119    399.942

>> variances = var([Z X])
variances =
1.04291    2607.28

>> hist(Z)
>> hist(X)
```

The command `format free` changes from the default short form scientific notation, which makes it a bit easier to compare the means and variances, in this case. We can see  $Z$  has mean and variance near 0 and 1, respectively, while  $X$  has a mean near 400 and variance near 2500, as expected. The histograms are identical, except for the scale on the horizontal axis (see, for example, Figure 5.13).  $\square$

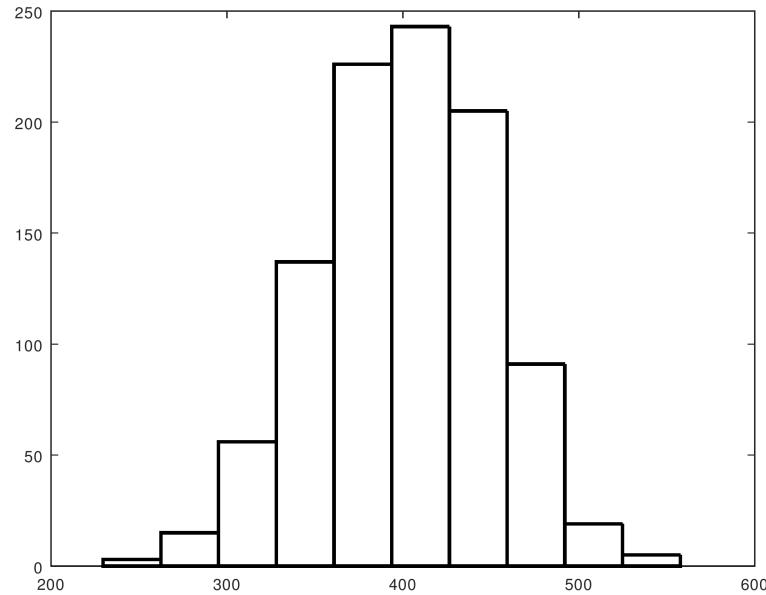
Octave can handle many other statistical functions. As a final example, we will consider a simple hypothesis test. See [2] for background on the basic theory of statistical tests. To perform a  $t$ -test, you will need to load the *statistics* package, which provides access to many additional tests and distributions.

**Example 5.4.2.** Consider the following set of sample data (from a normally distributed population):

$$\{24.9, 22.8, 16.2, 10.8, 32.0, 19.2\}$$

Test the following hypotheses at significance level  $\alpha = 0.01$ :

$$\begin{aligned} H_0 : \mu &= 30 \\ H_a : \mu &< 30 \end{aligned}$$

Figure 5.13:  $X$ -distribution

**Solution.** Enter the data and calculate the mean.

```
>> x = [24.9 22.8 16.2 10.8 32.0 19.2] '
x =
24.900
22.800
16.200
10.800
32.000
19.200

>> mean(x)
ans = 20.983
```

Is  $\bar{x} = 20.983$  good evidence that  $\mu < 30$ ? We can use the `ttest` command. The basic format is `ttest(X, mu)`, which will return 1 if the null hypothesis is rejected, 0 otherwise. The default options are for a two-tailed test using significance level  $\alpha = 0.05$ . Options are set using name-value string pairs. We need to specify a left-tailed test and set the significance level. Additional output values are possible. We will ask for both the conclusion and the  $P$ -value:

```
>> pkg load statistics
>> [h pval] = ttest(x, 30, 'tail', 'left', 'alpha', 0.01);
h = 0
pval = 0.014932
```

We can see that the  $P$ -value is greater than  $\alpha$  and we fail to reject the null hypothesis.  $\square$

## 5.5 Differential equations

### 5.5.1 Slope fields

The `quiver` function we used to plot vector fields in Section 5.3 can also be used to plot the slope field of a differential equation. The key is recognizing that a differential equation of the form  $dy/dx = f(x, y)$  is a function that gives us slopes, which we can interpret as vectors. This will be illustrated with a simple example.

**Example 5.5.1.** Plot the slope field along with several solutions of the differential equation

$$\frac{dy}{dx} = x$$

**Solution.** The solution is  $y = \frac{1}{2}x^2 + C$ . For differential equations that cannot be solved so easily, plotting the slope field can be used to get a sense of the solutions. In this example, since we know the solution, we can show how the solutions follow the slope field.

We need to define the input range as a meshgrid, define the function, then use the function to calculate slopes. To get a good looking graph, we then scale these slope vectors to a unit length. Finally, we plot some solutions for different values of  $C$ .

```
>> % define input values
>> x = linspace(-5, 5, 30);
>> y = x;
>> [X Y] = meshgrid(x, y);

>> % define function
>> f = @(x, y) x;

>> % delta-y, relative to 1 unit delta-x
>> dY = f(X, Y);
>> dX = ones(size(dY));

>> % factor to scale to unit length
>> L = sqrt(1 + dY.^2);

>> % plot the field
>> quiver(X, Y, dX./L, dY./L, 0.5) % scaling factor 0.5
>> axis([-4 4 -4 4])
>> grid on
>> xlabel('x')
>> ylabel('y')

>> % add some particular solutions to graph for comparison
>> hold on
>> for C = -4:3
>>     plot(x, 0.5*x.^2 + C, 'r', 'linewidth', 2)
>> end
```

The results are shown in Figure 5.14. □

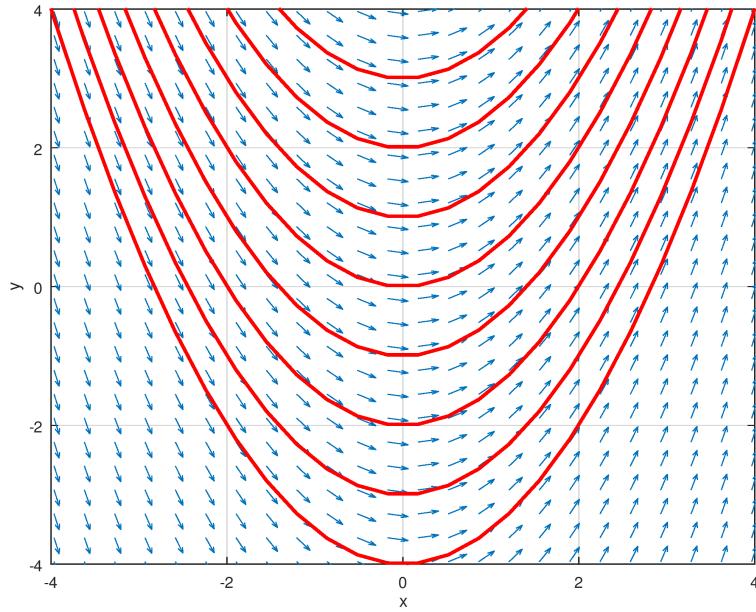


Figure 5.14: Slope field and solutions

### 5.5.2 Euler's method

Euler's method is probably the simplest numerical technique for solving an ordinary differential equation.

Given a differential equation  $y' = f(x, y)$  with initial condition  $y(x_0) = y_0$ , Euler's method gives approximate solutions:

$$y_{i+1} = y_i + h f(x_i, y_i) \quad (5.7)$$

The value of  $h$  is the *step size*. If the interval  $[x_0, b]$  is divided into  $n$  equally spaced subintervals, then  $h = \frac{b - x_0}{n}$ . To see how this works, let's look at an example.

**Example 5.5.2.** Solve

$$y' = e^{-3x} - 3y, \quad y(0) = 1$$

on  $[0, 3]$  using a step size of 1.

**Solution.** We will generate a series of approximate  $y$ -values at  $x = 0, 1, 2, 3$ . The value  $y_0$  is given. We compute the remaining values using Equation 5.7. Here is the first step:

$$\begin{aligned} y_1 &= y_0 + h f(x_0, y_0) \\ &= 1 + (1)f(0, 1) \\ &= 1 + (1)(-2) \\ &= -1 \end{aligned}$$

This is then used to compute  $y_2$ .

$$\begin{aligned}y_2 &= y_1 + hf(x_1, y_1) \\&= -1 + (1)f(1, -1) \\&= 2.0498\end{aligned}$$

One more step:

$$\begin{aligned}y_3 &= y_2 + hf(x_2, y_2) \\&= 2.0498 + (1)f(2, 2.0498) \\&= -4.0971\end{aligned}$$

Our approximate solutions are summarized in the following table.

$x$	$y$
0	1.0000
1	-1.0000
2	2.0498
3	-4.0971

Unfortunately, these solutions are not very accurate. But, we can do much better by decreasing the step size, as shown in the next example.  $\square$

These repetitive computations are best implemented in an Octave script. This allows using a smaller step size, which gives a finer range of solution values and also improves the overall accuracy. Refer to [8] for a fuller discussion of the accuracy of Euler's method and a range of more sophisticated algorithms.

**Example 5.5.3.** Solve

$$y' = e^{-3x} - 3y, \quad y(0) = 1$$

on  $[0, 3]$  using a step size of 0.1.

**Solution.** We will write a fairly general Octave script that can be easily modified for different functions, intervals, and step sizes.

---

#### Octave Script 5.4: Euler's method

---

```

1 % Euler 's method solution for
2 % dy/dx = e^(-3x) - 3y, y(0) = 1 on [0 , 3]
3
4 % define function and initial condition
5 f = @(x, y) exp(-3*x) - 3*y;
6 y0 = 1;
7
8 % define interval and step size
9 a = 0;
10 b = 3;
11 h = 0.1; % note: step size must divide b-a
12 n = (b - a)/h;
13
```

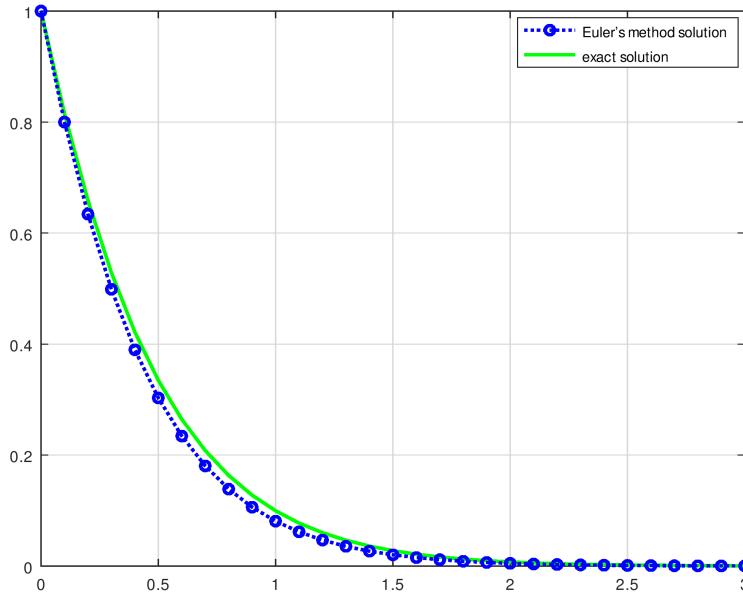


Figure 5.15: Euler's method solution for Example 5.5.3

```

14 % define x-values
15 clear x;
16 x = [a : h : b];
17
18 % calculate y-values
19 clear y;
20 y(1) = y0;
21 for i = 1:n
22     y(i + 1) = y(i) + h*f(x(i), y(i));
23 end
24
25 % plot solutions
26 >> plot(x, y, 'o:', 'linewidth', 2)

```

Figure 5.15 shows the approximated solution compared to the exact solution, which is known to be  $y = e^{-3x}(x + 1)$ .  $\square$

### 5.5.3 The Livermore solver

Octave has a built-in function for solving differential equations numerically, called `lsode`, which implements the FORTRAN routine of the same name (Livermore solver for ordinary differential equations). The command `lsode(f, x_0, t)` solves differential equation  $dx/dt = f(x, t)$  with initial condition  $x(t_0) = x_0$  over the range specified by  $t$ . Notice that the initial value  $x_0$  needs to correspond to the first value of the vector  $t$ . Refer to the documentation for further details.

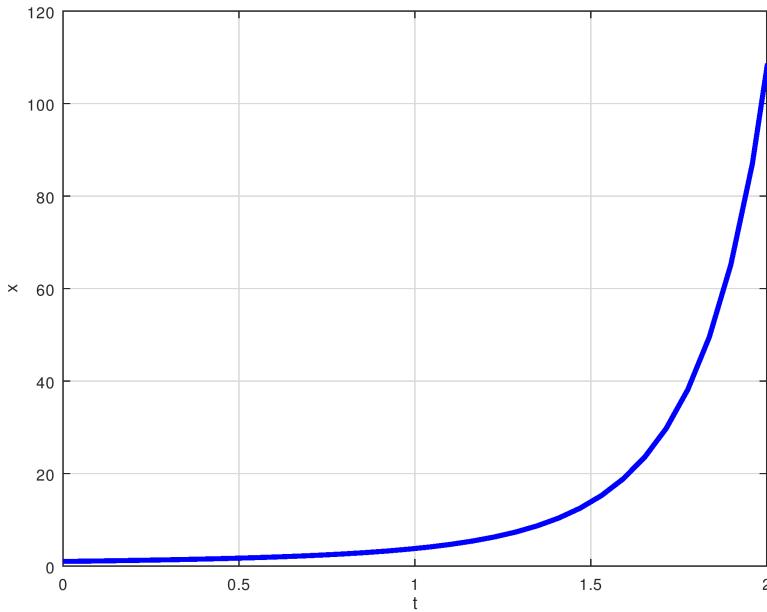


Figure 5.16: lsode numeric solution

**Example 5.5.4.** Use `lsode` to solve the differential equation

$$\frac{dx}{dt} = x(t^2 + 1)$$

on  $[0, 2]$ , with initial condition  $x(0) = 1$ .

**Solution.** To solve using `lsode`, we define the function listing  $x$  first, then  $t$ .

```
>> % define the function, input values, and initial condition
>> f = @(x, t) x.* (t.^2 + 1); % x first, then t
>> t = linspace(0, 2, 50);
>> x0 = 1;

>> % calculate the solutions
>> x_sol = lsode(f, x0, t);

>> % plot the solutions
>> plot(t, x_sol, 'linewidth', 2)
>> grid on
>> xlabel('t')
>> ylabel('x')
```

The solution is shown in Figure 5.16. □

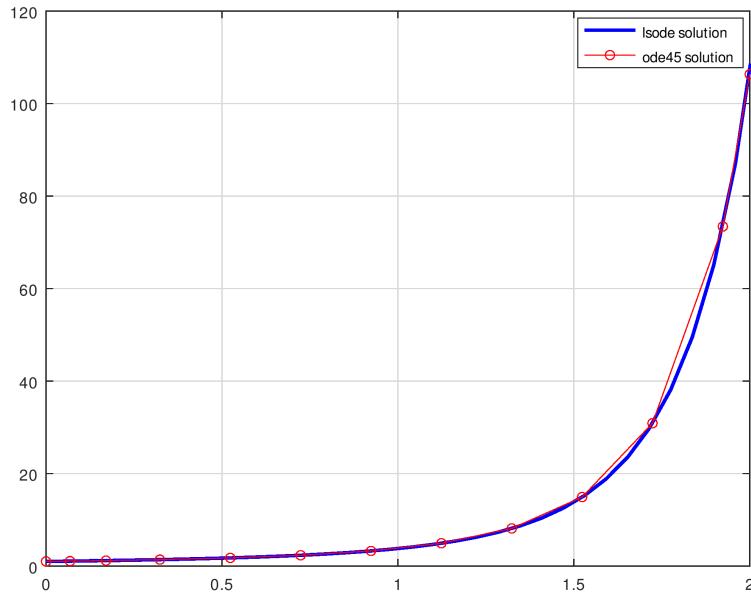


Figure 5.17: ode45 vs lsode numeric solutions

### 5.5.4 ODE45

For compatibility with MATLAB, several other solvers are available. Let's revisit Example 5.5.4 and solve using the MATLAB-equivalent command `ode45`.

**Example 5.5.5.** Use `ode45` to solve the differential equation

$$\frac{dx}{dt} = x(t^2 + 1)$$

on  $[0, 2]$ , with initial condition  $x(0) = 1$ . Compare to the `lsode` solution from Example 5.5.4.

**Solution.** We need to redefine the function. MATLAB convention requires giving the independent variable first, the opposite of what `lsode` required.

```
>> % define the function, input values, and initial condition
>> f = @(t, x) x.* (t.^2 + 1);    % t first, then x
>> tspan = [0 2];
>> x0 = 1;

>> % calculate the solutions
>> [t_sol, x_sol] = ode45(f, tspan, x0);

>> % plot the solutions
>> plot(t_sol, x_sol, 'o-')
```

Figure 5.17 compares the `lsode` and `ode45` solutions. The solutions seem to agree. □

## Chapter 5 Exercises

1. Graph the function  $\mathbf{r}(t) = \langle e^{-t}, t, \sin(t) \rangle$ .
2. Graph the function  $f(x, y) = \sin(xy) + 1$ .
3. Find a vector function that represents the curve of intersection of the circular cylinder  $x^2 + y^2 = 4$  and the parabolic cylinder  $z = x^2$ . Graph the two surfaces and the curve of intersection.  
The command `[X Y Z] = cylinder([2 2])` can be used to obtain a cylinder of radius 2.
4. Calculate the volume of the bumpy sphere from Example 5.1.1.
5. A cylindrical drill with radius 1 is used to bore a hole through the center of a sphere of radius 5. Graph the ring shaped solid that remains and find its volume.
6. Use `dblquad` to evaluate the double integral

$$\iint_D x \cos y \, dA$$

where  $D$  is bounded by  $y = 0$ ,  $y = x^2$ , and  $x = 2$ .

7. Let  $f(x, y) = x + 2y^2$ , defined on  $R = [0, 2] \times [0, 4]$ . Write a vectorized algorithm to compute a double Riemann sum using midpoints of each subrectangle as the sample points. Use a partition with  $m = n = 1000$ . Compare your results to the value computed using `dblquad('f', 0, 2, 0, 4)` and to the estimate using upper right hand corner sample points.
8. Plot the vector field  $\mathbf{F}(x, y) = \tan^{-1}(\frac{y}{x})\mathbf{i} + \ln(x^2)\mathbf{j}$ .
9. Plot the vector field  $\mathbf{F}(x, y, z) = \frac{-x}{(x^2+y^2+z^2)^{3/2}}\mathbf{i} + \frac{-y}{(x^2+y^2+z^2)^{3/2}}\mathbf{j} + \frac{-z}{(x^2+y^2+z^2)^{3/2}}\mathbf{k}$ .
10. The function `binopdf(x, n, p)` gives the probability of  $x$  successes in  $n$  trials of a binomial experiment with a probability of success  $p$  on each trial. Plot binomial distributions for  $n = 10, 25$ , and  $50$  with  $p = 0.8$ . This can be done with the command `bar(x, B)`, where  $x$  is the vector of possible outcomes and  $B$  is the corresponding vector of binomial probabilities. What happens to the shape of the distribution as  $n$  increases?
11. Use Euler's method to solve the differential equation

$$\frac{dx}{dt} = x(t^2 + 1)$$

with initial condition  $x(0) = 1$  on  $[0, 2]$  using a step size  $h = 0.1$ . Compare to the `lsode` and `ode45` solutions shown in Figure 5.17.

12. Use separation of variables to find the exact solution for

$$\frac{dx}{dt} = x(t^2 + 1)$$

with initial condition  $x(0) = 1$ . Graph the solution on  $[0, 2]$  and compare to the numeric solutions shown in Figure 5.17.

13. Graph the slope field for the logistic equation  $\frac{dy}{dx} = y(1 - y)$ . Verify that  $y = 1/(1 + e^{-x})$  is a solution to the equation. Graph this function over the slope field and set the axes to an appropriate range.
14. Use `lsode` or `ode45` to solve the differential equation from Exercise 13 if  $y(0) = 0.5$ . Plot the solution over the slope field. Does the solution agree with the previous solution?



# Chapter 6

## Applied projects

What is any of this stuff good for? Lots! This chapter contains several extended projects suitable for calculus and linear algebra students. Major mathematical topics include the singular value decomposition applied to image compression, nonlinear curve-fitting, cubic spline curves, arc length and curvature, and visualizing space curves and surfaces.

Some projects require packages from Octave Forge. To see a list of your installed packages, type `pkg list`. If you do not already see the package you need listed, type `pkg install --forge NAME`. Once installed, the package is loaded with the command: `pkg load NAME`.

### 6.1 SVD and digital image compression

How do we reduce large images to manageable file sizes? One approach uses the singular value decomposition (SVD). A digital image can be represented as a matrix, where each entry represents a pixel and we assign a numeric value to each color. The singular values of the matrix are the key. Typically some of these are large, but many are very small. By keeping only the significant singular values and throwing out the rest, we can significantly reduce the amount of data that we need to store.

To illustrate the idea, we have imported a small grayscale image file. It is  $133 \times 150$ , which means the matrix has 19,950 entries. The SVD is then used to generate several approximations at significantly reduced file sizes. The original and reduced images are shown in Figure 6.1 (the original, exact image is at the far right).

The first approximation uses only three singular values. That means we keep three  $\sigma$ s, plus three columns of  $U$  and three columns of  $V$ . We can simply set the other values to 0 (then we don't need to store that data), or delete them. We then multiply these smaller matrices back together to obtain a full size approximation of the original image. The upshot is we only have to store  $3 + (3 \times 133) + (3 \times 150) = 852$  data values, compared to the original total of 19,950. That is only 4% of the original size! Keeping a few more singular values, the second approximation uses 10 singular values and is 14% of the original size. The image quality is not bad, considering how much of the original data we threw away. The third approximation, with 30 singular values,

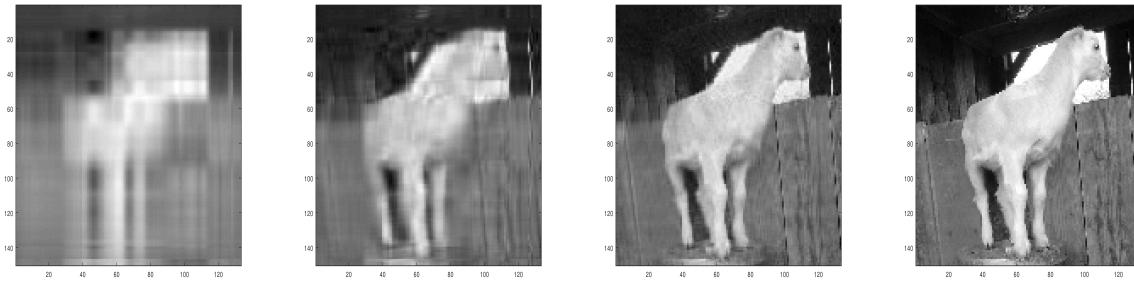


Figure 6.1: SVD approximations

looks almost as good as the original. But, it is only 43% of the original size. For comparison, the exact image is shown on the far right.

Octave supports several image file types. We will use .jpg files, which are loaded as RGB (red, green, blue) images, represented as a set of three  $m \times n$  matrices containing the color values for each pixel. For simplicity, we will convert this to a single  $m \times n$  grayscale matrix. Some of the Octave commands needed for basic image processing are listed in the table below.

#### IMAGE PROCESSING COMMANDS

Syntax	Description
<code>pkg install --forge image ...</code>	install the image package from Octave Forge
<code>pkg load image .....</code>	load the image package
<code>im = imread('filename.jpg');</code>	load an image
<code>name = imresize(im, 0.5); ..</code>	reduce image size by a specified factor (e.g., 0.5)
<code>name = rgb2gray(im); .....</code>	convert to grayscale
<code>imshow(im) .....</code>	display an image
<code>imagesc(im) .....</code>	display a matrix as a scaled image
<code>colormap('gray') .....</code>	set colormap to grayscale
<code>colormap('default') .....</code>	restore colormap to default

## Problems

- For this problem, you will use the SVD to produce a compressed image using  $k$  singular values. You choose  $k$  (something between 5 and 50 would be suitable). To begin, you will need a digital photo in .jpg format. Make sure you have loaded the image package.
  - Load the image in Octave as ‘imcolor,’ then convert to a grayscale image.
  - Check the size of your grayscale image and if it is larger than approximately  $320 \times 280$ , determine an appropriate reduction factor and reduce it. Reducing to a modest size makes it easier to open the variables in the variable editor to inspect their values. Name the reduced, grayscale format image ‘im.’ This is the image that will be compressed via the SVD method. Display the reduced grayscale image using `imagesc` and verify that it still looks like the original. Include a copy of this grayscale image with your problem solutions and state its size.

- (c) Find the SVD of the matrix representation ‘im.’
  - (d) Use the SVD to calculate an approximation using  $k$  singular values. That means you should only keep the first  $k$  columns of  $U$ , the  $k$  largest values of  $\Sigma$ , and the first  $k$  columns of  $V$ . Set the other values to 0 (or delete the extra columns altogether), then compute  $U\Sigma V^T$  to recover an approximation of the original image. Save it as ‘im2’ and display it using `imagesc`. Include a copy of the reduced image with your problem solution.
  - (e) How many nonzero values are saved in the compressed factorization compared to the original?
2. Using the ‘outer product’ expansion of  $A = U\Sigma V^T$ , the matrix  $A$  can be calculated column-by-column as
- $$A = \sigma_1 \mathbf{u}_1 \mathbf{v}_1^T + \sigma_2 \mathbf{u}_2 \mathbf{v}_2^T + \cdots + \sigma_r \mathbf{u}_r \mathbf{v}_r^T$$

where each term is an  $m \times n$  matrix. For any  $k < r$ , the sum of the first  $k$  terms will be an approximation using  $km + kn + k$  data values.

- (a) Use the steps outlined in problem 1 to load a grayscale image matrix.
  - (b) Write a for-loop to generate an outer product expansion using  $k$  singular values.
  - (c) Run the loop through 1, 5, 10, 20, and 30 iterations, saving a copy of the output image each time.
  - (d) How many singular values do you think are needed before the quality of the reduced image is “good enough”?
  - (e) At what  $k$ -value does the SVD approximation actually require saving *more* data than the original image?
3. Use the iterative outer product method of problem 2 to create a slide show showing the progressive quality improvement as the number of singular values increases from 1 up to the point where the approximation and original are indistinguishable.

You will need to use a loop that produces an approximation for each  $i$  from 1 to  $k$ . Some special formatting is needed to create a series of file names that increment as you cycle through the loop. Load your grayscale image and find the SVD. Then use the code below as a template to generate a series of progressively better approximations.

```
>> % initialize approximation and set number of singular values
>> approx = zeros(size(im));
>> k = 25

>> % loop to create approximations and save as image files
>> for i = 1 : k
>>   approx = approx + S(i, i)*U(:, i)*V(:, i)';
>>   h = imagesc(approx);
>>   name = sprintf('%s%d.png', 'approx', i);
>>   saveas(h, name)
>> end
```

## 6.2 The Gini index and nonlinear curve-fitting

The subject of wealth and income inequality has featured prominently in the media and political campaigns recently. Is there a fair, mathematically quantifiable method to describe income inequality and track how it changes over time? This project will look at how Lorenz curves and the Gini index are used to measure inequality and make comparisons.

The US Census Bureau reports shares of aggregate income by *quintile*. Quintiles divide the population into equal fifths. For example, in 2017, the bottom quintile or poorest 20% of the population earned 3.1% of the total income. In a perfectly egalitarian society (equal income distribution), each 20% of the population would earn 20% of the income. The table below shows the income range and share of the total income as reported by US Census Bureau for 2017<sup>1</sup>.

INCOME DISTRIBUTION

Shares of Aggregate Income	Income Range	Share of Income	Cumulative Share
Lowest Quintile	\$24,638 or less	3.1%	3.1%
Second Quintile	\$24,639 – \$47,110	8.2%	
Third Quintile	\$47,111 – \$77,552	14.3%	
Fourth Quintile	\$77,553 – \$126,855	23.0%	
Highest Quintile	\$126,856 or higher	51.5%	100%

### Problems

- Fill in the column for cumulative share of income in the table above. This gives the share of total income earned by the bottom 20%, the bottom 40%, the bottom 60%, the bottom 80%, and finally by 100%.
- A *Lorenz curve* is obtained by plotting  $(a/100, b/100)$  if the bottom  $a\%$  earn at most  $b\%$  of the income. Fill in the table below with the decimal form of the cumulative shares, then plot the points and sketch in a smooth curve.

$x$	$L(x)$
0.00	0.000
0.20	
0.40	
0.60	
0.80	
1.00	1.000

Notice that the curve passes through  $(0, 0)$  and  $(1, 1)$ . The curve is also increasing and concave up (it never crosses above the line  $y = x$  or drops below the line  $y = 0$ ). It lies in between the curve of perfect equality,  $y = x$ , and perfect inequality. Maximum inequality would be when the top income earner earns 100% of the income and everyone else earns 0. This is the line  $y = 0$  for  $0 < x < 1$ , then a jump to the point  $(1, 1)$ . Plot the curves of perfect equality and inequality.

<sup>1</sup>Source: *Income and Poverty in the United States: 2017*, US Census Bureau (September, 2018). Retrieved from <https://www.census.gov/content/dam/Census/library/publications/2018/demo/p60-263.pdf>.

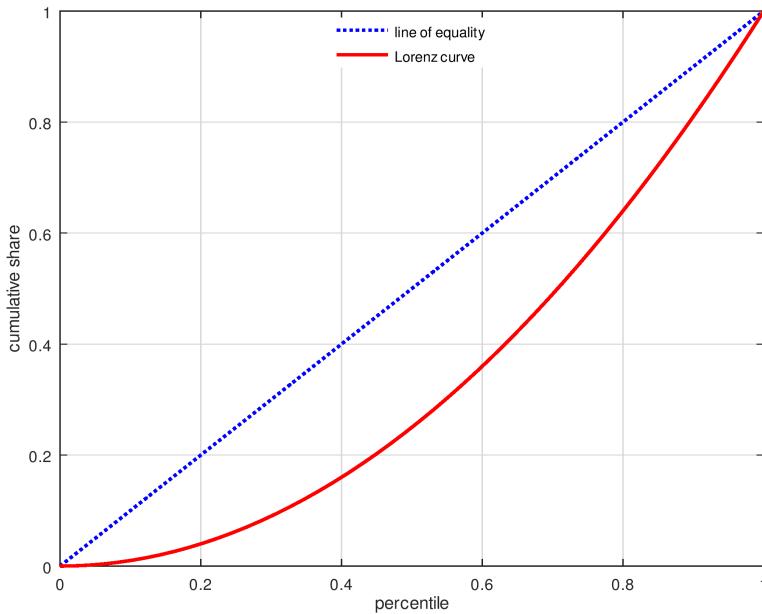


Figure 6.2: Lorenz curves

3. Lorenz functions satisfy these four properties:

- |                 |                                   |
|-----------------|-----------------------------------|
| (i) $L(0) = 0$  | (iii) $L'(x) > 0$ for $0 < x < 1$ |
| (ii) $L(1) = 1$ | (iv) $L''(x) > 0$ for $0 < x < 1$ |

Show that each of the following functions are Lorenz functions by verifying properties i–iv.

- (a)  $L(x) = x^2$
- (b)  $L(x) = x^n$ , where  $n \geq 2$
- (c)  $L(x) = a(e^x - 1)$ , where  $a = 1/(e - 1)$
- (d)  $L(x) = a(e^{kx} - 1)$ , where  $a = 1/(e^k - 1)$ ,  $k > 0$

4. The *Gini index* (or *Gini coefficient*),  $G$ , measures how much a given income distribution differs from perfect equality. Specifically, it is defined to be the area between the line of perfect equality and the Lorenz curve, divided by the total area under the line of perfect equality. Show that

$$G = 2 \int_0^1 [x - L(x)] \, dx$$

What are the values of  $G$  for perfect equality and for maximum inequality?

5. Load the optimization package. Then use the data from problem 2 and the nonlinear curve-fitting function `nonlin_curvefit` to approximate the Lorenz curve for 2017 US income as a function of the form  $L(x) = x^n$ . Use this model to calculate the Gini index. The US Census Bureau reports the Gini index as 0.482. How well does your answer agree?

The following code shows the basic syntax, assuming ‘`xdata`’ and ‘`ydata`’ contain the  $x$ - and  $L(x)$ -values from the income distribution.

```

>> % load the optim package (must already be installed)
>> pkg load optim

>> % define the model
>> % power function y = x^n
>> f = @(n, x) x.^n;

>> % initial guess for parameter n
>> init = 2;

>> % calculate the model
>> [n, model_values] = nonlin_curvefit(f, init, xdata, ydata)

```

Plot the data values and the Lorenz function together on the same axes. Include a legend and axis labels.

6. Repeat problem 5 using a Lorenz function of the form  $L(x) = a(e^{kx} - 1)$ , where  $a = 1/(e^k - 1)$ . How does the value of  $G$  compare to the result from problem 5 and the US Census Bureau figure?
7. The following table gives values of the Lorenz function for the US in 1970 and 1990 (derived from US Census Bureau figures). Use the power function method of problem 5 to calculate the Gini index for each of those years. How has the Gini index changed since 1970? If it has gone up, by what percent has it increased from 1970 to 2017?

x	1970	1990
0.00	0.000	0.000
0.20	0.041	0.038
0.40	0.149	0.134
0.60	0.323	0.293
0.80	0.568	0.530
1.00	1.000	1.000

8. How has income inequality in the US changed in recent history? Do some research and cite reputable sources to describe how the Gini index has changed over the last 100 years.
9. How does income inequality in the US compare to the rest of the world? Again, do some basic research and cite reputable sources to back up your assessment of how the US Gini index compares to other nations.

### 6.3 Designing a helical strake: arc length and curvature

In this project, we will tackle a real engineering problem. First, you will calculate the dimensions necessary to build a “helical strake” and construct a computer model to visualize it. Then you will build a physical model to test whether our methods work in the real world. A strake is a metal strip, used to reduce vibrations due to wind shear, attached on edge to the outside of a smokestack or other cylinder in a spiral. See Figure 6.3<sup>2</sup>.



Figure 6.3: Chimney with helical strake

There are two basic mathematical problems that must be solved to construct this. First, we need to know the (inside) linear length of the metal strip – that is the arc length of the helix:

$$s = \int_a^b \|\mathbf{r}'(t)\| dt$$

Secondly, the circular metal strips are cut out of flat metal sheets, then twisted into shape. What inside radius will make the strake fit flush against the smokestack? The correct approach

---

<sup>2</sup>Steel chimney with spiral, by ‘StomBer’ (CC-BY). <https://commons.wikimedia.org/wiki/File:SchornsteinwendelSKL.jpg>

is to build the strake with the right *radius of curvature*<sup>3</sup>. The radius of curvature is  $\rho = 1/\kappa$ , where  $\kappa$  is the curvature, defined as the rate of change of the unit tangent with respect to arc length:

$$\kappa = \left\| \frac{d\mathbf{T}}{ds} \right\|$$

Refer to [5, §11.5] for easier-to-use computational formulas for curvature.

## Problems

Choose a cylinder. You could use something as small as an empty paper towel roll or something as large as a cardboard concrete pier form. Measure the height and the radius of your cylinder. We want the helix to make exactly one revolution over the height of the tube. Before building the actual model, we will construct a virtual model.

1. Determine the equations of your cylinder and the helix that fits flush against it.
2. Plot a graph of the cylinder and helix on the same axes. Decide on a width for your strake and then plot the outside radius on the same axes to complete the model. Here are some commands that will help you plot the cylinder:

```
>> [X Y Z] = cylinder([r r]);
>> Z = h*Z;
>> surf(X, Y, Z)
```

This generates the  $X$ ,  $Y$ , and  $Z$  meshgrid arrays for a cylinder with radius  $r$  and height 1. The values of  $r$  are for the radii at the top and the bottom. For an ordinary right-circular cylinder, both numbers are the same. To stretch the height out to match the height of your cylinder, we multiply the  $Z$ -coordinate by  $h$ . If you don't like the way the plot from the `surf(X,Y,Z)` command looks, try `mesh(X,Y,Z)`. Once you have the cylinder plotted, use `hold on` and add a plot of the helix, with radius  $r$ . That represents the inside of the strake. To plot the outside edge, plot another helix of radius  $r + w$ , where  $w$  is the width of the strake. Optionally, add two line segments to join the two helices at the ends.

3. Calculate the arc length of the helix.
4. Calculate the radius of curvature of the helix.
5. Build a physical model. You can use construction paper, poster board, cardboard, or foam board. The material needs to be flexible enough to be twisted into the correct shape. To attach the spiral to your cylinder, you can use tape or glue. Duct tape or packaging tape should work, but a stout glue will show the interface between the strake and cylinder more clearly. In any case, we don't need something attractive; we just need to know whether the pieces fit!

Choose an appropriate outside radius for the strake, then cut out the pieces and build the model. You may need to use a nail or thumb tack and a measured length of string to mark your radius before cutting.

---

<sup>3</sup>Morgan, Frank. *Riemannian Geometry: A Beginner's Guide* (Second Edition). AK Peters, Ltd., Wellesley, MA (1998).

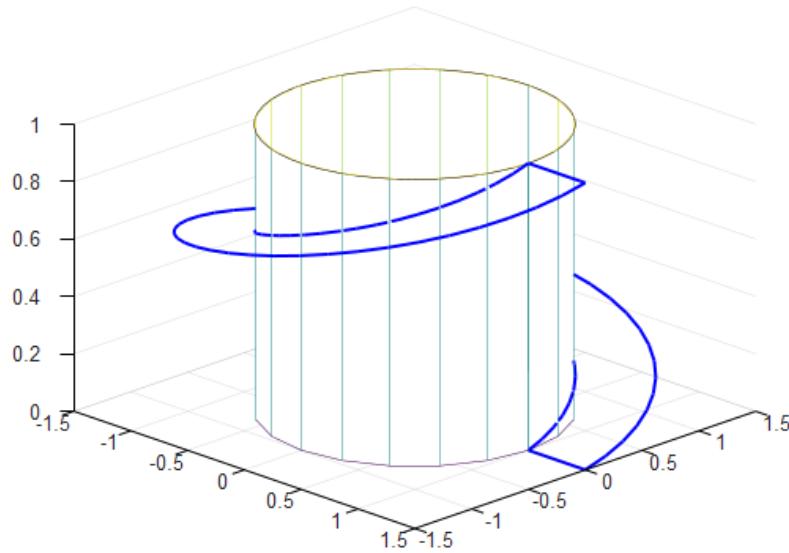


Figure 6.4: Computer model

6. Do the calculations agree with the reality of the physical model?
  - (a) Does the inside length of strake, as measured with a string, equal the calculated arc length?
  - (b) Do the pieces fit flush against the cylinder?
  - (c) Does the helix make exactly one revolution?

If something did not work out correctly, try to explain what you think went wrong.
7. Many chimneys have a wider base and narrow as the height increases. How does the problem change if we wish to wrap our strake around a more complex shape?
  - (a) Find the correct equations and create a computer model of a strake wrapped around a frustum of a cone with lower base radius 5, upper radius of 1, and height 10.
  - (b) Construct the computer model to illustrate the strake.
  - (c) Calculate the arc length of the helix.
  - (d) Calculate the curvature of the strake for  $t = 0, \pi/2, \pi, 3\pi/2$ , and  $2\pi$ , where  $t \in [0, 2\pi]$  corresponds to one complete revolution.
  - (e) You do not need to construct a physical model, but briefly discuss what difficulties would be encountered if we wished to construct this model.

## 6.4 Modeling a cave passage: cubic spline curves

In a cave survey, three dimensional data is collected between survey points. There are three measurements: distance, compass bearing ( $0^\circ$  to  $360^\circ$  azimuth), and inclination ( $-90^\circ$  to  $90^\circ$  vertical angle). The first step in generating a cave map is to reduce this data to rectangular coordinates and generate line plots of the survey. We will then construct mathematical models for the walls, floor and ceiling, and use these to set-up integrals to estimate the floor area, average passage height, and overall volume of the cave. This might be useful, for example, to a scientist who wished to determine the amount of limestone that dissolved during the formation of the cave, or the size of the stream which once flowed through it.

Survey data for *Skunk Cave* (Smyth County, Virginia) was collected during fieldwork by members of Walker Mountain Grotto and the Wytheville Community College Outdoor Club. The raw data is given below.

Distance (ft)	Azimuth ( $^\circ$ )	Inclination ( $^\circ$ )
30.05	248.5	$-15.5$
10.30	237.5	$-25.5$
3.20	245.0	11.0
17.00	269.0	$-5.0$
10.00	271.0	$-10.0$
14.35	280.0	3.0
11.50	308.5	6.0
49.65	296.0	12.5
5.30	315.0	$-23.0$

Converting this spherical data to rectangular coordinates is accomplished with the following transformations:

$$\begin{aligned}x &= d \cos(\phi) \sin(\theta) \\y &= d \cos(\phi) \cos(\theta) \\z &= d \sin(\phi)\end{aligned}$$

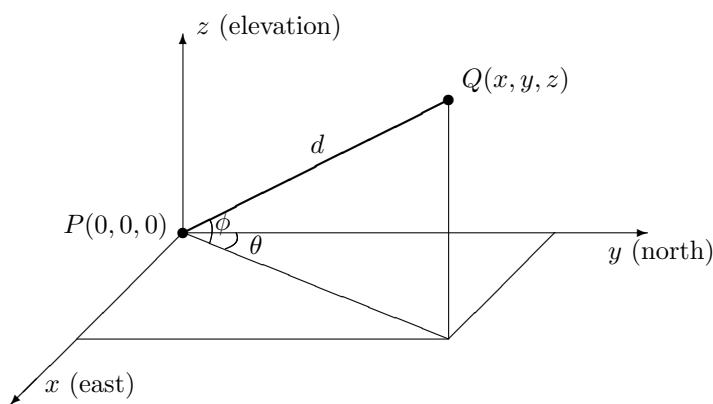


Figure 6.5: Spherical coordinates

Note that these formulas are slightly different from the standard spherical to rectangular identities, to reflect how the measurements are actually taken in the field. To apply these formulas, we must use an iterative process. Start from the point  $(0, 0, 0)$ . The  $(x, y, z)$ -coordinates of the next point are found using the given formulas. Then, this becomes the starting point for the next transformation. Thus, for each  $i = 2, 3, 4, \dots, 10$ , the relationship is:

$$\begin{aligned}x_i &= x_{i-1} + d_{i-1} \cos(\phi_{i-1}) \sin(\theta_{i-1}) \\y_i &= y_{i-1} + d_{i-1} \cos(\phi_{i-1}) \cos(\theta_{i-1}) \\z_i &= z_{i-1} + d_{i-1} \sin(\phi_{i-1})\end{aligned}$$

## Problems

1. Determine rectangular coordinates for each point in the survey. These should be in the form of  $10 \times 1$  column vectors for  $x$ ,  $y$ , and  $z$ . You can carry out each step one at a time, but using a loop in Octave will be more efficient. Note that you must convert the degree angle measures to radians to obtain correct results.
2. Plot the overhead plan view using the command `plot(x, y)`. For a more accurate perspective, you can force equal  $x$ - and  $y$ -axis scales by using the command `axis('equal')`.
3. Notice that the passage is aligned primarily in an east-west direction. Plot an east-west profile view by using the command `plot(x, z)`. Force equal axes for a more accurate view.
4. Plot a 3-dimensional model using the command `plot3(x, y, z)`.

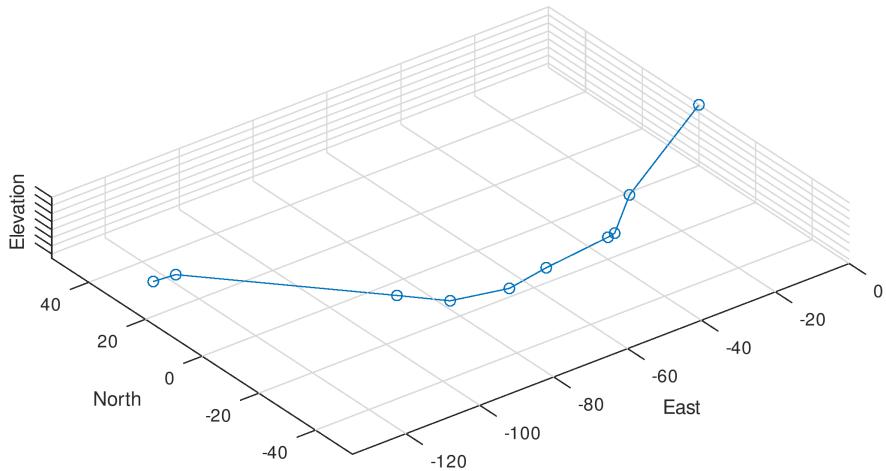


Figure 6.6: 3-dimensional model of survey line

We need additional data to model the passage outline. During the survey, estimates of the distances to the left wall, right wall, ceiling (up), and floor (down) were collected at each point. Cave surveyors call this ‘LRUD’ data (i.e., left, right, up, down). There are ten survey stations and nine passage segments. Here is a table containing the LRUD data. The stations have been indexed 1 through 10, with 1 representing the entrance.

Station index	Left wall	Right wall	Ceiling (up)	Floor (down)
1	10.0	8.0	5.0	0.0
2	3.0	5.0	3.0	2.0
3	3.0	0.0	1.5	0.5
4	0.0	1.0	0.5	1.5
5	3.0	0.5	4.0	2.0
6	4.0	0.0	5.0	2.0
7	0.0	3.0	5.0	3.0
8	6.0	2.0	4.0	2.0
9	3.0	2.0	0.0	3.0
10	1.0	0.5	3.0	0.5

Since the cave segment consists of a single passage, oriented in an east-west direction, we can simplify things by partitioning the  $x$ -axis at the coordinates determined in problem 1. The simplest model uses straight line segments, as shown in Figure 6.7.

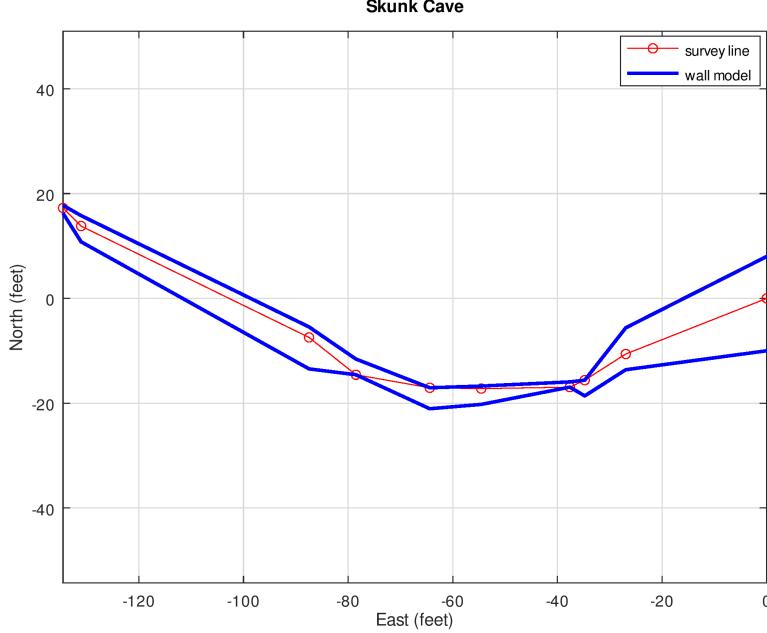


Figure 6.7: Straight line wall model

Notice that the breaks in the left and right walls occur at the  $x$ -coordinates of the corresponding survey station (i.e., straight up and down). This looks useful, but cave walls are not straight,

so we will use a more sophisticated model, based on cubic splines<sup>4</sup>.

The following script will generate cubic Hermite spline models for the walls, floor, and ceiling.

Octave Script 6.1: Cubic spline model

---

```

1 % script file 'skunk.m'
2 % generates spline curves for walls and floor
3 % plots plan and profile views of survey line and spline model
4 % requires 10x1 station coordinate vectors x, y, and z and 10x4 lrud data
5 % matrix
6 % extract left , right , up , down from lrud data matrix
7 L = lrud(:, 1);
8 R = lrud(:, 2);
9 U = lrud(:, 3);
10 D = lrud(:, 4);
11
12 % calculate left and right walls , floor and ceiling
13 y_left = y - L;
14 y_right = y + R;
15 z_down = z - D;
16 z_up = z + U;
17
18 % generate cubic spline wall models as piecewise polynomials
19 pp1 = interp1(x, y_left, 'pchip', 'pp');
20 pp2 = interp1(x, y_right, 'pchip', 'pp');
21 xx = linspace(min(x), max(x), 50);
22 yy1 = ppval(pp1, xx);
23 yy2 = ppval(pp2, xx);
24
25 % display breaks and coefficients
26 [breaks1, coeffs1] = unmkpp(pp1);
27 [breaks2, coeffs2] = unmkpp(pp2);
28 breaks = breaks1(1 : size(breaks1, 2) - 1)'
29 left_wall_coeff = coeffs1
30 right_wall_coeff = coeffs2
31
32 % plot plan view
33 figure(1);
34 plot(x, y, 'ro-', xx, yy1, 'linewidth', 2, 'b', xx, yy2, 'linewidth', 2, 'b');
35 grid on;
36 axis('equal');
37 title('Skunk Cave - Plan View')
38 legend('survey line', 'cubic spline model')
39 xlabel('East (feet)')
40 ylabel('North (feet)')
41
42 % generate cubic spline floor and ceiling models as piecewise polynomials
43 pp3 = interp1(x, z_down, 'pchip', 'pp');
44 pp4 = interp1(x, z_up, 'pchip', 'pp');
```

---

<sup>4</sup>see <http://mathworld.wolfram.com/CubicSpline.html> and [https://en.wikipedia.org/wiki/Cubic\\_Hermite\\_spline](https://en.wikipedia.org/wiki/Cubic_Hermite_spline)

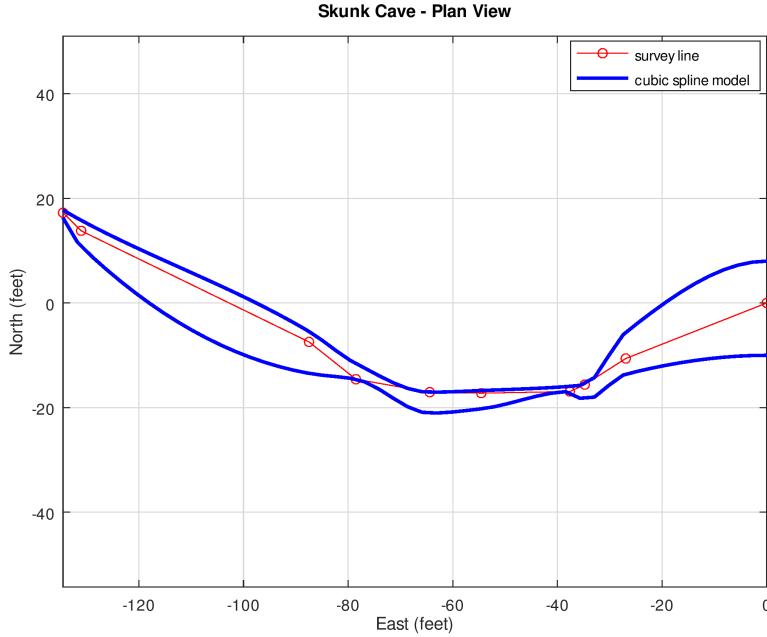


Figure 6.8: Cubic spline plan view

```

45 zz1 = ppval(pp3, xx);
46 zz2 = ppval(pp4, xx);
47
48 % display coefficients
49 [breaks3, coeffs3] = unmkpp(pp3);
50 [breaks4, coeffs4] = unmkpp(pp4);
51 floor_coeff = coeffs3
52 ceiling_coeff = coeffs4
53
54 % plot profile view
55 figure(2);
56 plot(x, z, 'ro-', xx, zz1, 'linewidth', 2, 'b', xx, zz2, 'linewidth', 2, 'b');
57 grid on;
58 axis('equal');
59 title('Skunk Cave - Profile View')
60 legend('survey line', 'cubic spline model')
61 xlabel('East (feet)')
62 ylabel('Elevation (feet)')

```

---

This code will produce piecewise polynomial functions for the walls, floor, and ceiling. These consist of 36 individual cubic polynomials for the walls, floor and ceiling, each with the form:

$$y = a(x - x_0)^3 + b(x - x_0)^2 + c(x - x_0) + d$$

where the  $x_0$ -values correspond to the  $x$ -coordinate breaks.

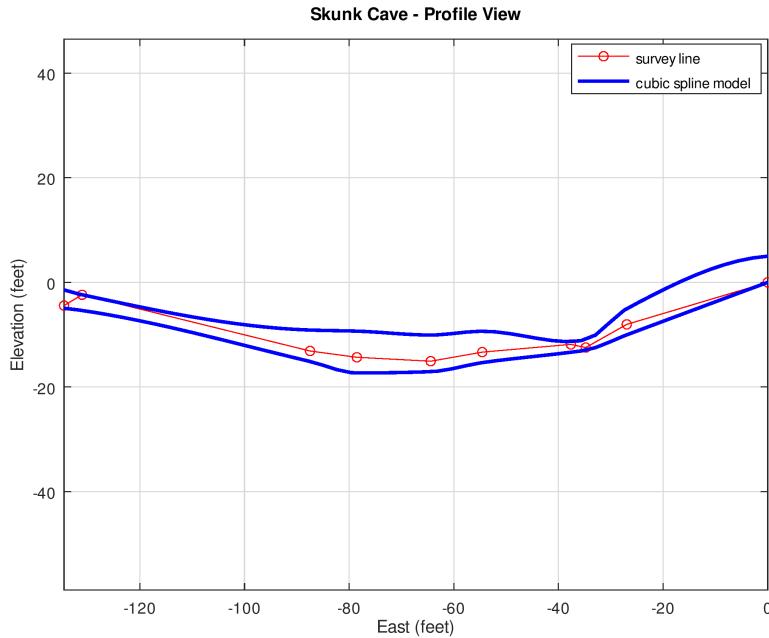


Figure 6.9: Cubic spline profile view

5. For each passage segment, the floor area can be calculated as

$$\int_a^b [\text{right wall} - \text{left wall}] \ dx$$

Use integration to calculate the floor area of each passage segment, and the total floor area.

You may want to define the integrand using the `ppval` function, then integrate using `quad`.

6. The average height can be found using

$$h = \frac{1}{b-a} \int_a^b [\text{ceiling} - \text{floor}] \ dx$$

Calculate the average passage height in each segment.

7. A volume estimate for each segment can be calculated as floor area times average passage height,  $V = Ah$ . Use the floor area and passage height estimates to estimate the total volume of the entire passage.
8. A double integral can be used to directly calculate the volume between the floor and ceiling functions over the irregular plane region defined by the walls of the passage. Write a script to evaluate:

$$\sum_{i=1}^9 \int_a^b \int_{\text{left wall}}^{\text{right wall}} [\text{ceiling} - \text{floor}] \ dA$$

## 6.5 Graphs of surfaces and 3D-printing

If  $z = f(x, y)$  is nonnegative on  $D$ , then  $\iint_D f(x, y) dA$  represents the volume under the graph of  $f$ , above the region  $D$  in the  $xy$ -plane. We have already seen how to calculate such volumes and how to visualize the surfaces by using three dimensional graphs in Octave. In this project, we will convert 3D-surfaces into solid blocks which can be printed in three dimensions. In addition to allowing us a more concrete means of modeling a mathematical surface, we can physically measure the volume of the object (by displacement) and compare to the theoretical results as predicted by calculus.

These printers require closed, “water tight” solids, typically produced using a triangular mesh and saved in an .stl file format (STereoLithography). There are several MATLAB script files available in the MathWorks File Exchange for producing the figures and .stl-output we need. While these scripts may run in Octave, it is a violation of the terms of service to use content from the Mathworks File Exchange in non-Mathworks software. If you are using a licensed version of MATLAB, try:

- <http://www.mathworks.com/matlabcentral/fileexchange/30709-surf2solid>  
surf2solid takes a function of two variables and turns it into a solid block by adding a “curtain” from the boundary of the surface down to the  $xy$ -plane and joining this to a flat plane below
- <http://www.mathworks.com/matlabcentral/fileexchange/4512-surf2stl>  
surf2stl takes a solid rectangular meshgrid and converts into a triangulated .stl surface

Inspired by these functions, we will write our own Octave function for this project. We have two goals:

1. For a surface  $z = f(x, y)$ , create a solid block that represents the volume below the surface and above a rectangular domain.
2. For any surface defined by meshgrid variables  $X, Y, Z$ , generate a triangulation and write an .stl file.

STeroLithography files in ASCII format have a simple structure:

```

solid name
facet normal n1 n2 n3
outer loop
    vertex v1 v2 v3
    vertex v1 v2 v3
    vertex v1 v2 v3
endloop
endfacet

endsolid name

```

If we start from a rectangular grid, as we do with a surface generated from meshgrid variables, to produce a triangulation we merely need to split each subrectangle of the partition into two triangles. The .stl format requires the vertices of these triangles, plus a unit normal vector for each of the triangular facets. Despite the requirement for a normal vector in the file standard, it is redundant, as the vertices alone uniquely determine the solid. Thus some software ignores the normal vectors. But, we will attempt to include correct unit normals calculated using a cross product.

In the `mesh2stl.m` function file below, lines 12–29 are all that is needed to triangulate an  $(X, Y, Z)$ -surface from Octave. Lines 92–123 will write the output in the standard file format. But, if we pass the function a minimum thickness, delta, then additional code is used. Assuming  $z = f(x, y)$  is a function over a rectangular domain, it is relatively simple to produce a solid block by dropping a “curtain” from the edge of the surface down to the  $(x, y)$ -plane and closing off the solid with a flat plane for the base. Lines 31–90 handle this.

This function file can be downloaded from <https://gist.github.com/jalachniet/>.

Octave Script 6.2: mesh2stl function file

---

```

1 function mesh2stl(filename , X, Y, Z, delta)
2 %MESH2STL writes an .stl (STereoLithography) file from meshgrid variables
3 % mesh2stl('filename', X, Y, Z)
4 % produces a triangulated mesh from meshgrid variables X, Y, Z
5 % and writes output to 'filename' in stl format
6 % --X, Y, Z must be two dimensional arrays of the same size
7 % --optional: if delta is provided, produce a solid block from the graph
8 % of surface z = f(x, y)
9 % where 'delta' gives minimum thickness between base of block
10 % and graph of surface
11
12 % determine dimensions
13 m = size(Z, 1);
14 n = size(Z, 2);
15
16 % construct triangular facets for surface
17 k = 0;
18 for i = 1:m-1
19   for j = 1:n-1
20     k = k + 1;
21     F(:, :, k) = [X(i ,j) ,      Y(i ,j) ,      Z(i ,j) ;
22                  X(i ,j+1) ,    Y(i ,j+1) ,    Z(i ,j+1) ;
23                  X(i+1,j+1) , Y(i+1,j+1) , Z(i+1,j+1) ];
24     k = k + 1;
25     F(:, :, k) = [X(i+1,j+1) , Y(i+1,j+1) , Z(i+1,j+1) ;
26                  X(i+1,j) ,    Y(i+1,j) ,    Z(i+1,j) ;
27                  X(i ,j) ,      Y(i ,j) ,      Z(i ,j) ];
28   end
29 end
30
31 if ( nargin > 4)
32   % calculate elevation and midpoint of base
33   z_base = min(min(Z)) - delta;
34   x_mid = (min(min(X)) + max(max(X))) / 2;
```

```

35 y_mid = (min(min(Y)) + max(max(Y)))/2;
36
37 % construct triangular facets for 'curtain' and base
38 for i = 1:n-1
39   k = k + 1;
40   F(:,:,k) = [X(1,i), Y(1,i), Z(1,i);
41                 X(1,i), Y(1,i), z_base;
42                 X(1,i+1), Y(1,i+1), Z(1,i+1)];
43   k = k + 1;
44   F(:,:,k) = [X(1,i+1), Y(1,i+1), Z(1,i+1);
45                 X(1,i), Y(1,i), z_base;
46                 X(1,i+1), Y(1,i+1), z_base];
47   k = k + 1;
48   F(:,:,k) = [x_mid, y_mid, z_base;
49                 X(1,i), Y(1,i), z_base;
50                 X(1,i+1), Y(1,i+1), z_base];
51   k = k + 1;
52   F(:,:,k) = [X(m,i), Y(m,i), Z(1,i);
53                 X(m,i), Y(m,i), z_base;
54                 X(m,i+1), Y(m,i+1), Z(1,i+1)];
55   k = k + 1;
56   F(:,:,k) = [X(m,i+1), Y(m,i+1), Z(1,i+1);
57                 X(m,i), Y(m,i), z_base;
58                 X(m,i+1), Y(m,i+1), z_base];
59   k = k + 1;
60   F(:,:,k) = [x_mid, y_mid, z_base;
61                 X(m,i), Y(m,i), z_base;
62                 X(m,i+1), Y(m,i+1), z_base];
63 end
64 for j = 1:m-1
65   k = k + 1;
66   F(:,:,k) = [X(j,1), Y(j,1), Z(j,1);
67                 X(j,1), Y(j,1), z_base;
68                 X(j+1,1), Y(j+1,1), Z(j+1,1)];
69   k = k + 1;
70   F(:,:,k) = [X(j+1,1), Y(j+1,1), Z(j+1,1);
71                 X(j,1), Y(j,1), z_base;
72                 X(j+1,1), Y(j+1,1), z_base];
73   k = k + 1;
74   F(:,:,k) = [x_mid, y_mid, z_base;
75                 X(j,1), Y(j,1), z_base;
76                 X(j+1,1), Y(j+1,1), z_base];
77   k = k + 1;
78   F(:,:,k) = [X(j,n), Y(j,n), Z(j,n);
79                 X(j,n), Y(j,n), z_base;
80                 X(j+1,n), Y(j+1,n), Z(j+1,n)];
81   k = k + 1;
82   F(:,:,k) = [X(j+1,n), Y(j+1,n), Z(j+1,n);
83                 X(j,n), Y(j,n), z_base;
84                 X(j+1,n), Y(j+1,n), z_base];
85   k = k + 1;
86   F(:,:,k) = [x_mid, y_mid, z_base;
87                 X(j,n), Y(j,n), z_base;
88                 X(j+1,n), Y(j+1,n), z_base];

```

```

89 end
90 end
91
92 % number of triangular facets
93 num_facets = k;
94
95 % save in stl format
96 fid = fopen(filename, 'w');
97 title_str = sprintf('Created with GNU Octave %s', datestr(now));
98 fprintf(fid, 'solid %s\r\n', title_str);
99 for k = 1:num_facets
100    % vertices
101    p1 = [F(1, 1, k) F(1, 2, k) F(1, 3, k)];
102    p2 = [F(2, 1, k) F(2, 2, k) F(2, 3, k)];
103    p3 = [F(3, 1, k) F(3, 2, k) F(3, 3, k)];
104
105    % normal vector
106    if ((p1 ~= p2) & (p1 ~= p3) & (p2 ~= p3))
107        n = cross(p2-p1, p3-p1)./norm(cross(p2-p1, p3-p1));
108    else
109        n = [0 0 0]; % unable to calculate normal vector
110    end
111
112    % write facets
113    fprintf(fid, 'facet normal %.7E %.7E %.7E\r\n', n(1), n(2), n(3));
114    fprintf(fid, 'outer loop\r\n');
115    fprintf(fid, 'vertex %.7E %.7E %.7E\r\n', p1);
116    fprintf(fid, 'vertex %.7E %.7E %.7E\r\n', p2);
117    fprintf(fid, 'vertex %.7E %.7E %.7E\r\n', p3);
118    fprintf(fid, 'endloop\r\n');
119    fprintf(fid, 'endfacet\r\n');
120 end
121
122 fprintf(fid, 'endsolid %s\r\n', title_str);
123 fclose(fid);
124
125 disp('Number of triangular facets:'), disp(num_facets)

```

---

Let's try producing a solid printable block with a modified version of the 'sombrero' function,

$$f(x, y) = 10 \left( \frac{\sin(\sqrt{x^2 + y^2})}{\sqrt{x^2 + y^2}} \right) + 3$$

```

>> [X Y Z] = sombrero;
>> Z = 10*Z + 3;
>> surf(X, Y, Z);

```

Now, we use `mesh2stl` to produce a solid figure and .stl file.

```

>> mesh2stl('sombrero.stl', X, Y, Z, 2);
Number of triangular facets:
3680

```

The output file is readable by most 3D-printer software. The option `delta = 2` tells the function to attempt to produce a solid block with a minimum thickness of 2. Note that units in .stl files are arbitrary, but most 3D printer software will interpret 1 unit in Octave as 1 mm. Thus our figure has a minimum thickness of 2 mm, measured between the base and the lowest point on the surface.

Use your 3D printer software or an online .stl viewer to preview the results and check the size in millimeters. Our figure is quite small, only  $16 \times 16 \times 14$  mm. It is generally an easy matter to resize to the desired final dimensions using printer software. Alternately, you can manually scale  $X$ ,  $Y$ , and  $Z$  before writing the file.

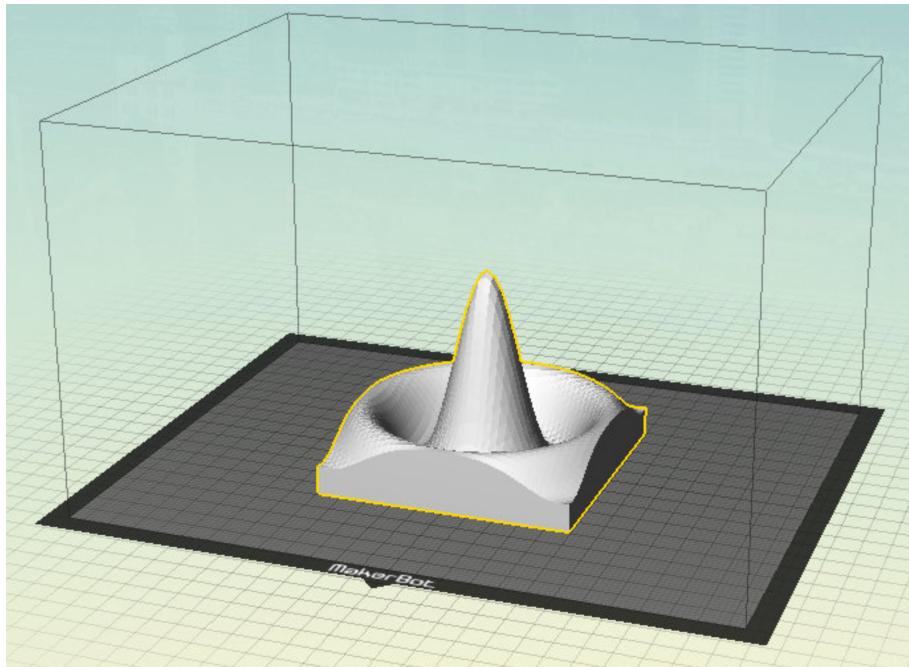


Figure 6.10: stl file ready for printing

## Problems

1. Use integration to determine the volume of the modified sombrero function generated above. You will need to take into account the difference in elevation between the base of the block and the lowest point on the surface.
2. Consider the example Octave surface “peaks.”

```
>> [X, Y, Z] = peaks;
```

Scale  $Z$  by a factor of  $1/5$  and shift up 2 units.

```
>> Z = Z/5 + 2;
```

Now convert the  $X$ ,  $Y$ ,  $Z$ -meshgrid variables to a printable .stl-format solid block. Calculate the volume of the resulting solid figure.

3. Let  $f(x, y) = \sin(xy) + 1$ .
- Compute (by-hand) the volume under the graph of  $f$  over the region  $[-\pi, \pi] \times [-\pi, \pi]$ .
  - Graph the function over the appropriate domain.
  - Convert the resulting  $[X, Y, Z]$  meshgrid variables to a solid block, saved in .stl format.

4. Suppose we have a solid radius-3 hemisphere and drill a radius-2 cylinder through the center. What volume remains? In rectangular coordinates, this is the volume under  $z = \sqrt{9 - x^2 - y^2}$  and above a washer shaped region in the  $xy$ -plane with inner radius 2 and outer radius 3.

- Sketch the region and calculate the volume by-hand. Use polar coordinates.
- Use an  $(r, \theta)$ -polar meshgrid to produce a 3D graph.
- Use the following code to produce a version of the solid in rectangular coordinates:

```
>> f = @(x, y) sqrt(9 - x.^2 - y.^2) .* ((x.^2 + y.^2 < 9) & (x
    .^2 + y.^2 > 4));
>> x = linspace(-3, 3, 100);
>> y = x;
>> [X Y] = meshgrid(x, y);
>> Z = f(X, Y);
>> surf(X, Y, Z)
>> mesh2stl('ring2.stl', 50*X, 50*Y, 50*Z, 0)
```

5. Consider the “bumpy sphere” from Example 5.1.1,

$$\rho = 1 + \frac{1}{4} \sin(5\phi) \cos(6\theta)$$

where  $0 \leq \theta \leq 2\pi, 0 \leq \phi \leq \pi$ .

- Set-up a triple integral in spherical coordinates to find the volume of this solid.
- Evaluate the integral to find a decimal approximation for the volume. You may use technology. Complete the first trivial integration by-hand. Then define  $\rho = f(\theta, \phi)$  and use `dblquad` command on the remaining double integral.
- Use the Symbolic Package to find the exact volume of the bumpy sphere.
- Graph the solid. You will need to create a  $(\theta, \phi)$ -meshgrid, then calculate  $\rho$  using these meshgrid variables. Finally,  $X$ ,  $Y$ , and  $Z$  are calculated using the standard spherical to rectangular coordinate identities. To scale the size up, multiply each  $X$ ,  $Y$ , and  $Z$  matrix by a factor of 50.
- Convert to .stl format. Note that this figure is already a closed solid, so do not use the delta option.

6. 3D printing can also help with visualizing space curves. However, a curve, on its own, has no thickness and therefore cannot be printed. A typical approach is to replace the curve with a thin tube. Script files are available to do this, for example `tubeplot.m` available from <http://www.aleph.se/Nada/Ray/Tubeplot/tubeplot.html>.

Even if you do not plan to 3D-print, a tubeplot can help with visualizing some complex space curves.

- (a) Let  $\mathbf{r}(t) = \cos(t)\mathbf{i} + \sin(t)\mathbf{j} + 0.3\sin(2t)\mathbf{k}$ . Graph the curve over the interval  $[0, 2\pi]$ . This is called the “Roller Coaster Curve” ([7, §3.1 Exercise 37]).
- (b) Create a 0.1-radius tube plot of the curve. Here is the correct syntax for the tubeplot script:
- ```
>> [X Y Z] = tubeplot(x, y, z, 0.1);
```
- (c) View the plot using `surf(X, Y, Z)`, then save in .stl format. The figure is essentially already a closed solid, so no option is needed for delta.
7. Here is your chance to be creative! Create a mathematically defined 3D-solid of your own design. You can use a rectangular function of two variables, or you may wish to try something in polar, cylindrical, or spherical form. In the end, it must be a closed solid that you can convert to a printer-ready .stl format. You may get ideas from your calculus book, experimentation in Octave, and/or online image searches.
- Define your function and state its domain (over which you will print the object).
  - Graph it.
  - Scale to a modest size (base roughly  $50 \times 50$  mm) and convert to .stl.
  - Give a description of any interesting mathematical properties of the object and include any relevant computations. Examples:
    - The volume calculated by integration
    - Location of maximums, minimums, or saddle points
    - A point where the limiting value is different along different lines of approach
    - A discontinuity
8. After one of your solid objects from problems 1–5 is printed, take it to the lab and measure its volume directly by fluid displacement. How does the measured volume compare to the calculated volume? Be sure to take into account any scaling factor used for the printed version. Give the absolute and relative volume errors and comment on any discrepancies.

## Appendix A

# MATLAB compatibility

Octave and MATLAB use similar syntax, but the programs are not identical. MATLAB, especially when extended with its various toolboxes, has many functions not available in Octave. However, most code in this book will work in MATLAB, so what you've learned here will easily transfer to more advanced MATLAB programming.

Octave allows some flexibility in syntax that MATLAB does not. This book has been written with MATLAB compatibility in mind, so when multiple forms of a command or operation are possible, the MATLAB-compatible option has been used. Here is a summary of a few of the potential coding differences.

- Comments in Octave can be preceded by `#` or `%`. MATLAB uses `%`.
- Octave recognizes single quotes and double quotes around strings. MATLAB requires single quotes.
- Blocks in Octave can be ended with `end` statements based on the initial command (`endfor`, `endfunction`, etc). MATLAB uses only `end`.
- The not-equal comparison can be written as `!=` or `~=` in Octave. MATLAB uses `~=`.
- Octave allows user-defined functions to be entered at the command line or in scripts. MATLAB requires the use of separate function files (recent releases now allow defining functions in scripts).
- There are significant differences between MATLAB Toolboxes and the Octave Forge packages used in Section 3.6 and some of the projects in Chapter 6, though many Octave packages use syntax similar or identical to the corresponding MATLAB functions. The Octave ‘symbolic’ package is similar to MATLAB’s Symbolic Toolbox. The Octave ‘optim’ package has capabilities similar to MATLAB’s Curve Fitting Toolbox. Octave’s ‘image’ package is similar to MATLAB’s Image Processing Toolbox.
- The `lsode` command is not implemented in MATLAB. For MATLAB-compatibility, `ode45` and several other MATLAB-compatible solvers are available in Octave (some require loading the package ‘odepkg’).



# Appendix B

## Octave command glossary

The names and basic syntax for many common commands are provided below. Many commands have additional options. Type `help NAME` at the Octave prompt or refer to [3] for more details. Note that some commands listed here require Octave Forge packages, including ‘statistics’ and ‘symbolic.’

LIST OF OCTAVE COMMANDS

| Syntax                                    | Description                                                        |
|-------------------------------------------|--------------------------------------------------------------------|
| <code>[a : step : b]</code>               | vector from $a$ to $b$ by increment ‘step’                         |
| <code>A'</code>                           | (conjugate) transpose of $A$                                       |
| <code>A.'</code>                          | transpose of $A$                                                   |
| <code>A*B</code>                          | matrix product $A \times B$                                        |
| <code>A\b</code>                          | left division, solves system $A\mathbf{x} = \mathbf{b}$            |
| <code>A^n</code>                          | matrix power                                                       |
| <code>A + B</code>                        | sum $A + B$                                                        |
| <code>x &lt; y</code>                     | less than comparison                                               |
| <code>x &gt; y</code>                     | greater than comparison                                            |
| <code>x == y</code>                       | equality comparison                                                |
| <code>x ~= y</code>                       | not equal comparison                                               |
| <code>x.*y</code>                         | elementwise product                                                |
| <code>x./y</code>                         | elementwise quotient                                               |
| <code>x.^n</code>                         | elementwise exponent                                               |
| <code>a &amp; b</code>                    | logical AND                                                        |
| <code>~a</code>                           | logical NOT                                                        |
| <code>a   b</code>                        | logical OR                                                         |
| <code>f = @(x1, x2, ...)</code> rule      | anonymous function of $x_1, x_2, \dots$ given by rule              |
| <code>abs(x)</code>                       | absolute value or modulus of $x$                                   |
| <code>acos(x)</code>                      | inverse cosine of $x$ in radians                                   |
| <code>angle(z)</code>                     | angle of complex variable $z$                                      |
| <code>ans</code>                          | result of last calculation                                         |
| <code>asin(x)</code>                      | inverse sine of $x$ in radians                                     |
| <code>assume(x, 'property')</code>        | assume $x$ has property (positive, integer, etc)                   |
| <code>atan(x)</code>                      | inverse tangent of $x$ in radians                                  |
| <code>axis ([Xmin Xmax Ymin Ymax])</code> | set axis limits                                                    |
| <code>bar(x, y)</code>                    | bar graph of $y$ vs. $x$                                           |
| <code>besselj(n, x)</code>                | order $n$ Bessel functions of the first kind                       |
| <code>binopdf(x, n, p)</code>             | binomial probability of $x$ successes                              |
| <code>ceil(x)</code>                      | $\lceil x \rceil$ , the least integer greater than or equal to $x$ |
| <code>clear var1</code>                   | clear variable (clear all if no variable listed)                   |

continued ...

... continued

| Syntax                                           | Description                                                          |
|--------------------------------------------------|----------------------------------------------------------------------|
| <code>clf</code> .....                           | clear plot window                                                    |
| <code>colormap('type')</code> .....              | set colormap to ‘type’ (e.g., ‘gray’, ‘default’)                     |
| <code>compass(z)</code> .....                    | compass plot of variable $z$ in the complex plane                    |
| <code>contour(X, Y, Z)</code> .....              | contour plot of surface                                              |
| <code>corr(x, y)</code> .....                    | linear correlation coefficient $r$                                   |
| <code>cos(x)</code> .....                        | cosine of $x$ ( $x$ in radians)                                      |
| <code>cosh(x)</code> .....                       | hyperbolic cosine of $x$                                             |
| <code>cross(u, v)</code> .....                   | cross product of vectors $\mathbf{u}$ and $\mathbf{v}$               |
| <code>cylinder([r r])</code> .....               | cylinder of radius $r$                                               |
| <code>dblquad('f', a, b, c, d)</code> .....      | double integral over rectangle                                       |
| <code>det(A)</code> .....                        | determinant of $A$                                                   |
| <code>diff(f, x)</code> .....                    | differentiate symbolic function with respect to $x$                  |
| <code>dir</code> .....                           | list files in current directory                                      |
| <code>dot(u, v)</code> .....                     | dot product of vectors $\mathbf{u}$ and $\mathbf{v}$                 |
| <code>double(x)</code> .....                     | convert $x$ to double precision floating point                       |
| <code>[v lambda] = eig(A)</code> .....           | find eigenvalues and eigenvectors                                    |
| <code>e</code> .....                             | the number $e$                                                       |
| <code>erf(x)</code> .....                        | the error function                                                   |
| <code>exp(x)</code> .....                        | natural exponential function                                         |
| <code>eye(n)</code> .....                        | $n \times n$ identity matrix                                         |
| <code>ezplot(f, [a b c d])</code> .....          | implicit plot of $f(x, y) = 0$ over domain $[a, b] \times [c, d]$    |
| <code>factor(f)</code> .....                     | factor a symbolic expression                                         |
| <code>floor(x)</code> .....                      | $\lfloor x \rfloor$ , the greatest integer less than or equal to $x$ |
| <code>for k = 1:n ... end</code> .....           | for loop                                                             |
| <code>format opt</code> .....                    | decimal format, options = short, long, free, bank, etc               |
| <code>fsolve('f', x1)</code> .....               | solve $f(x) = 0$ , initial guess $x_1$                               |
| <code>function y = f(x) ... end</code> .....     | define a function                                                    |
| <code>[DX DY] = gradient(Z)</code> .....         | gradient field of $Z$                                                |
| <code>gamma(x)</code> .....                      | the gamma function                                                   |
| <code>grid on/off</code> .....                   | toggle plot grid                                                     |
| <code>help NAME</code> .....                     | get documentation for command ‘NAME’                                 |
| <code>hist(X, B)</code> .....                    | histogram of $X$ , optional $B$ specifies bins                       |
| <code>hold on/off</code> .....                   | add to current plot toggle on/off                                    |
| <code>i/I</code> .....                           | the imaginary unit                                                   |
| <code>imag(z)</code> .....                       | imaginary part of $z$                                                |
| <code>imagesc(A)</code> .....                    | display matrix as scaled image                                       |
| <code>int(f, x, a, b)</code> .....               | integrate symbolic function (optional limits)                        |
| <code>interp1(x, y, 'method')</code> .....       | interpolate using type ‘method’ (linear, cubic, pchip, etc)          |
| <code>inv(A)</code> .....                        | inverse of matrix $A$                                                |
| <code>j/J</code> .....                           | the imaginary unit                                                   |
| <code>legend('plot1', 'plot2', ...)</code> ..... | plot legend                                                          |
| <code>linspace(a, b, n)</code> .....             | vector of $n$ evenly spaced points from $a$ to $b$                   |
| <code>load filename</code> .....                 | load saved variables                                                 |

continued ...

... continued

| Syntax                                         | Description                                                 |
|------------------------------------------------|-------------------------------------------------------------|
| <code>log(x)</code> .....                      | natural logarithm                                           |
| <code>lsode('f', x0, t)</code> .....           | solves $dx/dt = f(x, t)$ , $x(0) = x_0$                     |
| <code>[L U P] = lu(A)</code> .....             | $LU$ decomposition of $A$ , with permutation                |
| <code>max(A)</code> .....                      | maximum of vector, or column-wise maximums of a matrix      |
| <code>max(max(A))</code> .....                 | maximum of all entries in matrix $A$                        |
| <code>mean(x)</code> .....                     | mean of $x$                                                 |
| <code>mesh(X, Y, Z)</code> .....               | surface plotted as a mesh                                   |
| <code>[X Y] = meshgrid(x, y)</code> .....      | generate $X, Y$ -meshgrid                                   |
| <code>min(A)</code> .....                      | minimum of vector, or column-wise minimums of a matrix      |
| <code>min(min(A))</code> .....                 | minimum of all entries in matrix $A$                        |
| <code>norm(u)</code> .....                     | norm (length) of vector $\mathbf{u}$                        |
| <code>normcdf(x, mu, sigma)</code> .....       | area under normal curve to the left of $x$                  |
| <code>norminv(a, mu, sigma)</code> .....       | inverse normal distribution given area $a$                  |
| <code>nthroot(number, index)</code> .....      | real $n$ th root                                            |
| <code>[t x] = ode45('f', tspan, x0)</code> ... | solve $dx/dt = f(t, x)$ with initial condition $x(0) = x_0$ |
| <code>ones(m, n)</code> .....                  | $m \times n$ matrix of ones                                 |
| <code>peaks</code> .....                       | example 3d graph of a surface with many local extrema       |
| <code>pi</code> .....                          | the number $\pi$                                            |
| <code>pinv(A)</code> .....                     | pseudoinverse of $A$                                        |
| <code>pkg install -forge NAME</code> .....     | download and install a package from Octave Forge            |
| <code>pkg list</code> .....                    | list installed packages                                     |
| <code>pkg load NAME</code> .....               | load an installed package                                   |
| <code>plot(x, y)</code> .....                  | plot of $x$ vs. $y$                                         |
| <code>plot3(x, y, z)</code> .....              | plot space curve                                            |
| <code>polar(theta, rho)</code> .....           | polar plot of radial distance $\rho$ vs. angle $\theta$     |
| <code>polyfit(x, y, order)</code> .....        | polynomial fit $x$ vs. $y$ of degree ‘order’                |
| <code>polyval(P, x)</code> .....               | evaluate polynomial $P$ at $x$                              |
| <code>ppval(P, x)</code> .....                 | evaluate piecewise polynomial $P$ at $x$                    |
| <code>print -dpng filename.png</code> .....    | save plot as png (substitute jpg, eps, etc)                 |
| <code>pwd</code> .....                         | print (list) current working directory                      |
| <code>[Q R] = qr(A)</code> .....               | $QR$ decomposition of $A$                                   |
| <code>quad('f', a, b)</code> .....             | definite integral of $f$ from $a$ to $b$                    |
| <code>quiver(X, Y, U, V)</code> .....          | plot vector field with components $U$ and $V$               |
| <code>quiver3(X, Y, Z, U, V, W)</code> .....   | plot 3d vector field with components $U, V, W$              |
| <code>rand(m, n)</code> .....                  | $m \times n$ random matrix (uniformly distributed entries)  |
| <code>randn(m, n)</code> .....                 | $m \times n$ random matrix (normally distributed entries)   |
| <code>rank(A)</code> .....                     | rank of $A$                                                 |
| <code>real(z)</code> .....                     | real part of $z$                                            |
| <code>save filename A, B, ...</code> .....     | save variables $A, B, \dots$                                |
| <code>sin(x)</code> .....                      | sine of $x$ ( $x$ in radians)                               |
| <code>sinh(x)</code> .....                     | hyperbolic sine of $x$                                      |
| <code>size(A, opt)</code> .....                | dimensions of $A$ ; dimension option: 1=rows, 2=cols        |
| <code>solve(a == b)</code> .....               | solve a symbolic equation                                   |

continued ...

... continued

| Syntax                                         | Description                                                        |
|------------------------------------------------|--------------------------------------------------------------------|
| <code>sqrt(x)</code>                           | principle square root of $x$                                       |
| <code>std(x)</code>                            | standard deviation of $x$                                          |
| <code>subs(f, x)</code>                        | evaluate symbolic expression $f$ at $x$                            |
| <code>sum(A)</code>                            | sum of vector components or column-wise sum of matrix $A$          |
| <code>sum(sum(A))</code>                       | sum of all entries in matrix $A$                                   |
| <code>surf(X, Y, Z)</code>                     | surface plot                                                       |
| <code>[U S V] = svd(A)</code>                  | singular value decomposition of $A$                                |
| <code>syms(x)</code>                           | define symbolic variable                                           |
| <code>taylor(f, x, a, 'order', n)</code>       | degree $n$ Taylor polynomial of $f$ about $a$                      |
| <code>tdcf(x, n)</code>                        | Students $t$ -distribution CDF with degrees of freedom $n$         |
| <code>tinv(a, n)</code>                        | inverse $t$ -distribution with degrees of freedom $n$              |
| <code>ttest(X, mu, 'name', 'value')</code>     | $t$ -test, name-value pairs set alpha and tail (left, right, both) |
| <code>tan(x)</code>                            | tangent of $x$ ( $x$ in radians)                                   |
| <code>tanh(x)</code>                           | hyperbolic tangent of $x$                                          |
| <code>title('name')</code>                     | assign plot title                                                  |
| <code>triplequad('f', a, b, c, d, e, f)</code> | triple integral over a rectangular box                             |
| <code>[x, p] = unmkpp(P)</code>                | extract components of piecewise polynomial $P$                     |
| <code>var(x)</code>                            | variance of $x$                                                    |
| <code>whos</code>                              | list variables in current scope                                    |
| <code>xlabel('name')</code>                    | horizontal axis label                                              |
| <code>ylabel('name')</code>                    | vertical axis label                                                |
| <code>zeros(m, n)</code>                       | $m \times n$ matrix of zeros                                       |

Note that most commands which accept a function as an argument expect the name to be in quotes ('*f*') if it is defined as a named function (using the `function ... end` construction, whether so-defined at the command line, in a script, or in a function file), but if  $f$  is a function *handle* (e.g., defined as anonymous function), then no quotes are used.

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Cover image: *Mandelbrot Set*, created with GNU Octave by the author.

These notes are intended to provide a brief, noncomprehensive introduction to GNU Octave, a free open source alternative to MATLAB. The basic syntax and usage is explained through concrete examples from the mathematics courses a math, computer science, or engineering major encounters in the first two years of college: linear algebra, calculus, and differential equations.

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