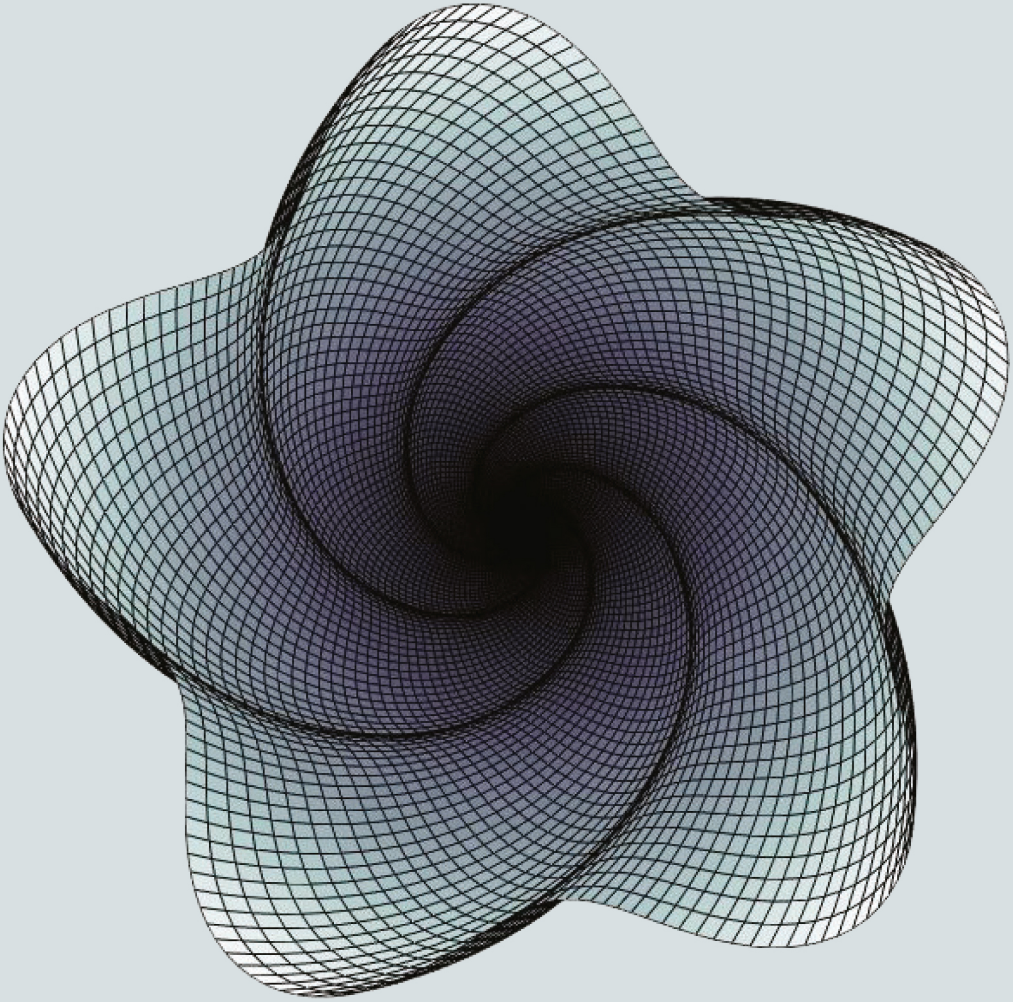

MATLAB®

A PRACTICAL INTRODUCTION TO PROGRAMMING AND PROBLEM SOLVING

SIXTH EDITION

MATLAB® examples

STORMY ATTAWAY

MATLAB®

A Practical Introduction to Programming and Problem Solving

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MATLAB®

A Practical Introduction to Programming and Problem Solving

Sixth Edition

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ELSEVIER

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Contents

PART 2 Advanced Topics for Problem Solving with MATLAB

Preface

MOTIVATION

The purpose of this book is to teach basic programming concepts and skills needed for basic problem solving using MATLAB® as the vehicle. MATLAB is a powerful software package that has built-in functions to accomplish a diverse range of tasks, from mathematical operations to three-dimensional imaging. Additionally, MATLAB has a complete set of programming constructs (basic coding building blocks) that allow users to customize programs to their own specifications.

There are many books that introduce MATLAB. There are two basic flavors of these books: those that demonstrate the use of the built-in functions in MATLAB, with a chapter or two on some programming concepts; and those that cover only the programming constructs without mentioning many of the built-in functions that make MATLAB efficient to use. Someone who learns just the built-in functions will be well-prepared to use MATLAB but would not understand basic programming concepts. That person would not be able to then learn a language such as C++ or Java without taking another introductory course, or reading another book, on the programming concepts. Conversely, anyone who learns only programming concepts first (using any language) would tend to write highly inefficient code using control statements to solve problems, not realizing that in many cases these are not necessary in MATLAB.

Instead, this book takes a hybrid approach, introducing both the traditional programming approaches and the efficient uses. The challenge for students is that it is nearly impossible to predict whether they will in fact need to know traditional programming concepts later on or whether a software package such as MATLAB will suffice for their careers. Therefore the best approach for beginning students is to give them both: the traditional programming concepts, and the efficient built-in functions. Because MATLAB is very easy to use, it is a perfect platform for this approach to teaching programming and problem solving.

Because programming concepts are critically important to this book, emphasis is not placed on the time-saving features that evolve with every new MATLAB release. For example, statistics on variables are available readily in the Workspace Window. This is not shown in any detail in the book because of the desire to explain the concepts in the book.

MODIFICATIONS IN THE SIXTH EDITION

The major modification is the introduction of concepts and terminology used in Data Science and Machine Learning. These are increasingly important topics, useful in all fields, but they are very complex. Therefore, rather than just adding another chapter to the end of this book, these concepts are introduced throughout the book. At the end of every chapter, a few topics that are related to that chapter will be introduced in a supplement of only approximately two pages. By doing this, the concepts and terminologies used in Data Science and Machine Learning are gradually introduced. These supplements also serve to add context to each chapter. Then, at the end, there is a new chapter on this material, but it is short because the first 30 pages of the chapter are already spread throughout the book.

Other changes in the Sixth Edition of this book include the following:

- Use of MATLAB Version R2021b
- New section introducing controls and tasks in the Live Editor
- New section on validating function arguments
- Earlier coverage of matrix operations and matrix properties
- Earlier coverage of live scripts
- Earlier coverage of .mat files
- Usage of built-in files, including .mat files, .csv files, and .jpg files
- More coverage of data structures including tables
- New section on reading from and writing to .csv and spreadsheet files using **readtable**, **writetable**, **readmatrix**, and **writematrix**, replacing the old **xlsread**, **xlswrite**, **csvread**, and **csvwrite** functions, which are no longer recommended
- More plot functions, including **scatter**, **gscatter**, **xline**, **yline**, **sgtitle**, and **subtitle**
- More "is" functions, including **ismethod** and **isnumeric**
- More table functions including **head**, **tail**, **preview**, **addvars**, **movevars**, **removevars**, and **renamevars**
- New basic functions including dimension functions **height** and **width**, and string function **append**
- Usage of functions that work with data including **normalize**, **rmoutliers**, **missing**, and **fillmissing**

- Usage of “mustBe” functions for validating function arguments
- Change in focus from **help** to the online Documentation pages
- Many modified and new end-of-chapter exercises (over 100 new, ∼25%, are new)

Some of the Advanced Mathematics topics that were previously covered in Chapter 14 have been moved. Coverage of statistical functions has been moved to the Machine Learning supplements at the end of Chapters 2 and 10 (and augmented in the supplements in Chapters 3 and 11). Fitting curves to data has been moved (and augmented) to the Machine Learning supplements at the end of Chapters 12 and 14.

KEY FEATURES

Side-by-Side Programming Concepts and Built-In Functions

The most important and unique feature of this book is that it teaches programming concepts and the use of the built-in functions in MATLAB, side-by-side. It starts with basic programming concepts such as variables, assignments, input/output, selection, and loop statements. Then, throughout the rest of the book, many times a problem will be introduced and then solved using the “traditional method” and also using the “efficient method.” This will not be done in every case to the point that it becomes tedious, but just enough to get the ideas across.

Systematic Approach

Another key feature is that the book takes a very systematic, step-by-step approach, building on concepts throughout the book. It is very tempting in a MATLAB text to show built-in functions or features early on with a note that says “we’ll do this later.” This book does not do that; functions are covered before they are used in examples. Additionally, basic programming concepts will be explained carefully and systematically. Very basic concepts such as looping to calculate a sum, counting in a conditional loop, and error-checking are not found in many texts but are covered here.

Data Transfer

Many applications in engineering and the sciences involve manipulating large data sets that are stored in external files. Most MATLAB texts at least mention the **save** and **load** functions, and in some cases also some of the lower-level file input/output functions. Because file input and output are so fundamental to so many applications, this book will cover several low-level file input/output functions, as well as reading from and writing to spreadsheet files and .csv files. Later chapters will also deal with audio and image files. These file input/output concepts are introduced gradually: first **load** and **save** in Chapter 3, then lower-level functions in Chapter 9, and finally sound and images in Chapter 13. A brief introduction to RESTFUL web functions, which import data from websites, is given in Chapter 9.

User-Defined Functions

User-defined functions are a very important programming concept, and yet many times the nuances and differences between concepts such as types of functions and function calls versus function headers can be very confusing to beginning programmers. Therefore these concepts are introduced gradually. First, arguably the easiest type of functions to understand, those that calculate and return one single value, are demonstrated in Chapter 3. Later, functions that return no values and functions that return multiple values are introduced in Chapter 6. Finally, advanced function features are shown in Chapter 10.

Advanced Programming Concepts

In addition to the basics, some advanced programming concepts such as text manipulation, data structures (e.g., structures, tables, and cell arrays), recursion, anonymous functions, and variable number of arguments to functions are covered. Sorting is also addressed. All of these are again approached systematically; for example, cell arrays are covered before they are used in file input functions and as labels on pie charts.

Problem-Solving Tools

In addition to the programming concepts, some basic mathematics necessary for solving many problems will be introduced. These will include statistical functions, solving sets of linear algebraic equations, and fitting curves to data. The use of complex numbers and some calculus (integration and differentiation) will also be introduced. The built-in functions in MATLAB to perform these tasks will be described.

Plots, Imaging, and Graphical User Interfaces

Simple two-dimensional plots are introduced very early in the book (Chapter 3) so that plot examples can be used throughout. A separate chapter, Chapter 12, shows more plot types and demonstrates customizing plots and how the graphics properties are handled in MATLAB. This chapter makes use of text and cell arrays to customize labels. Also, there is an introduction to image processing and the basics necessary to understand programming Graphical User Interfaces (GUIs) in Chapter 13. App Designer, which creates GUIs using object-oriented code, is also introduced in Chapter 13.

Vectorized Code

Efficient uses of the capabilities of the built-in operators and functions in MATLAB are demonstrated throughout the book. To emphasize the importance of using MATLAB efficiently, the concepts and built-in functions necessary for writing vectorized code are treated very early in Chapter 2. Techniques such as preallocating vectors and using logical vectors are then covered in Chapter 5 as alternatives to selection statements and looping through vectors and matrices. Methods of determining how efficient the code is are also covered.

Object-Oriented Programming

Creating objects and classes in MATLAB has been an option for some time, but as of R2014b, all Graphics objects are truly objects. Thus, object-oriented programming (OOP) is a very important part of MATLAB programming. Applications using App Designer reinforce the concepts.

Data Science

Many concepts related to data science, such as normalizing vectors, finding correlations between vectors, randomizing data, visualizing data, and data scrubbing are introduced in the end-of-chapter supplements and also in Chapter 15.

Machine Learning

Concepts related to Machine Learning, including types of algorithms (supervised learning: classification and regression; unsupervised learning: clustering), binning/bucketing, one-hot encoding, assessing model performance, confusion matrices, split and cross validation, hyperparameter tuning, feature engineering, splitting data, and basic workflows are introduced in the end-of-chapter supplements and in Chapter 15.

LAYOUT OF TEXT

This text is divided into two parts: the first part covers programming constructs and demonstrates the programming method versus efficient use of built-in functions to solve problems. The second part covers tools that are used for basic problem solving, including plotting, image processing, and techniques to solve systems of linear algebraic equations, fit curves to data, and perform basic statistical analyses. The first six chapters cover the very basics in MATLAB and in programming, and are all prerequisites for the rest of the book. After that, many chapters in the problem solving section can be introduced when desired, to produce a customized flow of topics in the book. This is true to an extent, although the order of the chapters has been chosen carefully to ensure that the coverage is systematic.

The individual chapters and which topics are required for each chapter are described here.

PART 1: INTRODUCTION TO PROGRAMMING USING MATLAB

Chapter 1: **Introduction to MATLAB** begins by covering the MATLAB Desktop Environment. Variables, assignment statements, and types are introduced. Mathematical and relational expressions and the operators used in them are covered, as are characters, random numbers, and the use of built-in functions and the Help browser. The use of .mat files to store variables is introduced. Alternate MATLAB platforms are also introduced.

Chapter 2: **Vectors and Matrices** introduce creating and manipulating vectors and matrices. Array operations, matrix operations (such as matrix multiplication), and matrix properties are explained. The use of vectors and matrices as function arguments and functions that are written specifically for vectors and matrices are covered. Logical vectors and other concepts useful in vectorizing code are emphasized in this chapter.

Chapter 3: **Introduction to MATLAB Programming** introduces the idea of algorithms and scripts. This includes simple input and output and commenting. Scripts are then used to create and customize simple plots and to do file input and output. Finally, the concept of a user-defined function is introduced with only the type of function that calculates and returns a single value. The Live Editor is introduced.

Chapter 4: **Selection Statements** introduce the use of logical expressions in **if** statements, with **else** and **elseif** clauses. The **switch** statement is also demonstrated, as is the concept of choosing from a menu. Also, functions that return **logical true** or **false** are covered.

Chapter 5: **Loop Statements and Vectorizing Code** introduce the concepts of counted (**for**) and conditional (**while**) loops. Many common uses such as summing and counting are covered. Nested loops are also introduced. Some more sophisticated uses of loops such as error-checking and combining loops and selection statements are also covered. Finally, vectorizing code, by using built-in functions and operators on vectors and matrices instead of looping through them, is demonstrated. Tips for writing efficient code are emphasized, and tools for analyzing code are introduced.

The concepts in the first five chapters are assumed throughout the rest of the book.

Chapter 6: **MATLAB Programs** cover more on scripts and user-defined functions. User-defined functions that return more than one value and also that do not return anything are introduced. The concept of a program in MATLAB, which normally consists of a script that calls user-defined functions, is demonstrated with examples. A longer, menu-driven program is shown as a reference but could be omitted. Local functions and scope of variables are also introduced, as are some debugging techniques. The use of controls and tasks in live scripts is covered.

The concept of a program is used throughout the rest of the book.

Chapter 7: **Text Manipulation** covers many built-in text manipulation functions and converting between string and number types. Several examples include using custom strings in plot labels and input prompts. The new string type is introduced.

Chapter 8: **Data Structures** introduce three main data structures: cell arrays, structures, and tables. Once structures are covered, more complicated data structures such as nested structures and vectors of structures are also introduced. Cell arrays are used in several applications in later chapters, such as file input in Chapter 9, variable number of function arguments in Chapter 10, and plot labels in Chapter 12, and are therefore considered important and are covered first. The section on structures can be omitted, although the use of structure variables to store object properties is shown in Chapter 11. The use of tables is common in Machine Learning so that coverage is important before Chapter 15. Other data structures such as categorical arrays are also introduced. Methods of sorting are described. Sorting a vector of structures is described, but this section can be omitted.

PART II: ADVANCED TOPICS FOR PROBLEM SOLVING WITH MATLAB

Chapter 9: **Data Transfer** covers lower-level file input/output statements that require opening and closing the file. Functions that can read the entire file at once and those that require reading one line at a time are introduced and examples that demonstrate the differences in their use are shown. Additionally, techniques for reading from and writing to spreadsheet files and .csv are introduced. Cell arrays and text functions are used extensively in this chapter. Reading data from websites is also introduced.

Chapter 10: **Advanced Functions** cover more advanced features of and types of functions, such as anonymous functions, nested functions, and recursive functions. Function handles and their use both with anonymous functions and function functions are introduced. The concept of having a variable number of input and/or output arguments to a function is introduced; this is implemented using cell arrays. String functions are also used in several examples in this chapter. The section on recursive functions is at the end and may be omitted. Validating function arguments is also included, but this section may be omitted.

Chapter 11: **Introduction to Object-Oriented Programming and Graphics**

As of version R2014b, all plot objects are actual objects. This chapter introduces Object-Oriented Programming (OOP) concepts and terminology using plot objects and then expands to how to write your own class definitions and create your own objects.

Chapter 12: **Advanced Plotting Techniques** continue with more on the plot functions introduced in Chapter 3. Different two-dimensional plot types, such as logarithmic scale plots, pie charts, and histograms are introduced, as are customizing plots using cell arrays and string functions. Three-dimensional plot functions and some functions that create the coordinates for specified objects are demonstrated. The notion of Graphics is covered, and some graphics properties such as line width and color are introduced. Core graphics objects and their use by higher-level plotting functions are demonstrated. Applications that involve reading data from files and then plotting use both cell arrays and string functions.

Chapter 13: **Sights and Sounds** briefly discuss sound files and introduce image processing. An introduction to programming Graphical User Interfaces (GUIs) is also given, including the creation of a button group and embedding images in a GUI. Nested functions are used in the GUI examples. The App Designer is introduced; it creates OOP code and builds on the concepts from Chapter 11.

Chapter 14: **Advanced Mathematics** covers five basic topics: it starts with some of the built-in set operations in MATLAB, then complex numbers, solving systems of linear algebraic equations, and integration and differentiation in calculus. Finally, some of the symbolic math toolbox functions are shown, including those that solve equations. This method returns a structure as a result.

Chapter 15: **Basic Machine Learning Algorithms and Concepts** build on the data science and machine learning supplements at the ends of all of the previous 14 chapters. All of this can be omitted, but it provides context and introduces real-world applications.

PATH THROUGH THE BOOK

It has come to my attention that not all courses that use this text use all sections. In particular, not everyone gets to images and apps, which are the cool applications! I have reorganized some of the chapters and sections to make it easier to get to the fun, motivating applications including images and App Designer. What follows is a path through the book to get there, including which sections can be skipped.

Chapter 1: The last two sections, 1.9 and 1.10, can be skipped

Chapter 2: Section 2.5 can be skipped

Chapters 3 and 4: Both are fundamental

Chapter 5: The last section on Timing can be skipped

Chapter 6: The last two sections can be skipped

Chapter 7: The last section can be skipped

Chapter 8: Cell arrays and structures are important, but the last two sections can be skipped

Chapter 9: This can be skipped entirely, although there are very cool applications in 9.3

Chapter 10: Variable number of arguments, nested functions, and anonymous functions are all used in App Designer, but the other sections can be skipped

Chapter 11: The first two sections are fundamental, but the rest can be skipped

Chapter 12: This can be skipped entirely

Chapter 13: Most sections are independent, although the concept of callback functions is explained in the GUI section and then used in the App Designer section

Chapter 14: All sections can be skipped

Chapter 15: All sections can be skipped

PEDAGOGICAL FEATURES

There are several pedagogical tools that are used throughout this book that are intended to make it easier to learn the material.

First, the book takes a conversational tone with sections called "***Quick Question!***" These are designed to stimulate thought about the material that has just been covered. The question is posed, and then the answer is given. It will be most beneficial to the reader to try to think about the question before reading the answer! In any case, they should not be skipped over because the answers often contain very useful information.

"Practice" problems are given throughout the chapters. These are very simple problems that drill the material just covered.

"Explore Other Interesting Features." This book is not intended to be a complete reference book and cannot possibly cover all of the built-in functions and tools available in MATLAB; however, in every chapter there will be a list of functions and/or commands that are related to the chapter topics, which readers may wish to investigate.

When some problems are introduced, they are solved both using ***"The Traditional Method"*** and also ***"The Efficient Method."*** This facilitates understanding the built-in functions and operators in MATLAB and the underlying programming concepts. ***"The Efficient Method"*** highlights methods that will save time for the programmer, and, in many cases, are also faster to execute in MATLAB.

Additionally, to aid the reader:

- Identifier names are shown in *italic*.
- MATLAB function names are shown in **bold**.
- Reserved words are shown in **<u>bold and underlined</u>**.
- Key important terms are shown in ***bold and italic***.

The end of chapter **"Summary"** contains, where applicable, several sections:

- **Common Pitfalls**: A list of common mistakes that are made and how to avoid them.
- **Programming Style Guidelines**: To encourage "good" programs that others can actually understand, the programming chapters will have guidelines that make programs easier to read and understand and therefore easier to work with and modify.
- **Key Terms**: A list of the key terms covered in the chapter, in sequence.
- **MATLAB Reserved Words**: A list of the reserved key words in MATLAB. Throughout the text, these are shown in bold, underlined type.
- **MATLAB Functions and Commands**: A list of the MATLAB built-in functions and commands covered in the chapter, in the order covered. Throughout the text, these are shown in bold type.
- **MATLAB Operators**: A list of the MATLAB operators covered in the chapter, in the order covered.
- **Exercises**: A comprehensive set of exercises, ranging from the rote to more engaging applications.

ADDITIONAL BOOK RESOURCES

A companion website with additional teaching resources is available for faculty using this book as a text for their course(s). Please visit https://educate.elsevier.com/book/details/9780323917506 to register for access to:

- Instructor solutions manual for end of chapter problems
- Instructor solutions manual for "Practice" problems
- Electronic figures from the text for creation of lecture slides
- Downloadable code files for all examples in the text

Other book-related resources will also be posted there from time to time.

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Finally, thanks go to all of my family, especially my parents, Roy Attaway and Jane Conklin, both of whom encouraged me at an early age to read and to write. Thanks also to my husband, Ted de Winter, for his encouragement.

The photo used in the image processing section was taken by Ron Roy.

1

PART

Introduction to Programming Using MATLAB®

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CHAPTER 1

Introduction to MATLAB®

KEY TERMS

prompt
programs
script files
toolstrip
variable
assignment statement
assignment operator
user
initializing
incrementing
decrementing
identifier names
reserved words
keywords
mnemonic
types
classes
double precision
floating point
unsigned
characters
character vectors

strings
default
continuation operator
ellipsis
unary
operand
binary
scientific notation
exponential notation
precedence
associativity
nested parentheses
inner parentheses
call a function
arguments
returning values
tab completion
constants
random numbers
seed
pseudorandom
open interval

global stream
character encoding
character set
relational expression
Boolean expression
logical expression
relational operators
logical operators
scalars
short-circuit operators
truth table
commutative
roundoff errors
range
casting
type casting
saturation arithmetic
locale setting
logarithm
common logarithm
natural logarithm
appending

CONTENTS

MATLAB® is a very powerful software package that has many built-in tools for solving problems and developing graphical illustrations. The simplest method for using the MATLAB product is interactive; an expression is entered by the user and MATLAB responds immediately with a result. It is also possible to write scripts and programs in MATLAB, which are essentially groups of commands that are executed sequentially.

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00001-9

This chapter will focus on the basics, including many operators and built-in functions that can be used in interactive expressions.

1.1 GETTING INTO MATLAB

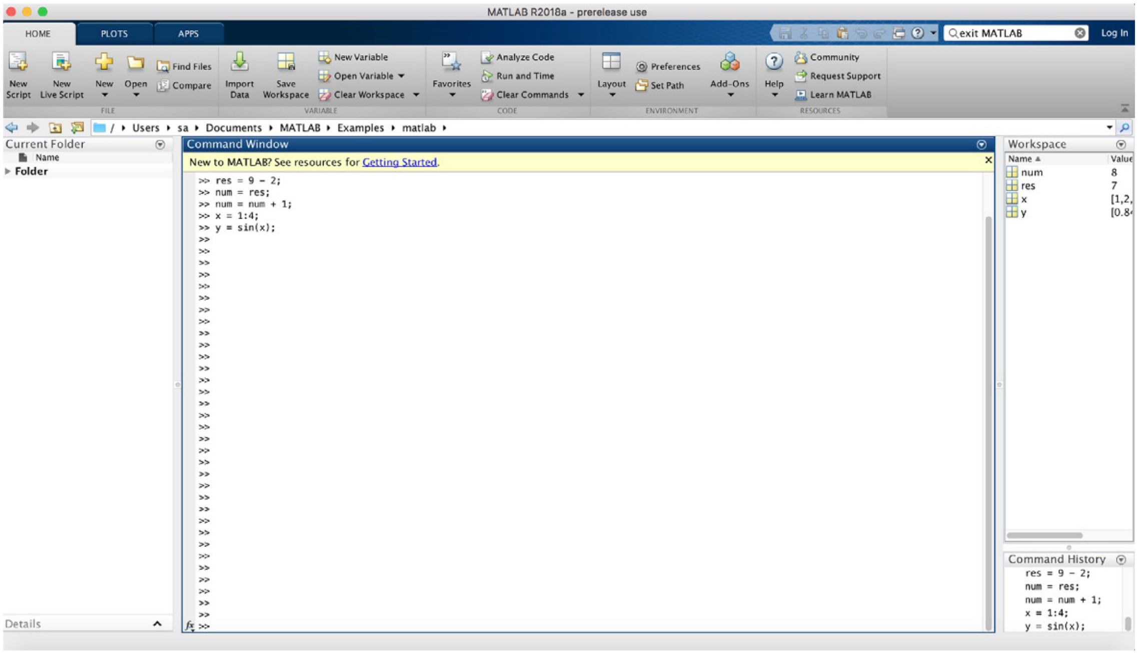
MATLAB is a mathematical and graphical software package with numerical, graphical, and programming capabilities. It includes an integrated development environment, as well as both procedural and object-oriented programming capabilities. It has built-in functions to perform many operations, and there are toolboxes that can be added to augment these functions (e.g., for signal processing or machine learning). There are versions available for different hardware platforms, in both professional and student editions. MathWorks releases two versions of MATLAB annually, named by the year and 'a' or 'b'. This book covers the releases through Version R2021b. In cases in which there have been changes in recent years, these are noted.

When the MATLAB software is started, a window opens in which the main part is the Command Window. See Fig. 1.1 for the configuration as of R2021b. In the Command Window, you should see:

```
>>
```

The >> is called the ***prompt***. In the Student Edition, the prompt instead is:

```
EDU>>
```



New to MATLAB? See resources for Getting Started.

```
>> res = 9 - 2;
>> num = res;
>> num = num + 1;
>> x = 1:4;
>> y = sin(x);
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
>>
fx >>
```

Name ▲	Value
num	8
res	7
x	[1,2,
y	[0.8

```
res = 9 - 2;
num = res;
num = num + 1;
x = 1:4;
y = sin(x);
```

FIGURE 1.1
MATLAB Command Window.

In the Command Window, MATLAB can be used interactively. At the prompt, any MATLAB command or expression can be entered, and MATLAB will respond immediately with the result.

It is also possible to write ***programs*** in MATLAB that are contained in ***script files*** or MATLAB code files. Programs will be introduced in Chapter 3.

The following commands can serve as an introduction to MATLAB and allow you to get help:

- **doc** brings up a documentation page in the online documentation
- **help** explains any function; **help help** will explain how help works
- **demo** brings up MATLAB examples in the documentation, which has examples of some of the features of MATLAB
- **lookfor** searches through the help for a specific word or phrase (Note: this can result in a long list)

The **doc** pages contain more detailed information than **help**.

To exit from MATLAB, either type **quit** or **exit** at the prompt, or click on the red "x" button.

1.2 THE MATLAB DESKTOP ENVIRONMENT

In addition to the Command Window, there are several other windows that can be opened and may be opened by default. What is described here is the default layout for these windows in Version R2021b, although there are other possible configurations. Different versions of MATLAB may show other configurations by default, and the layout can always be customized. Therefore, the main features will be described briefly here.

To the left of the Command Window is the Current Folder Window. The folder that is set as the Current Folder is where files will be saved. This window shows the files that are stored in the Current Folder. These can be grouped in many ways, for example by type, and sorted, for example by name. If a file is selected, information about that file is shown underneath the list.

To the right of the Command Window are the Workspace Window on top and the Command History Window on the bottom. The Command History Window shows commands that have been entered, not just in the current session (in the current Command Window), but previously as well. The Workspace Window will be described in the next section.

This default configuration can be altered by clicking the down arrow at the top right corner of each window. This will show a menu of options (different for each window), including, for example, closing that particular window and undocking that window. To make any of these windows the active window, click the mouse in it. By default, the active window is the Command Window.

The Desktop has a ***toolstrip***. By default, three tabs are shown: "HOME", "PLOTS", and "APPS".

Under the "HOME" tab there are many useful features, which are divided into functional sections "FILE", "VARIABLE", "CODE", "ENVIRONMENT", and "RESOURCES" (these labels can be seen on the very bottom of the gray toolstrip area). For example, under "ENVIRONMENT", hitting the down arrow under Layout allows for customization of the windows within the Desktop Environment. Other toolstrip features will be introduced in later chapters when the relevant material is explained.

1.3 VARIABLES AND ASSIGNMENT STATEMENTS

To store a value in a MATLAB session, or in a program, a ***variable*** is used. The Workspace Window shows variables that have been created and their values. One easy way to create a variable is to use an ***assignment statement***. The format of an assignment statement is

```
variablename = expression
```

The variable is always on the left, followed by the = symbol, which is the ***assignment operator*** (unlike in mathematics, the single equal sign does *not* mean equality), followed by an expression. The expression is evaluated and then that value is stored in the variable. Here is an example and how it would appear in the Command Window:

```
>> mynum = 6
mynum =
     6
>>
```

Here, the ***user*** (the person working in MATLAB) typed "mynum = 6" at the prompt, and MATLAB stored the integer 6 in the variable called *mynum*, and then displayed the result followed by the prompt again. Because the equal sign is the assignment operator, and does not mean equality, the statement should be read as "mynum gets the value of 6" (*not* "mynum equals 6").

Note that the variable name must always be on the left, and the expression on the right. An error will occur if these are reversed.

```
>> 6 = mynum
  6 = mynum
    ↑
Incorrect use of '=' operator. Assign a value to a variable
using '=' and compare values for equality using '=='.
>>
```

Putting a semicolon at the end of a statement suppresses the output. For example,

```
>> res = 9 - 2;
>>
```

This would assign the result of the expression on the right side, the value 7, to the variable *res*; it just does not show that result. Instead, another prompt appears immediately. However, at this point in the Workspace Window, both the variables *mynum* and *res* and their values can be seen.

The spaces in a statement or expression do not affect the result, but make it easier to read. The following statement, which has no spaces, would accomplish exactly the same result as the previous statement:

Note that in the remainder of the book, the prompt that appears after the result will not be shown. What the user types will be shown in italics.

```
>> res=9-2;
```

MATLAB uses a default variable named *ans,* if an expression is typed at the prompt and it is not assigned to a variable. For example, the result of the expression 6 + 3 is stored in the variable *ans*:

```
>> 6 + 3
ans =
      9
```

This default variable, *ans*, is reused any time that only an expression, not an assignment statement, is typed at the prompt.

A shortcut for retyping commands is to hit the up arrow ↑, which will go back to the previously typed command(s). For example, if you decide to assign the result of the expression 6 + 3 to a variable named *result* instead of using the default variable *ans*, you could hit the up arrow and then the left arrow to modify the command rather than retyping the entire statement:

Note that it is not a good idea to use *ans* as a name yourself or in expressions.

```
>> result = 6 + 3
result =
      9
```

This is very useful, especially if a long expression is entered and it contains an error, and it is desired to go back to correct it.

It is also possible to choose command(s) in the Command History Window and to re-run them by right-clicking and choosing Evaluate Selection. Consecutive commands can be chosen by clicking on the first or last and then holding down the Shift and up or down arrows.

To change a variable, another assignment statement can be used, which assigns the value of a different expression to it. Consider, for example, the following sequence of statements:

```
>> mynum = 3
mynum =
          3
>> mynum = 4 + 2
mynum =
          6
>> mynum = mynum + 1
mynum =
          7
```

In the first assignment statement, the value 3 is assigned to the variable *mynum*. In the next assignment statement, *mynum* is changed to have the value of the expression 4+2, or 6. In the third assignment statement, *mynum* is changed again, to the result of the expression *mynum* + *1*. Because at that time *mynum* had the value 6, the value of the expression was 6+1, or 7.

At that point, if the expression *mynum+3* is entered, the default variable *ans* is used since the result of this expression is not assigned to a variable. Thus, the value of *ans* becomes 10 but *mynum* is unchanged (it is still 7). Just typing the name of a variable will display its value (the value can also be seen in the Workspace Window).

```
>> mynum + 3
ans =
      10

>> mynum
mynum =
       7
```

Note

that the value can also be seen in the Workspace Window. Also, by clicking on the down arrow in the Workspace Window, and choosing Choose Columns, additional information can be seen for each variable.

1.3.1 Initializing, Incrementing, and Decrementing

Frequently, values of variables change, as shown previously. Putting the first or initial value in a variable is called ***initializing*** the variable.

Adding to a variable is called ***incrementing***. For example, the statement

```
mynum = mynum + 1;
```

increments the variable *mynum* by 1.

QUICK QUESTION!

How can 1 be subtracted from the value of a variable called num?

Answer: `num = num - 1;`

This is called ***decrementing*** the variable.

1.3.2 Variable Names

Variable names are an example of ***identifier names***. We will see other examples of identifier names, such as function names, in future chapters. The rules for identifier names are as follows:

- The name must begin with a letter of the alphabet. After that, the name can contain letters, digits, and the underscore character (e.g., *value_1*), but it cannot have a space.
- There is a limit to the length of the name; the built-in function **namelengthmax** tells what this maximum length is (any extra characters are truncated).
- MATLAB is case-sensitive, which means that there is a difference between upper and lowercase letters. So, variables called *mynum*, *MYNUM*, and *Mynum* are all different (although this would be confusing and should not be done).
- Although underscore characters are valid in a name, their use can cause problems with some programs that interact with MATLAB, so some programmers use mixed case instead (e.g., *partWeights* instead of *part_weights*)
- There are certain words called ***reserved words***, or ***keywords***, that cannot be used as variable names.
- Names of built-in functions (described in the next section) can, but should not, be used as variable names.

Additionally, variable names should always be ***mnemonic***, which means that they should make some sense. For example, if the variable is storing the radius of a circle, a name such as *radius* would make sense; *x* probably would not.

The following commands relate to variables:

- **who** shows variables that have been defined in this Command Window (this just shows the names of the variables)
- **whos** shows variables that have been defined in this Command Window (this shows more information on the variables, similar to what is in the Workspace Window)
- **clearvars** clears out all variables so that they no longer exist
- **clearvars** *variablename* clears out a particular variable
- **clearvars** *variablename1 variablename2* … clears out a list of variables (note: separate the names with spaces, not commas)
- **clear** is similar to **clearvars** but also clears out functions

If nothing appears when **who** or **whos** is entered, that means there are not any variables! For example, in the beginning of a MATLAB session, variables could be created and then selectively cleared (remember that the semicolon suppresses output).

```
>> who
>> mynum=3;
>> mynum+5;
>> who
Your variables are:
ans      mynum
>> clear mynum
>> who
Your variables are:
ans
```

These changes can also be seen in the Workspace Window.

1.3.3 Types

Every variable has a ***type*** associated with it. MATLAB supports many types, which are called ***classes***. (Essentially, a class is a combination of a type and the operations that can be performed on values of that type, but, for simplicity, we will use these terms interchangeably for now. More on classes will be covered in Chapter 11.)

For example, there are types to store different kinds of numbers. For float or real numbers, or in other words numbers with a decimal place (e.g., 5.3), there are two basic types: **single** and **double**. The name of the type **double** is short for ***double precision***; it stores larger numbers than the **single** type. MATLAB uses a ***floating point*** representation for these numbers.

There are many integer types, such as **int8**, **int16**, **int32**, and **int64**. The numbers in the names represent the number of bits used to store values of that type. For example, the type **int8** uses eight bits altogether to store the integer and its sign. As one bit is used for the sign, this means that seven bits are used to store actual numbers (0s or 1s). There are also ***unsigned*** integer types **uint8**, **uint16**, **uint32**, and **uint64**. For these types, the sign is not stored, meaning that the integer can only be positive (or 0).

The larger the number in the type name, the larger the number that can be stored in it. We will for the most part use the type **int32** when an integer type is required.

By default, numbers are stored as the type **double** in MATLAB. The function **class** can be used to see the type of any variable:

```
>> num = 6 + 3;
>> class(num)
ans =
     'double'
```

The type **char** is used to store either single ***characters*** (e.g., 'x') or ***character vectors***, which are sequences of characters (e.g., 'cat'). Both characters and character vectors are enclosed in single quotes.

The type **string** is used to store ***strings*** (e.g., "hello"). Strings are enclosed in double quotes.

The type **logical** is used to store **true**/**false** values.

The class of a variable can be shown in the Workspace Window.

1.4 NUMERICAL EXPRESSIONS

Expressions can be created using values, variables that have already been created, operators, built-in functions, and parentheses. For numbers, these can include operators such as multiplication and functions such as trigonometric functions. An example of such an expression is:

```
>> 2 * sin(1.4)
ans =
    1.9709
```

1.4.1 The Format Command and Ellipsis

The ***default*** in MATLAB is to display numbers that have decimal points with four decimal places, as shown in the previous example. (The default means if you do not specify otherwise, this is what you get.) The **format** command can be used to specify the output format of expressions.

There are many options, including making the format **short** (the default) or **long**. For example, changing the format to **long** will result in 15 decimal places. This will remain in effect until the format is changed back to **short**, as demonstrated in the following.

```
>> format long
>> 77/888
ans =
   0.086711711711712
>> format short
>> 77/888
ans =
    0.0867
```

The **format** command can also be used to control the spacing between the MATLAB command or expression and the result; it can be either **loose** (the default) or **compact**.

```
>> format loose
>> 5*33
```

```
ans =

   165

>> format compact
>> 5*33
ans =
   165
>>
```

Especially long expressions can be continued on the next line by typing three (or more) periods, which is the ***continuation operator***, or the ***ellipsis***. To do this, type part of the expression followed by an ellipsis, then hit the Enter key and continue typing the expression on the next line.

```
>> 3 + 55 - 62 + 4 - 5 ...
+ 22 - 1

ans =

    16
```

1.4.2 Operators

There are in general two kinds of operators: ***unary*** operators, which operate on a single value, or ***operand***; and ***binary*** operators, which operate on two values or operands. The symbol "-", for example, is both the unary operator for negation and the binary operator for subtraction.

Here are some of the common operators that can be used with numerical expressions:

```
+ addition
- negation, subtraction
* multiplication
/ division (divided by e.g., 10/5 is 2)
\ division (divided into e.g., 5\10 is 2)
^ exponentiation (e.g., 5^2 is 25)
```

In addition to displaying numbers with decimal points, numbers can also be shown using ***scientific or exponential notation***. This uses ***e*** for the exponent of 10 raised to a power. For example, 2 * 10 ^ 4 could be written two ways:

```
>> 2 * 10^4
ans =
        20000
>> 2e4
ans =
        20000
```

1.4.2.1 Operator Precedence Rules

Some operators have ***precedence*** over others. For example, in the expression 4 + 5 * 3, the multiplication takes precedence over the addition, so first 5 is multiplied by 3, then 4 is added to the result. Using parentheses can change the precedence in an expression:

```
>> 4 + 5 * 3
ans =
    19
>> (4 + 5) * 3
ans =
    27
```

Within a given precedence level, the expressions are evaluated from left to right (this is called ***associativity***).

Nested parentheses are parentheses inside of others; the expression in the ***inner parentheses*** is evaluated first. For example, in the expression `5-(6*(4+2))`, first the addition is performed, then the multiplication, and finally the subtraction, to result in `-31`. Parentheses can also be used simply to make an expression clearer. For example, in the expression `((4+(3*5))-1)`, the parentheses are not necessary but are used to show the order in which the parts of the expression will be evaluated.

For the operators that have been covered thus far, the following is the precedence (from the highest to the lowest):

```
( )      parentheses
^        exponentiation
-        negation
*, /, \  all multiplication and division
+, -     addition and subtraction
```

PRACTICE 1.1

Think about what the results would be for the following expressions, and then type them in to verify your answers:

```
1\2
- 5 ^ 2
(-5) ^ 2
10-6/2
5*4/2*3
```

1.4.3 Built-in Functions and Help

There are many built-in functions in MATLAB. The **help** and the **doc** commands can be used to identify MATLAB functions, and how to use them.

To find out what a particular function does and how to call it, type **help** and then the name of the function. For example, the following will give a description of the **sin** function.

```
>> help sin
```

The **doc** page provides more information and examples:

```
>> doc sin
```

Also, to see lists of functions, either just type **doc** or choose the Help button under Resources. Then, choose MATLAB, and then on top choose the Functions tab. This will bring up a long list of all of the MATLAB functions, by category.

To ***call a function***, the name of the function is given followed by the ***argument(s)*** that are passed to the function in parentheses. Most functions then ***return value(s)***. For example, to find the absolute value of -4, the following expression would be entered:

```
>> abs(-4)
```

which is a ***call*** to the function **abs**. The number in the parentheses, the `-4`, is the ***argument***. The value 4 would then be ***returned*** as a result.

QUICK QUESTION!

What would happen if you used the name of a function, for example, **abs**, as a variable name?

Answer: This is allowed in MATLAB, but then **abs** could not be used as the built-in function until the variable is cleared (using either **clear** or **clearvars**). For example, examine the following sequence:

```
>> clearvars
>> abs(-6)
ans =
     6
>> abs = 11
abs =
      11
>> abs(-6)
Array indices must be positive integers or
logical values.
'abs' appears to be both a function and a
variable. If this is unintentional, use
'clear abs' to remove the variable 'abs' from
the workspace.
 >> who

 Your variables are:
 abs ans
 >> clear abs
 >> who
 Your variables are:
 ans
 >> abs(-6)
 ans =
        6
```

All of the operators have a functional form. For example, 2+5 can be written using the **plus** function as follows.

```
>> plus(2,5)
ans =
     7
```

MATLAB has a useful shortcut that is called the ***tab completion*** feature. If you type the beginning characters in the name of a function, and hit the tab key, a list of functions that begin with the typed characters pop up. Capitalization errors are automatically fixed.

Also, if a function name is typed incorrectly, MATLAB will suggest a correct name.

```
>> abso(-4)
Unrecognized function or variable 'abso'.
Did you mean:
>> abs(-4)
```

1.4.4 Constants

Variables are used to store values that might change, or for which the values are not known ahead of time. Most languages also have the capacity to store ***constants***, which are values that are known ahead of time and cannot possibly change. An example of a constant value would be **pi**, or π, which is 3.14159… In MATLAB, there are functions that return some of these constant values, some of which include the following:

pi	3.14159….
i	$\sqrt{-1}$
j	$\sqrt{-1}$
inf	infinity ∞
NaN	stands for "not a number," such as the result of 0/0

Frequently, missing data from files are read into MATLAB as NaN.

1.4.5 Random Numbers

When a program is being written to work with data, and the data are not yet available, it is often useful to test the program first by initializing the data variables to ***random numbers***. Random numbers are also useful in simulations. There are several built-in functions in MATLAB that generate random numbers, some of which will be illustrated in this section.

Random number generators or functions are not truly random. Basically, the way it works is that the process starts with one number, which is called the ***seed***. Frequently, the initial seed is either a predetermined value or it is obtained from the built-in clock in the computer. Then, based on this seed, a process determines the next "random number." Using that number as the seed the next time, another random number is generated, and so forth. These are actually called ***pseudorandom***. They are not truly random because there is a process that determines the next value each time.

The function **rand** can be used to generate uniformly distributed random real numbers; calling it generates one random real number in the ***open interval*** (0,1), which means that the endpoints of the range are not included. There are no arguments passed to the **rand** function in its simplest form. Here are two examples of calling the **rand** function:

```
>> rand
ans =
    0.8147
>> rand
ans =
    0.9058
```

The seed for the **rand** function will always be the same each time MATLAB is started, unless the initial seed is changed. The **rng** function sets the initial seed. There are several ways in which it can be called:

```
>> rng('shuffle')
>> rng(intseed)
>> rng('default')
```

With 'shuffle', the **rng** function uses the current date and time that are returned from the built-in **clock** function to set the seed, so the seed will always be different. An integer can also be passed to be the seed. The 'default' option will set the seed to the default value used when MATLAB starts up. The **rng** function can also be called with no arguments, which will return the current state of the random number generator:

Note

the words after the % are comments and are ignored by MATLAB.

```
>> state_rng = rng; % gets state
>> randone = rand
randone =
    0.1270
>> rng(state_rng);  % restores the state
>> randtwo = rand   % same as randone
randtwo =
    0.1270
```

The random number generator is initialized when MATLAB starts, which generates what is called the ***global stream*** of random numbers. All of the random functions get their values from this stream.

As **rand** returns a real number in the open interval (0, 1), multiplying the result by an integer N would return a random real number in the open interval (0, N). For example, multiplying by 10 returns a real in the open interval (0, 10), so the expression

```
rand*10
```

would return a result in the open interval (0, 10).

To generate a random real number in the range from *low* to *high*, first create the variables *low* and *high*. Then, use the expression rand*(high-low)+low. For example, the sequence

```
>> low = 3;
>> high = 5;
>> rand*(high-low)+low
```

would generate a random real number in the open interval (3, 5).

The function **randn** is used to generate normally distributed random real numbers.

1.4.5.1 Generating Random Integers

As the **rand** function returns a real number, this can be rounded to produce a random integer. For example,

```
>> round(rand*10)
```

would generate one random integer in the range from 0 to 10 inclusive (`rand*10` would generate a random real in the open interval (0, 10); rounding that will return an integer). However, these integers would not be evenly distributed in the range. A better method is to use the function **randi**, which in its simplest form **randi(imax)** returns a random integer in the range from 1 to imax, inclusive. For example, **randi(4)** returns a random integer in the range from 1 to 4. A range can also be passed, for example, **randi([imin, imax])** returns a random integer in the inclusive range from imin to imax:

```
>> randi([3, 6])
ans =
     5
```

PRACTICE 1.2

Generate a random

- real number in the range (0,1)
- real number in the range (0, 100)
- real number in the range (20, 35)
- integer in the inclusive range from 1 to 100
- integer in the inclusive range from 20 to 35

1.5 CHARACTERS AND STRINGS

A character in MATLAB is represented using single quotes (e.g., ‘a’ or ‘x’). The quotes are necessary to denote a character; without them, a letter would be interpreted as a variable name. MATLAB also handles character vectors, which are sequences of characters in single quotes, and strings, which are sequences of characters in double quotes.

```
>> myword = 'hello'
myword =
     'hello'
>> yourword = "ciao"
yourword =
     "ciao"
```

Characters are put in an order using what is called a ***character encoding***. In the character encoding, all characters in the computer’s ***character set*** are placed in a sequence and given equivalent integer values. The character set includes all letters of the alphabet, digits, and punctuation marks; basically, all of the keys on a keyboard are characters. Special characters, such as the Enter key, are also included. Therefore, ‘x’, ‘!’, and ‘3’ are all characters. With quotes, ‘3’ is a character, not a number.

The most common character encoding is the American Standard Code for Information Interchange, or ASCII. Standard ASCII has 128 characters, which have equivalent integer values from 0 to 127. The first 32 (integer values 0 through 31) are nonprinting characters. The letters of the alphabet are in order, which means ‘a’ comes before ‘b’, then ‘c’, and so forth. MATLAB actually can use a much larger encoding sequence, which has the same first 128 characters as ASCII. More on the character encoding, and converting characters to their numerical values, will be covered in Section 1.7.

1.6 RELATIONAL EXPRESSIONS

Expressions that are conceptually either true or false are called ***relational expressions***; they are also sometimes called ***Boolean expressions*** or ***logical expressions.*** These expressions can use both ***relational operators***, which relate two expressions of compatible types, and ***logical operators***, which operate on **logical** operands.

The relational operators in MATLAB are:

Operator	Meaning
>	greater than
<	less than
>=	greater than or equals
<=	less than or equals
==	equality
~=	inequality

All of these concepts should be familiar, although the actual operators used may be different from those used in other programming languages, or in mathematics classes. In particular, it is important to note that the operator for equality is two consecutive equal signs, not a single equal sign (as the single equal sign is already used as the assignment operator).

For numerical operands, the use of these operators is straightforward. For example, `3 < 5` means "3 less than 5", which is, conceptually, a true expression. In MATLAB, as in many programming languages, "true" is represented by the **logical** value 1, and "false" is represented by the **logical** value 0. Therefore, the expression `3 < 5` actually displays in the Command Window the value 1 (**logical**) in MATLAB. Displaying the result of expressions like this in the Command Window demonstrates the values of the expressions.

```
>> 3 < 5
ans =
  logical
   1
>> 2 > 9
ans =
  logical
   0
>> class(ans)
ans =
     'logical'
```

The type of the result is **logical**, not **double**. MATLAB also has built-in **true** and **false** functions.

```
>> true
ans =
  logical
   1
```

In other words, **true** is equivalent to **logical 1** and **false** is equivalent to **logical 0**.

Note

the class names **char** and **string** are not shown because the class is obvious from the single quotes (for **char**) or double quotes (for **string**).

The output in the Command Window shows a header for most classes except for the default number type **double**, **char**, and **string**. If the type of a number result is not the default of **double**, the type (or class) is shown above the resulting value, as in the underlined "logical" in the previous expressions. However, to save room, these types will frequently not be shown for the rest of the book.

Although these are **logical** values, mathematical operations could be performed on the resulting 1 or 0 (which would result in the type **double**).

```
>> logresult = 5 < 7
logresult =
     1
>> logresult + 3
ans =
     4
```

Comparing characters (e.g., 'a' < 'c') is also possible. Characters are compared using their ASCII equivalent values in the character encoding. Therefore, 'a' < 'c' is a **true** expression because the character 'a' comes before the character 'c'.

```
>> 'a' < 'c'
ans =
     1
```

The logical operators are:

Operator	Meaning
||	or
&&	and
~	not

All logical operators operate on **logical** or Boolean operands. The **not** operator is a unary operator; the others are binary. The **not** operator will take a **logical** expression, which is **true** or **false**, and give the opposite value. For example, `~(3 < 5)` is **false** as `(3 < 5)` is **true**. The **or** operator has two **logical** expressions as operands. The result is **true** if either or both of the operands are **true**, and **false** only if both operands are **false**. The **and** operator also operates on two **logical** operands. The result of an **and** expression is **true** only if both operands are **true**; it is **false** if either or both are **false**. The or/and operators shown here are used for ***scalars***, or single values. Other or/and operators will be explained in Chapter 2.

The || and && operators in MATLAB are examples of operators that are known as ***short-circuit*** operators. What this means is that if the result of the expression can be determined based on the first part, then the second part will not even be evaluated. For example, in the expression:

```
2 < 4 || 'a' == 'c'
```

the first part, 2 < 4, is **true** so the entire expression is **true**; the second part 'a' == 'c' would not be evaluated.

In addition to these logical operators, MATLAB also has a function **xor**, which is the exclusive or function. It returns **logical true** if one (and only one) of the arguments is **true**. For example, in the following only the first argument is **true**, so the result is **true**:

```
>> xor(3 < 5, 'a' > 'c')
ans =
     1
```

In this example, both arguments are **true**, so the result is **false**:

```
>> xor(3 < 5, 'a' < 'c')
ans =
     0
```

Given the **logical** values of **true** and **false** in variables *x* and *y*, the ***truth table*** (see Table 1.1) shows how the logical operators work for all combinations. Note that the logical operators are ***commutative*** (e.g., x || y is the same as y || x).

As with the numerical operators, it is important to know the operator precedence rules. Table 1.2 shows the rules for the operators that have been covered thus far in the order of precedence.

Table 1.1 Truth Table for Logical Operators

x	y	~x	x || y	x && y	xor(x,y)
true	true	false	true	true	false
true	false	false	true	false	true
false	false	true	false	false	false

Table 1.2 Operator Precedence Rules

Operators	Precedence
parentheses: ( )	Highest
power ^	
unary: negation (-), not (~)	
multiplication, division *, /, \	
addition, subtraction +, -	
relational <, <=, >, >=, ==, ~=	
and &&	
or ||	Lowest

QUICK QUESTION!

Assume that there is a variable *x* that has been initialized. What would be the value of the expression

```
3 < x < 5
```

if the value of *x* is 4? What if the value of *x* is 7?

Answer: The value of this expression will always be **logical true**, or 1, regardless of the value of the variable *x*. Expressions are evaluated from left to right. Therefore, first the expression 3 < x will be evaluated. There are only two possibilities: either this will be **true** or **false**, which means that either the expression will have the **logical** value 1 or 0. Then, the rest of the expression will be evaluated, which will be either 1 < 5 or 0 < 5. Both of these expressions are **true**. So, the value of *x* does not matter: the expression 3 < x < 5 would be **true** regardless of the value of the variable *x*. This is a logical error; it would not enforce the desired range. If we wanted an expression that was **logical true** only if *x* was in the range from 3 to 5, we could write `3 < x && x < 5` (note that parentheses are not necessary).

PRACTICE 1.3

Think about what would be produced by the following expressions, and then type them in to verify your answers.

```
3 == 5 + 2
'b' < 'a' + 1
10 > 5 + 2
(10 > 5) + 2
'c' == 'd' - 1 && 2 < 4
'c' == 'd' - 1 || 2 > 4
xor('c' == 'd' - 1, 2 > 4)
xor('c' == 'd' - 1, 2 < 4)
10 > 5 > 2
```

Note: be careful about using the equality and inequality operators with numbers. Occasionally, ***roundoff errors*** appear, which means that numbers are close to their correct value but not exactly. For example, cos(pi/2) should be 0. However, because of a roundoff error, it is a very small number but not exactly 0.

```
>> cos(pi/2)
ans =
   6.1232e-17
>> cos(pi/2) == 0
ans =
     0
```

1.7 TYPE RANGES AND TYPE CASTING

The ***range*** of a type, which indicates the smallest and largest numbers that can be stored in the type, can be calculated. For example, the type **uint8** stores 2^8 or 256 integers, ranging from 0 to 255. The range of values that can be stored in **int8**, however, is from −128 to +127. The range can be found for any type by passing the name of the type as a string or character vector (which means in single quotes) to the functions **intmin** and **intmax**. For example,

```
>> intmin('int8')
ans =
 -128
>> intmax('int8')
ans =
  127
```

There are many functions that convert values from one type to another. The names of these functions are the same as the names of the types. These names can be used as functions to convert a value to that type. This is called ***casting*** the value to a different type, or ***type casting***. For example, to convert a value from the type **double**, which is the default, to the type **int32**, the function **int32** would be used. Entering the assignment statement

```
>> val = 6 + 3;
```

would result in the number 9 being stored in the variable *val*, with the default type of **double**, which can be seen in the Workspace Window. Subsequently, the assignment statement

```
>> val = int32(val);
```

would change the type of the variable to **int32** but would not change its value. Here is another example using two different variables.

```
>> num = 6 + 3;
>> numi = int32(num);
>> whos
   Name       Size         Bytes   Class     Attributes
   num        1x1              8   double
   numi       1x1              4   int32
```

Note

that **whos** shows the type (class) of the variables and the number of bytes used to store the value of a variable. One byte is equivalent to eight bits, so the type **int32** uses 4 bytes.

QUICK QUESTION!

What would happen if you go beyond the range for a particular type? For example, the largest integer that can be stored in **int8** is 127, so what would happen if we type cast a larger integer to the type **int8**?

```
>> int8(200)
```

Answer: The value would be the largest in the range, in this case 127. If, instead, we use a negative number that is smaller than the lowest value in the range, its value would be -128. This is an example of what is called ***saturation arithmetic***.

```
>> int8(200)
ans =
   127
>> int8(-130)
ans =
  -128
```

PRACTICE 1.4

- Calculate the range of integers that can be stored in the types **int16** and **uint16**. Use **intmin** and **intmax** to verify your results.
- Enter an assignment statement and view the type of the variable in the Workspace Window. Then, change its type and view it again. View it also using **whos**.

There is also a function **cast** that can cast a variable to a particular type. This has an option to cast a variable to the same type as another, using 'like'.

```
>> a = uint16(43);
>> b = 11;
>> whos
   Name      Size          Bytes   Class      Attributes
   a         1x1               2   uint16
   b         1x1               8   double
>> b = cast(b,'like',a);
>> whos
   Name      Size          Bytes   Class      Attributes
   a         1x1               2   uint16
   b         1x1               2   uint16
```

The numeric functions can also be used to convert a character to its equivalent numerical value (e.g., **double** will convert to a **double** value, and **int32** will convert to an integer value using 32 bits). For example, to convert the character 'a' to its numerical equivalent, the following statement could be used:

```
>> numequiv = double('a')
numequiv =
    97
```

This stores the **double** value 97 in the variable *numequiv*, which shows that the character ‘a’ is the 98th character in the character encoding (as the equivalent numbers begin at 0). It does not matter which number type is used to convert ‘a’; for example,

```
>> numequiv = int32('a')
```

would also store the integer value 97 in the variable *numequiv*. The only difference between these will be the type of the resulting variable (**double** in the first case, **int32** in the second).

The function **char** does the reverse; it converts from any number to the equivalent character:

```
>> char(97)
ans =
    'a'
```

As the letters of the alphabet are in order, the character ‘b’ has the equivalent value of 98, ‘c’ is 99, and so on. Math can be done on characters. For example, to get the next character in the character encoding, 1 can be added either to the integer or the character:

```
>> numequiv = double('a');
>> char(numequiv + 1)
ans =
    'b'

>> 'a' + 2
ans =
    99
```

The first 128 characters are equivalent to the 128 characters in standard ASCII. MATLAB uses an encoding, however, that has 65,535 characters. The characters from 128 to 65,535 depend on your computer’s ***locale setting***, which sets the language for your interface; for example, ‘en_US’ is the locale for English in the United States.

To shift the characters of a character vector “up” in the character encoding, an integer value can be added to a character vector. For example, the following expression will shift by one:

```
>> char('abcd' + 1)
ans =
    'bcde'
```

The **string** function can be used to cast a character vector to a string.

```
>> word = string('hello')
word =
    "hello"
```

PRACTICE 1.5

- Find the numerical equivalent of the character 'x'.
- Find the character equivalent of 107.

1.8 BUILT-IN NUMERICAL FUNCTIONS

There are many built-in numerical functions. Some will be listed here; others can be found in the documentation.

MATLAB has many built-in trigonometric functions for sine, cosine, tangent, and so forth. For example, **sin** is the sine function in radians. The inverse, or arcsine function in radians is **asin**, the hyperbolic sine function in radians is **sinh**, and the inverse hyperbolic sine function is **asinh**. There are also functions that use degrees rather than radians: **sind** and **asind**. Similar variations exist for the other trigonometric functions.

MATLAB also has some rounding and remainder functions that are very useful. Some of these include **fix**, **floor**, **ceil**, **round**, **mod**, **rem**, and **sign**.

Both the **rem** and **mod** functions return the remainder from a division; for example 5 goes into 13 twice with a remainder of 3, so the result of this expression is 3:

```
>> rem(13,5)
ans =
     3
```

QUICK QUESTION!

What would happen if you reversed the order of the arguments by mistake, and typed the following:

```
rem(5,13)
```

Answer: The **rem** function is an example of a function that has two arguments passed to it. In some cases, the order in which the arguments are passed does not matter, but for the **rem** function the order does matter. The **rem** function divides the second argument into the first. In this case, the second argument, 13, goes into 5 zero times with a remainder of 5, so 5 would be returned as a result.

The **sign** function returns 1 if the argument is positive, 0 if it is 0, and −1 if it is negative. For example,

```
>> sign(-5)
ans =
    -1

>> sign(3)
ans =
     1
```

PRACTICE 1.6

Use **help** or **doc** to find out what the rounding functions **fix**, **floor**, **ceil**, and **round** do. Experiment with them by passing different values to the functions, including some negative, some positive, and some with fractions less than 0.5, and some greater. *It is very important when testing functions that you test thoroughly by trying different kinds of arguments!*

The **round** function has an option to round to a specified number of digits.

```
>> round(pi,3)
ans =
     3.1420
```

MATLAB has the exponentiation operator ^, and also the function **sqrt** to compute square roots and **nthroot** to find the nth root of a number. For example, the following expression finds the third root of 64.

```
>> nthroot(64,3)
ans =
     4
```

For the case in which $x = b^y$, y is the ***logarithm*** of x to base b, or in other words, $y = \log_b(x)$. Frequently used bases include $b = 10$ (called the ***common logarithm***), $b = 2$ (used in many computing applications), and $b = e$ (the constant e, which equals 2.7183); this is called the ***natural logarithm***. For example,

$$100 = 10^2 \text{ so } 2 = \log_{10}(100)$$
$$32 = 2^5 \text{ so } 5 = \log_2(32)$$

MATLAB has built-in functions to return logarithms:

log(x) returns the natural logarithm
log2(x) returns the base 2 logarithm
log10(x) returns the base 10 logarithm

MATLAB also has a built-in function **exp(n)**, which returns the constant e^n.

Note

Do not confuse the value e with the e used in MATLAB to specify an exponent for scientific notation.

QUICK QUESTION!

There is no built-in constant for e (2.718), so how can that value be obtained in MATLAB?

Answer: Use the exponential function **exp**; e or e^1 is equivalent to **exp(1)**.

```
>> exp(1)
ans =
     2.7183
```

MATLAB also has some conversion functions, e.g., **deg2rad** and **rad2deg** to convert between degrees and radians:

```
>> deg2rad(180)
ans =
     3.1416
```

1.9 USING MAT-FILES FOR VARIABLES

MATLAB has functions that can both save variables to files, and read them from files. These files are called MAT-files (because the extension on the file name is .mat), and they store the names and contents of variables. Variables can be written to new MAT-files, added to existing MAT-files (***appending***), and read from them. Rather than just storing data, MAT-files store the variable names in addition to their values. These files are typically used only within MATLAB; they are not used to share data with other programs.

1.9.1 Writing Variables to a File

The **save** command can be used to write variables to a MAT-file, or to append variables to a MAT-file. By default, the **save** function writes to a MAT-file, so the .mat extension is not necessary. It can either save all variables that have been created or a subset (including, e.g., just one variable). The **save** function will save the MAT-file in the Current Folder, so it is important to set that correctly first.

To save all variables to a file, the command is:

```
save filename
```

The '.mat' extension is added to the filename automatically. The contents of the file can be displayed using **who** with the '-file' qualifier:

```
who -file filename
```

For example, in the following session in the Command Window, two variables are created; these are then displayed using **who**. Then, the variables are saved to a file named "sess1.mat". The **who** function is then used to display the variables stored in that file.

```
>> x = 33;
>> y = x - 11;
>> who
Your variables are:
x       y

>> save sess1
>> who -file sess1
Your variables are:
x      y
```

To save just one variable to a file, the format is

```
save filename variablename
```

For example, just the variable *x* is saved to a file called *sess2*:

```
>> save sess2 x
>> who -file sess2
Your variables are:
x
```

1.9.2 Appending Variables to a MAT-File

Appending to a file adds to what has already been saved in a file, and is accomplished using the –append option. For example, assuming that the variable *x* has already been stored in the file "sess2.mat" as just shown, this would append the variable *y* to the file:

```
>> save -append sess2 y
>> who -file sess2
Your variables are:
x      y
```

Without specifying variable(s), just **save –append** would add all variables that have been created to the file. When this happens, if the variable is not in the file, it is appended. If there is a variable with the same name in the file, it is replaced by the current value.

1.9.3 Reading From a MAT-file

The **load** function can load all variables from the file or only a subset. For example, in a new Command Window session in which no variables have yet been created, the **load** function could load from the files created in the previous section:

```
>> who
>> load sess2
>> who
Your variables are:
x      y
```

A subset of the variables in a file can be loaded by specifying them in the form:

```
load filename variable list
```

MATLAB has some built-in MAT-files that will be used in subsequent sections in this book.

1.10 ADDITIONAL MATLAB PRODUCTS

MathWorks® has many products related to MATLAB, and several websites and associated apps. To view the products, go to the official website:

https://www.mathworks.com

Clicking on Products will bring up a list of the products and services that are available. These include many toolboxes to use with MATLAB. Additional services include MATLAB® Mobile™, MATLAB® Online™, and MATLAB® Drive™.

MATLAB® Mobile™ is a free app that is available for Android and Apple devices. The interface provides a command prompt that allows you to enter MATLAB commands and have them evaluated, just like in the Command Window. It also provides a history of commands. With MATLAB® Mobile™, you can connect to MATLAB sessions running in the cloud using MATLAB® Online™. Also available is a set of sensor data. Hitting the Sensors icon brings up the ability to get data from the sensors that are built into your device. These include Position (including Latitude and Longitude), Acceleration, and Orientation (including Azimuth, Pitch, and Roll). By connecting your mobile device, you can acquire and log the sensor data in MATLAB. For example, you could take your device on a trip and then plot where it went! To do this, it is necessary to download both the MATLAB® Mobile™ app and to download the sensor package for your computer. The **connector** command connects the devices, and the **mobiledev** function creates an object (more on objects in Chapter 11) that is used to acquire the sensor data. Read the MATLAB® Mobile™ documentation online for more details.

MATLAB® Online™ was introduced in R2017a. Most MATLAB licenses include access to MATLAB® Online™. No download is necessary, but you do need to log in to a MathWorks account. MATLAB® Online™ is hosted on the cloud and includes MATLAB and most toolboxes.

MATLAB® Drive™ provides cloud storage for MATLAB files (including for MATLAB® Online™ and MATLAB® Mobile™), and is available with any MathWorks account. It can be used for collaboration and sharing of files, and can be synchronized with your desktop.

Also available through the website are options for practicing MATLAB code, reading blogs, posting questions, and sharing code files. The Cody™ website, found under Community, has a collection of problems that you can solve in order to practice your skills with MATLAB. An offshoot of Cody™ is MATLAB® Grader™, which is a website that allows instructors to post problems for students to solve, and includes the ability for instructors to create auto-graders for the students' codes.

Data Science and Machine Learning Supplement

Introduction to Machine Learning

Machine Learning (ML) is becoming a very important topic in all fields. Machine Learning combines Data Science (DS), Artificial Intelligence (AI), probability and statistics, and computer coding and has broad applications. With Machine Learning, data sets (frequently very large) are inputs into computer programs, which then find patterns in the data in order to help us make predictions. To begin learning about Machine Learning, there is a lot of background information, and a lot of terminology.

At the end of every chapter in this book, a few ML topics will be introduced that are relevant to that chapter. The last chapter in the book, Chapter 15, builds on these short sections and further introduces the discipline of Machine Learning and Statistics and Machine Learning Toolbox™. By introducing topics gradually throughout the book, the goal is for the terminology to not be so intimidating once the final chapter is reached. Also, these sections provide context for the concepts from the chapters.

An algorithm is a sequence of steps taken in order to solve a problem. The algorithm is then coded in a particular language (MATLAB for us!). With ML, there are lots of different algorithms. They are basically categorized as ***Supervised Learning*** and ***Unsupervised Learning***.

With supervised learning, you want to be able to answer a question for which you already have answers for some data. ***Classification algorithms*** predict categories for data, whereas ***regression algorithms*** predict continuous data (real numbers). As an example of a classification algorithm, let us say you are creating a system that will classify an email as either spam or not. You have some data in the form of emails that have already been classified as 'spam' or 'not spam' (this is called ***labeled*** data). So, you have the input (the emails) and the output (whether or not they are spam). This is actually a ***binary classifier***, in that it classifies in one of two categories. The basic idea is that you choose a classification algorithm, and build a model. You use the data to ***train*** and ***test*** your model, and once your model has the desired level of accuracy, you can then use it to decide whether new email messages are spam or not. An example of a regression algorithm might be predicting the average miles per gallon (mpg) for cars. Again, you would have labeled data. This might consist of the make of the car, model, country in which it is manufactured, weight, year, etc., and you would have the known average mpg for these cars. You train your model on this data and then use the model to predict mpg for cars for which the mpg is not known.

With unsupervised learning, you do not have labeled data. Instead, you want the system to be able to find patterns that are not yet known. For example, you may have a very large database of hospital patient information. You might feed that into a ML algorithm so that it can discover correlations between features of the patients (weight and heart disease, for example); these correlations can then be used to make predictions for other patients. These are called ***clustering algorithms*** because they group data together in clusters based on patterns that are discovered.

To summarize, there are lots of different types of ML algorithms, and there are hybrid combinations of algorithms. We will concentrate on:

- Supervised Learning:
  - Classification algorithms that predict categories (e.g., spam/not spam)
  - Regression algorithms that predict real numbers (e.g., miles per gallon)
- Unsupervised Learning:
  - Clustering algorithms that group data into clusters based on patterns in the data

Assessing Classification Model Performance

For a classification model, the algorithm either correctly classifies an observation, or it does not. For example, let us say that we have a simple binary classifier, such as a model that classifies email as spam or not spam. For every email, there are four possibilities:

- The email is spam and the model classified it as spam: this is a True Positive (TP)
- The email is not spam and the model classified it as not spam: this is a True Negative (TN)
- The email is spam and the model classified it as not spam: this is a False Negative (FN)
- The email is not spam and the model classified it as spam: this is a False Positive (FP)

Let us say that out of a data set of 280 emails, the results were: TP is 50, TN is 200, FN is 20, and FP is 10.

The model ***accuracy*** is the percentage of emails that were correctly classified, which is the sum of the correct classifications (the sum of the TP and TN) divided by the total number of emails. In this case, the accuracy is 250/280, or 0.893, or 89.3%.

There are other metrics that are used to assess the performance of the model. One other metric, the ***precision***, measures how accurately the positive outcome was predicted. The precision is the TP divided by the sum of TP + FP. In this case, the precision was 50/60, or 0.833.

Explore Other Interesting Features

This section lists some features and functions in MATLAB, related to those explained in this chapter, that you wish to explore on your own.

- Workspace Window: There are many other aspects of the Workspace window to explore. To try this, create some variables. Make the Workspace window the active window by clicking the mouse in it. From there, you can choose which attributes of variables to make visible by choosing

Choose Columns from the menu. Also, if you double click on a variable in the Workspace window, this brings up a Variable Editor window that allows you to modify the variable.

- Use **help** to learn about the **path** function and related directory functions such as **addpath** and **which**.
- The **pow2** function.
- Functions related to type casting including **typecast**.
- Find the accuracy of the floating point representation for single and double precision using the **eps** function.
- The **sinpi** and **cospi** functions, introduced in R2018b. ■

SUMMARY

COMMON PITFALLS

It is common when learning to program to make simple spelling mistakes and to confuse the necessary punctuation. Examples are given here of very common errors. Some of these include:

- Putting a space in a variable name
- Confusing the format of an assignment statement as

  ```
  expression = variablename
  ```

  rather than

  ```
  variablename = expression
  ```

  The variable name must always be on the left.
- Using a built-in function name as a variable name, and then trying to use the function
- Confusing the two division operators / and \
- Forgetting the operator precedence rules
- Confusing the order of arguments passed to functions – for example, to find the remainder of dividing 3 into 10 using **rem(3,10)** instead of **rem(10,3)**
- Not using different types of arguments when testing functions
- Forgetting to use parentheses to pass an argument to a function (e.g., "fix 2.3" instead of "**fix(2.3)**"). MATLAB returns the ASCII equivalent for each character when this mistake is made (what happens is that it is interpreted as the function of a string, "**fix('2.3')**").
- Confusing && and ||
- Confusing || and **xor**
- Putting a space in 2-character operators (e.g., typing "< =" instead of "<=")
- Using = instead of == for equality

PROGRAMMING STYLE GUIDELINES

Following these guidelines will make your code much easier to read and understand, and therefore easier to work with and modify.

- Use mnemonic variable names (names that make sense; for example, *radius* instead of *xyz*).
- Although variables named *result* and *RESULT* are different, avoid this as it would be confusing.
- Do not use names of built-in functions as variable names.
- Store results in named variables (rather than using *ans*) if they are to be used later.
- Do not use *ans* in expressions.
- Make sure variable names have fewer characters than **namelengthmax**.
- If different sets of random numbers are desired, set the seed for the random functions using **rng**.

MATLAB Functions and Commands

- doc
- help
- demo
- lookfor
- quit
- exit
- namelengthmax
- who
- whos
- clearvars
- clear
- single
- double
- int8
- int16
- int32
- int64
- uint8
- uint16
- uint32
- uint64
- class
- char
- string
- logical
- true
- false
- format
- sin
- abs
- plus
- pi
- i
- j
- inf
- NaN
- rand
- rng
- clock
- randn
- randi
- xor
- intmin
- intmax
- cast
- asin
- sinh
- asinh
- sind
- asind
- fix
- floor
- ceil
- round
- mod
- rem
- sign
- sqrt
- nthroot
- log
- log2
- log10
- exp
- deg2rad
- rad2deg
- save
- load
- connector
- mobiledev

MATLAB Operators

- assignment =
- ellipsis, or continuation ...
- addition +
- negation –
- subtraction –
- multiplication *
- divided by /
- divided into \
- exponentiation ^
- parentheses ( )
- greater than >
- less than <
- greater than or equals >=
- less than or equals <=
- equality ==
- inequality ~=
- or for scalars ||
- and for scalars &&
- not ~

Exercises

1. Create a variable *myage* and store your age in it. Add 2 to the value of the variable. Subtract 3 from the value of the variable. Observe the Workspace Window and Command History Window as you do this.
2. Explain the difference between these two statements:

```
result = 9*2
result = 9*2;
```

3. Give the result of the expression 4 + 2 / 4 and explain how it is obtained.
4. Use the built-in function **namelengthmax** to find out the maximum number of characters that you can have in an identifier name under your version of MATLAB.
5. Create two variables to store a weight in pounds and ounces. Use **who** and **whos** to see the variables. Use **class** to see the types of the variables. Clear one of them using **clearvars** and then use **who** and **whos** again.
6. Explore the **format** command in more detail. Use **help format** to find options. Experiment with **format bank** to display dollar values.
7. Find a **format** option that would result in the following output format:

```
>> 5/16 + 2/7
ans =

      67/112
```

8. Think about what the results would be for the following expressions, and then type them in to verify your answers.

```
13 - 2 * 5
 4^2/2
 3e2 - 5^2
```

9. There are 1.6093 kilometers in a mile. Create a variable to store a number of miles. Convert this to kilometers, and store in another variable.
10. The following assignment statements either contain at least one error, or could be improved in some way. Assume that *radius* is a variable that has been initialized. First, identify the problem, and then fix and/or improve them:

```
33 = number
my variable = 11.11;
area = 3.14 * radius^2;
x = 2 * 3.14 * radius;
```

11. Experiment with the functional form of some operators such as **plus**, **minus**, and **times**.
12. Explain the difference between constants and variables.
13. Generate a random

- real number in the range (0, 30)
- real number in the range (10, 100)

- integer in the inclusive range from 1 to 20
- integer in the inclusive range from 0 to 20
- integer in the inclusive range from 30 to 80

14. Get into a new Command Window, and type **rand** to get a random real number. Make a note of the number. Then, exit MATLAB and repeat this, again making a note of the random number; it should be the same as before. Finally, exit MATLAB and again get into a new Command Window. This time, change the seed before generating a random number; it should be different.
15. What is the difference between x and 'x'?
16. What is the difference between 5 and '5'?
17. Give the result of the following expression and explain how it is obtained:

```
3 - 5 * 2 == (3 - 5) * 2
```

18. Is the expression 2 < 6 < 4 the same as the expression (2 < 6) && (6 < 4)? Why or why not?
19. Assuming that a variable x has been initialized, is the expression 5 < x < 10 the same as the expression (5 < x) && (x < 10)? Why or why not?
20. Create two variables *x* and *y* and store numbers in them. Write an expression that would be **true** if the value of *x* is greater than five or if the value of *y* is less than ten, but not if both of those are **true**.
21. In the ASCII character encoding, the letters of the alphabet are in order: 'a' comes before 'b' and also 'A' comes before 'B'. However, which comes first - lower or uppercase letters?
22. Are there equivalents to **intmin** and **intmax** for real number types? Use **help** to find out.
23. Use **intmin** and **intmax** to determine the range of values that can be stored in the types **uint32** and **uint64**.
24. Use **help elfun** or experiment to answer the following questions:

- Is fix(3.5) the same as floor(3.5)?
- Is fix(3.4) the same as fix(−3.4)?
- Is fix(3.2) the same as floor(3.2)?
- Is fix(−3.2) the same as floor(−3.2)?
- Is fix(−3.2) the same as ceil(−3.2)?

25. For what range of values is the function **round** equivalent to the function **floor**? For what range of values is the function **round** equivalent to the function **ceil**?
26. Use **help** or **doc** to determine the difference between the **rem** and **mod** functions.
27. Use the equality operator to verify that log10(1000) is 3.
28. Explain why it is not necessary to know the integer equivalent of '?' in order to evaluate this expression:

```
char(int32('?'))
```

29. In special relativity, the Lorentz factor is a number that describes the effect of speed on various physical properties when the speed is significant relative to the speed of light. Mathematically, the Lorentz factor is given as:

    $$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

    Use 3 × 10^8 m/s for the speed of light, *c*. Create variables for *c* and the speed *v* and from them a variable *lorentz* for the Lorentz factor.
30. A company manufactures a part for which there is a desired weight. There is a tolerance of N percent, meaning that the range between minus and plus N% of the desired weight is acceptable. Create a variable that stores a weight, and another variable for N (e.g., set it to 2). Create variables that store the minimum and maximum values in the acceptable range of weights for this part.
31. A chemical plant releases an amount *A* of pollutant into a stream. The maximum concentration *C* of the pollutant at a point which is a distance *x* from the plant is:

    $$\mathrm{c} = \frac{A}{x}\sqrt{\frac{2}{\prod e}}$$

    Create variables for the values of *A* and *x*, and then for *C*. Assume that the distance *x* is in meters. Experiment with different values for *x*.

32. The geometric mean g of n numbers x_i is defined as the nth root of the product of x_i:

    $$\mathrm{g} = \sqrt[n]{x_1 x_2 x_3 \ldots x_n}$$

    (This is useful, for example, in finding the average rate of return for an investment which is something you would do in engineering economics). If an investment returns 15% the first year, 50% the second, and 30% the third year, the average rate of return would be `(1.15*1.50*1.30)`⅓.) Compute this.
33. Use the **deg2rad** function to convert 180 degrees to radians.
34. Create two variables and save the to a MAT-file. Clear the variables, and view the from the file. Create another variable and append it to the MAT-file. Read all variables from the MAT-file.
35. If you have an Apple or Android device, install MATLAB Mobile and investigate the sensor information. This can be done without connecting the device to MATLAB.

Data Science and Machine Learning

36. For the results of a ML classification model, create variables storing values for the TP, TN, FN, and FP. Let us say that TP is 50, TN is 200, FN is 20, and FP is 10. Use these variables to determine the accuracy of the model, and also the precision of the model.
37. For the results of a ML classification model, the ***False Positive Rate*** is:

    FPR = FP / (FP + TN)

    The ***True Positive Rate***, also called the ***recall***, is:

    TPR = TP / (TP + FN)

    Using your variables from the previous problem, calculate the FPR and recall.

CHAPTER 2

Vectors and Matrices

KEY TERMS

vectors
matrices
row vector
column vector
scalar
elements
array
array operations
colon operator
iterate
step value
concatenating
index
subscript
index vector
transpose
square matrix
subscripted indexing
unwinding a matrix
linear indexing
column major order
columnwise
dimensions
vector of variables
empty vector
deleting elements
three-dimensional matrices
cumulative sum
cumulative product
running sum
nesting calls
scalar multiplication
array operations
array multiplication
array division
logical vector
logical indexing
zero crossings
matrix multiplication
inner dimensions
outer dimensions
dot product
inner product
cross product
outer product
main diagonal
diagonal matrix
trace
identity matrix
symmetric matrix

CONTENTS

MATLAB® is short for Matrix Laboratory. Everything in MATLAB is written to work with vectors and matrices. This chapter will introduce vectors and matrices. Operations on vectors and matrices and built-in functions that can be used to simplify code will also be explained. The matrix operations and functions described in this chapter will form the basis for vectorized coding, which will be explained in Chapter 5.

2.1 VECTORS AND MATRICES

Vectors and ***matrices*** are used to store sets of values, all of which are the same type. A matrix can be visualized as a table of values. The dimensions of a matrix are $r \times c$, where r is the number of rows and c is the number of columns. This is

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00002-0

pronounced "r by c". A vector can be either a ***row vector*** or a ***column vector***. If a vector has *n* elements, a row vector would have the dimensions *1* × *n*, and a column vector would have the dimensions *n* × *1*. A ***scalar*** (one value) has the dimensions *1* × *1*. Therefore, vectors and scalars are actually just special cases of matrices.

Here are some diagrams showing, from left to right, a scalar, a column vector, a row vector, and a matrix:

5

3
7
4

5	88	3	11

9	6	3
5	7	2

The scalar is *1* × *1*, the column vector is *3* × *1* (three rows by one column), the row vector is *1* × *4* (one row by four columns), and the matrix is *2* × *3* (two rows by three columns). All of the values stored in these matrices are stored in what are called ***elements***.

MATLAB is written to work with matrices and so it is very easy to create vector and matrix variables, and there are many operations and functions that can be used on vectors and matrices.

A vector in MATLAB is equivalent to what is called a one-dimensional ***array*** in other languages. A matrix is equivalent to a two-dimensional array. Usually, even in MATLAB, some operations that can be performed on either vectors or matrices are referred to as ***array operations***. The term *array* is also frequently used to mean generically either a vector or a matrix.

2.1.1 Creating Row Vectors

There are several ways to create row vector variables. The most direct way is to put the values that you want in the vector in square brackets, separated by either spaces or commas. For example, both of these assignment statements create the same vector *v*:

```
>> v = [1   2   3   4]
   v =
      1   2   3   4

>> v = [1,2,3,4]
   v =
      1   2   3   4
```

Both of these create a row vector variable that has four elements; each value is stored in a separate element in the vector. The vector is *1* × *4*.

2.1.1.1 *The Colon Operator and Linspace Function*

If, as in the preceding examples, the values in the vector are regularly spaced, the ***colon operator*** can be used to ***iterate*** through these values. For example, 2:6 results in all of the integers from 2 to 6 inclusive:

```
>> vec = 2:6
vec =
      2       3       4       5       6
```

Note

that in this case, the brackets [ ] are not necessary to define the vector.

In this vector, there are five elements; the vector is a *1* × *5* row vector.

With the colon operator, a ***step value*** can also be specified by using another colon, in the form (first:step:last). For example, to create a vector with all integers from 1 to 9 in steps of 2:

```
>> nv = 1:2:9
nv =
        1   3   5   7   9
```

QUICK QUESTION!

What happens if adding the step value would go beyond the range specified by the last, for example,

```
1:2:6
```

Answer: This would create a vector containing 1, 3, and 5. Adding 2 to the 5 would go beyond 6, so the vector stops at 5; the result would be

```
1       3       5
```

QUICK QUESTION!

How can you use the colon operator to generate the vector shown below?

```
9       7       5       3       1
```

Answer: `9:-2:1`

The step value can be a negative number, so the resulting sequence is in descending order (from highest to lowest).

The **linspace** function creates a linearly spaced vector; **linspace(x,y,n)** creates a vector with *n* values in the inclusive range from *x* to *y*. If *n* is omitted, the default is 100 elements. For example, the following creates a vector with five values linearly spaced between 3 and 15, including the 3 and 15:

```
>> ls = linspace(3,15,5)
ls =
      3       6       9       12       15
```

Similarly, the **logspace** function creates a logarithmically spaced vector; **logspace(x,y,n)** creates a vector with *n* values in the inclusive range from 10^x to 10^y. If *n* is omitted, the default is 50 elements. For example, logspace(1,4,4) creates a vector with four elements, logarithmically spaced between 10^1 and 10^4, or in other words 10^1, 10^2, 10^3, and 10^4.

```
>> logspace(1,4,4)
ans =
          10          100          1000          10000
```

Vector variables can also be created using existing variables. For example, a new vector is created here consisting first of all of the values from *nv* followed by all values from *ls*:

```
>> newvec = [nv  ls]
newvec =
    1    3    5    7    9    3    6    9    12    15
```

Putting two vectors together like this to create a new one is called ***concatenating*** the vectors.

2.1.1.2 Referring to and Modifying Elements

The elements in a vector are numbered sequentially; each element number is called the ***index***, or ***subscript***. In MATLAB, the indices start at 1. Normally, diagrams of vectors and matrices show the indices. For example, for the variable *newvec* created earlier, the indices 1–10 of the elements are shown above the vector:

newvec

1	2	3	4	5	6	7	8	9	10
1	3	5	7	9	3	6	9	12	15

A particular element in a vector is accessed using the name of the vector variable and the index or subscript in parentheses. For example, the fifth element in the vector *newvec* is a 9.

```
>> newvec(5)
ans =
     9
```

The expression *newvec(5)* would be pronounced "newvec sub 5", where *sub* is short for the word *subscript*. A subset of a vector, which would be a vector itself, can also be obtained using the colon operator. For example, the following statement would get the fourth through sixth elements of the vector *newvec* and store the result in a vector variable *b*:

```
>> b = newvec(4:6)
b =
     7    9    3
```

Any vector can be used for the indices into another vector, not just one created using the colon operator. The indices do not need to be sequential. For example, the following would get the first, tenth, and fifth elements of the vector *newvec*:

```
>> newvec([1 10 5])
ans =
     1    15     9
```

The vector [1 10 5] is called an ***index vector***; it specifies the indices in the original vector that are being referenced.

The value stored in a vector element can be changed by specifying the index or subscript. For example, to change the second element from the preceding vector *b* to now store the value 11 instead of 9:

```
>> b(2) = 11
b =
     7    11     3
```

By referring to an index that does not yet exist, a vector can also be extended. For example, the following creates a vector that has three elements. By then assigning a value to the fourth element, the vector is extended to have four elements.

```
>> rv = [3 55 11]
rv =
     3    55    11

>> rv(4) = 2
rv =
     3    55    11     2
```

If there is a gap between the end of the vector and the specified element, 0s are filled in. For example, the following extends the variable *rv* again:

```
>> rv(6) = 13
rv =
     3    55    11     2     0    13
```

As we will see later, this is actually not a good idea. It is not very efficient because it can take extra time.

It is also possible to index into a character vector:

```
>> chararr = 'hello';

>> chararr(2)
ans =
    'e'
```

Indexing into strings is not quite as straight-forward and will be covered in Chapter 7.

PRACTICE 2.1

Think about what would be produced by the following sequence of statements and expressions, and then type them in to verify your answers:

```
pvec = 3:2:10

pvec(2) = 15

pvec(7) = 33

pvec([2:4 7])

linspace(5,11,3)

logspace(2,4,3)
```

2.1.2 Creating Column Vectors

One way to create a column vector is to explicitly put the values in square brackets, separated by semicolons (rather than commas or spaces):

```
>> c = [1; 2; 3; 4]
c =
     1
     2
     3
     4
```

There is no direct way to use the colon operator to get a column vector. However, any row vector created using any method can be ***transposed*** to result in a column vector. In general, the transpose of a matrix is a new matrix in which the rows and columns are interchanged. For vectors, transposing a row vector results in a column vector, and transposing a column vector results in a row vector. In MATLAB, the apostrophe (or single quote) is built in as the transpose operator.

```
>> r = 1:3;
>> c = r'
c =
     1
     2
     3
```

2.1.3 Creating Matrix Variables

Creating a matrix variable is simply a generalization of creating row and column vector variables. That is, the values within a row are separated by either spaces or commas, and the different rows are separated by semicolons. For example, the matrix variable *mat* is created by explicitly entering values:

```
>> mat = [4 3 1; 2 5 6]
mat =
    4    3   1
    2    5   6
```

If you attempt to create a matrix in which there are different numbers of values in the rows, the result will be an error message, such as in the following:

```
>> mat = [3 5 7; 1 2]
Error using vertcat
Dimensions of arrays being concatenated are not consistent.
```

Note

There must always be the same number of values in each row and each column of a matrix.

Iterators can be used for the values in the rows using the colon operator. For example:

```
>> mat = [2:4; 3:5]
mat =
   2   3   4
   3   4   5
```

The separate rows in a matrix can also be specified by hitting the Enter key after each row instead of typing a semicolon when entering the matrix values, as in:

```
>> newmat = [2 6 88
33 5 2]

newmat =
     2      6    88
    33      5     2
```

Matrices of random numbers can be created using the **rand** function. If a single value *n* is passed to **rand**, an *n x n* matrix will be created; this is called a ***square matrix*** (same number of rows and columns).

```
>> rand(2)
ans =
     0.2311     0.4860
     0.6068     0.8913
```

If instead two arguments are passed, they specify the number of rows and columns in that order.

```
>> rand(1,3)
ans =
    0.7621     0.4565     0.0185
```

Matrices of random integers can be generated using **randi**; after the range is passed, the dimensions of the matrix are passed (again, using one value *n* for an *n x n* matrix, or two values for the dimensions):

```
>> randi([5, 10], 2)
ans =
     8     10
     9      5

>> randi([10, 30], 2, 3)
ans =
    21     10     13
    19     17     26
```

Note that the range can be specified for **randi**, but not for **rand**. The format for calling these functions is different. There are a number of ways in which **randi** can be called; use **doc** to see them.

MATLAB also has several functions that create special matrices. For example, the **zeros** function creates a matrix of all zeros and the **ones** function creates a matrix of all ones. Like **rand**, either one argument can be passed (which will be both the number of rows and columns), or two arguments (first the number of rows and then the number of columns).

```
>> zeros(3)
ans =
     0     0     0
     0     0     0
     0     0     0
>> ones(2,4)
ans =
     1     1     1     1
     1     1     1     1
```

Note

that there is no twos function, or tens, or fifty-threes—just **zeros** and **ones**!

2.1.3.1 Referring to and Modifying Matrix Elements

To refer to matrix elements, the row and then the column subscripts are given in parentheses (always the row first and then the column). For example, this creates a matrix variable *mat* and then refers to the value in the second row, third column of *mat*:

```
>> mat = [2:4; 3:5]
mat =
   2   3   4
   3   4   5
>> mat(2,3)
ans =
   5
```

This is called ***subscripted indexing***; it uses the row and column subscripts. It is also possible to refer to a subset of a matrix. For example, this refers to the first and second rows, second and third columns:

```
>> mat(1:2,2:3)
ans =
   3   4
   4   5
```

Using just one colon by itself for the row subscript means all rows, regardless of how many, and using a colon for the column subscript means all columns. For example, this refers to all columns within the first row or, in other words, the entire first row:

```
>> mat(1,:)
ans =
   2   3   4
```

This refers to the entire second column:

```
>> mat(:, 2)
ans =
   3
   4
```

If a single index is used with a matrix, MATLAB ***unwinds*** the matrix column by column. For example, for the matrix *intmat* created here, the first two elements are from the first column, and the last two are from the second column:

```
>> intmat = [100 77; 28 14]
intmat =
   100    77
    28    14
>> intmat(1)
ans =
   100
>> intmat(4)
ans =
    14
```

This is called ***linear indexing***.

Note

that it is usually much better style when working with matrices to use subscripted indexing.

MATLAB stores matrices in memory in ***column major order***, or ***columnwise***, which is why linear indexing refers to the elements in order by columns.

An individual element in a matrix can be modified by assigning a new value to it.

```
>> mat = [2:4; 3:5];
>> mat(1,2) = 11
mat =
     2    11     4
     3     4     5
```

An entire row or column could also be changed. For example, the following replaces the entire second row with values from a vector obtained using the colon operator.

```
>> mat(2,:) = 5:7
mat =
     2    11     4
     5     6     7
```

Notice that as the entire row is being modified, a vector with the correct length must be assigned (although that vector could be either a row or a column).

Any subset of a matrix can be modified, as long as what is being assigned has the same number of rows and columns as the subset being modified.

```
>> mat(1:2, 2:3) = 4:5
Unable to perform assignment because the size of the left side is
2-by-2 and the size of the right side is 1-by-2.
>> mat(1:2, 2:3) = zeros(2)
mat =
     2     0     0
     5     0     0
```

The exception to this rule is that a scalar can be assigned to any size subset of a vector or matrix; what happens is that the same scalar is assigned to every element referenced. For example,

```
>> m = randi([10 50], 3,5)
m =
    38    11    38    11    41
    11    13    23    27    42
    21    43    48    25    17
>> m(2:3,3:5) = 1
m =
    38    11    38    11    41
    11    13     1     1     1
    21    43     1     1     1
```

To extend a matrix, an individual element could not be added because that would mean that there would no longer be the same number of values in every row. However, an entire row or column could be added. For example, the following would add a fourth column to the matrix *mat* created previously.

Note

a row vector with two elements could also be assigned. MATLAB would transpose it to a column vector.

```
>> mat(:,4) = [9 2]'
mat =
     2     0     0     9
     5     0     0     2
```

Just as we saw with vectors, if there is a gap between the current matrix and the row or column being added, MATLAB will fill in with zeros.

```
>> mat(4,:) = 2:2:8
mat =
     2     0     0     9
     5     0     0     2
     0     0     0     0
     2     4     6     8
```

2.1.4 Dimensions

The **length** and **size** functions in MATLAB are used to find ***dimensions*** of vectors and matrices. The **length** function returns the number of elements in a vector. The **size** function returns the number of rows and columns in a vector or matrix. For example, the following vector *vec* has four elements, so its length is 4. It is a row vector, so the size is *1* × *4*.

```
>> vec = -2:1
vec =
   -2  -1   0   1
>> length(vec)
ans =
   4
>> size(vec)
ans =
   1    4
```

To create the following matrix variable *mat*, iterators are used on the two rows and then the matrix is transposed so that it has three rows and two columns or, in other words, the size is *3 x 2*.

```
>> mat = [1:3; 5:7]'
mat =
   1     5
   2     6
   3     7
```

The **size** function returns the number of rows and then the number of columns; therefore, to capture these values in separate variables, we put a ***vector of variables*** (two) on the left of the assignment. The variable *r* stores the first value returned, which is the number of rows, and *c* stores the number of columns.

Note that this example demonstrates very important and unique concepts in MATLAB: the ability to have a function return multiple values and the ability to have a vector of variables on the left side of an assignment in which to store the values.

```
>> [r, c] = size(mat)
r  =
   3
c  =
   2
```

If called as just an expression, the **size** function will return both values in a vector:

```
>> size(mat)
ans =
  3  2
```

For a matrix, the **length** function will return either the number of rows or the number of columns, whichever is largest (in this case the number of rows, 3).

```
 >> length(mat)
ans =
   3
```

QUICK QUESTION!

How could you create a matrix of zeros with the same size as another matrix?

Answer: For a matrix variable *mat*, the following expression would accomplish this:

```
zeros(size(mat))
```

The **size** function returns the size of the matrix, which is then passed to the **zeros** function, which then returns a matrix of zeros with the same size as *mat*. It is not necessary in this case to store the values returned from the **size** function in variables.

In R2020b, the functions **height** and **width** were introduced. The **height** function is the number of rows, and the **width** function is the number of columns.

MATLAB also has a function **numel**, which returns the total number of elements in any array (vector or matrix):

```
>> vec = 9:-2:1
vec =
     9     7     5     3     1
>> numel(vec)
ans =
     5
>> mat = [3:2:7; 9 33 11]
mat =
     3     5     7
     9    33    11
>> numel(mat)
ans =
     6
```

For vectors, **numel** is equivalent to the **length** of the vector. For matrices, it is the product of the number of rows and columns.

It is important to note that in programming applications, it is better to not assume that the dimensions of a vector or matrix are known. Instead, to be general, use either the **length** or **numel** function to determine the number of elements in a vector, and use **size** (and store the result in two variables) for a matrix.

MATLAB also has a built-in expression **end** that can be used to refer to the last element in a vector; for example, *v(end)* is equivalent to *v(length(v))*. For matrices, it can refer to the last row or column. So, for example, using **end** for the row index would refer to the last row.

In this case, the element referred to is in the first column of the last row:

```
>> mat = [1:3; 4:6]'
mat =
     1     4
     2     5
     3     6
>> mat(end,1)
ans =
     3
```

Using **end** for the column index would refer to a value in the last column (e.g., the last column of the second row):

```
>> mat(2,end)
ans =
     5
```

The expression **end** can only be used as an index.

2.1.4.1 Changing Dimensions

In addition to the transpose operator, MATLAB has several built-in functions that change the dimensions or configuration of matrices (or in many cases vectors), including **reshape**, **fliplr**, **flipud**, **flip**, and **rot90**.

The **reshape** function changes the dimensions of a matrix. The following matrix variable *mat* is 3×4 or, in other words, it has 12 elements (each in the range from 1 to 100).

```
>> mat = randi(100, 3, 4)
    14    61     2    94
    21    28    75    47
    20    20    45    42
```

These 12 values could instead be arranged as a 2×6 matrix, 6×2, 4×3, 1×12, or 12×1. The **reshape** function iterates through the matrix columnwise. For example, when reshaping *mat* into a 2×6 matrix, the values from the first column in the original matrix (14, 21, and 20) are used first, then the values from the second column (61, 28, 20), and so forth.

Note that in these examples *mat* is unchanged; instead, the results are stored in the default variable *ans* each time.

```
>> reshape(mat,2,6)
ans =
    14    20    28     2    45    47
    21    61    20    75    94    42
```

There are several functions that flip arrays. The **fliplr** function "flips" the matrix from left to right (in other words the left-most column, the first column, becomes the last column and so forth), and the **flipud** function flips up to down.

```
>> mat
mat =
    14    61     2    94
    21    28    75    47
    20    20    45    42
>> fliplr(mat)
ans =
    94     2    61    14
    47    75    28    21
    42    45    20    20

>> mat
mat =
    14    61     2    94
    21    28    75    47
    20    20    45    42
>> flipud(mat)
ans =
    20    20    45    42
    21    28    75    47
    14    61     2    94
```

The **flip** function flips any array; it flips a vector (left to right if it is a row vector or up to down if it is a column vector) or a matrix (up to down by default).

The **rot90** function rotates the matrix counterclockwise 90 degrees, so for example, the value in the top right corner becomes instead the top left corner and the last column becomes the first row.

```
>> mat
mat =
    14    61     2    94
    21    28    75    47
    20    20    45    42
>> rot90(mat)
ans =
    94    47    42
     2    75    45
    61    28    20
    14    21    20
```

QUICK QUESTION!

Is there a ***rot180*** function? Is there a ***rot-90*** function (to rotate clockwise)?

Answer: Not exactly, but a second argument can be passed to the **rot90** function, which is an integer *n*; the function will rotate 90*n degrees. The integer can be positive or negative. For example, if 2 is passed, the function will rotate the matrix 180 degrees (therefore, it would be the same as rotating the result of **rot90** another 90 degrees).

```
>> mat
mat =
    14    61     2    94
    21    28    75    47
    20    20    45    42
>> rot90(mat,2)
ans =
    42    45    20    20
    47    75    28    21
    94     2    61    14
```

If a negative number is passed for *n*, the rotation would be in the opposite direction, that is, clockwise.

```
>> mat
mat =
    14    61     2    94
    21    28    75    47
    20    20    45    42
>> rot90(mat,-1)
ans =
    20    21    14
    20    28    61
    45    75     2
    42    47    94
```

The function **repmat** can be used to create a matrix; **repmat(mat,m,n)** creates a larger matrix that consists of an $m \times n$ matrix of copies of *mat*. For example, here is a 2×2 random matrix:

```
>> intmat = randi(100,2)
intmat =
    50    34
    96    59
```

Replicating this matrix six times as a 3×2 matrix would produce copies of *intmat* in this form:

intmat	intmat
intmat	intmat
intmat	intmat

```
>> repmat(intmat,3,2)
ans =
    50    34    50    34
    96    59    96    59
    50    34    50    34
    96    59    96    59
    50    34    50    34
    96    59    96    59
```

The function **repelem**, on the other hand, replicates each element from a matrix in the dimensions specified.

```
>> repelem(intmat,3,2)
ans =
       50     50     34     34
       50     50     34     34
       50     50     34     34
       96     96     59     59
       96     96     59     59
       96     96     59     59
```

2.1.5 Empty Vectors

An ***empty vector*** (a vector that stores no values) can be created using empty square brackets:

```
>> evec = []
evec =
        []
>> length(evec)
ans =
     0
```

Note

that there is a difference between having an empty vector variable and not having the variable at all.

Values can then be added to an empty vector by concatenating, or adding, values to the existing vector. The following statement takes what is currently in *evec*, which is nothing, and adds a 4 to it.

```
>> evec = [evec 4]
evec =
        4
```

The following statement takes what is currently in *evec*, which is 4, and adds an 11 to it.

```
>> evec = [evec 11]
evec =
        4     11
```

This can be continued as many times as desired to build a vector up from nothing. Sometimes this is necessary, although generally it is not a good idea if it can be avoided because it can be quite time consuming.

Empty vectors can also be used to ***delete elements*** from vectors. For example, to remove the third element from a vector, the empty vector is assigned to it:

```
>> vec = 4:8
vec =
        4      5      6      7      8
>> vec(3) = []
vec =
        4      5      7      8
```

The elements in this vector are now numbered 1 through 4. Note that the variable *vec* has actually changed.

Subsets of a vector could also be removed. For example:

```
>> vec = 3:10
vec =
     3     4     5     6     7     8     9    10
>> vec(2:4) = []
vec =
     3     7     8     9    10
```

Entire rows or columns could be removed from a matrix. For example, to remove the second column:

```
>> mat = [7 9 8; 4 6 5]
mat =
     7     9     8
     4     6     5
>> mat(:,2) = []
mat =
     7     8
     4     5
```

Individual elements cannot be removed from matrices because matrices always have to have the same number of elements in every row.

```
>> mat(1,2) = [];
A null assignment can have only one non-colon index.
```

Also, if linear indexing is used with a matrix to delete an element, the matrix will be reshaped into a row vector.

```
>> mat = [7 9 8; 4 6 5]
mat =
     7     9     8
     4     6     5
>> mat(3) = []
mat =
     7     4     6     8     5
```

(Again, using linear indexing is not a good idea.)

PRACTICE 2.2

Think about what would be produced by the following sequence of statements and expressions, and then type them in to verify your answers.

```
mat = [1:3; 44 9 2; 5:-1:3]

mat(3,2)

mat(2,:)
```

```
size(mat)

mat(:,4) = [8;11;33]

numel(mat)

v = mat(3,:)

v(v(2))

v(1) = []

reshape(mat,2,6)
```

2.1.6 Three-Dimensional Matrices

The matrices that have been shown so far have been two-dimensional; these matrices have rows and columns. Matrices in MATLAB are not limited to two dimensions, however. In fact, in Chapter 13 we will see image applications in which ***three-dimensional matrices*** are used. For a three-dimensional matrix, imagine a two-dimensional matrix as being flat on a page, and then the third dimension consists of more pages on top of that one (so, they are stacked on top of each other).

Three-dimensional matrices can be created using the **zeros**, **ones**, and **rand** functions by specifying three dimensions to begin with. For example, **zeros(2,4,3)** will create a $2 \times 4 \times 3$ matrix of all 0s.

Unless specified otherwise, in the remainder of this book "matrices" will be assumed to be two-dimensional.

2.2 VECTORS AND MATRICES AS FUNCTION ARGUMENTS

In MATLAB, an entire vector or matrix can be passed as an argument to a function; the function will be evaluated on every element. This means that the result will be the same size as the input argument.

For example, let us find the absolute value of every element of a vector *vec*. The **abs** function will automatically return the absolute value of each individual element and the result will be a vector with the same length as the vector argument.

```
>> vec = -2:1
vec =
    -2    -1     0     1
>> absvec = abs(vec)
absvec =
     2     1     0     1
```

For a matrix, the resulting matrix will have the same size as the original argument matrix. For example, the **sign** function will find the sign of each element in a matrix:

```
>> mat = [0 4 -3; -1 0 2]
mat =
     0     4    -3
    -1     0     2
>> sign(mat)
ans =
     0     1    -1
    -1     0     1
```

Functions such as **abs** and **sign** can have either scalars or arrays (vectors or matrices) passed to them. There are a number of functions that are written specifically to operate on vectors or on columns of matrices; these include the functions **min**, **max**, **sum**, and **prod**. These functions will be demonstrated, first with vectors, and then with matrices.

For example, assume that we have the following vector variables:

```
>> vec1 = 1:5;
>> vec2 = [3 5 8 2];
```

The function **min** will return the minimum value from a vector, and the function **max** will return the maximum value.

```
>> min(vec1)
ans =
     1
>> max(vec2)
ans =
     8
```

The function **sum** will sum all of the elements in a vector. For example, for *vec1* it will return 1+2+3+4+5 or 15:

```
>> sum(vec1)
ans =
    15
```

The function **prod** will return the product of all of the elements in a vector; for example, for *vec2* it will return 3*5*8*2 or 240:

```
>> prod(vec2)
ans =
   240
```

There are also functions that return cumulative results; the functions **cumsum** and **cumprod** return the ***cumulative sum*** or ***cumulative product***, respectively. A cumulative, or ***running sum***, stores the sum so far at each step because it adds the elements from the vector. For example, for *vec1*, it would store the first element, 1, then 3 (1+2), then 6 (1+2+3), then 10 (1+2+3+4), then, finally, 15 (1+2+3+4+5). The result is a vector that has as many elements as the input argument vector that is passed to it:

```
>> cumsum(vec1)
ans =
     1     3     6    10    15
```

The **cumprod** function stores the cumulative products because it multiplies the elements in the vector together; again, the resulting vector will have the same length as the input vector:

```
>> cumprod(vec1)
ans =
     1     2     6    24   120
```

For matrices, all of these functions operate on every individual column. If a matrix has dimensions *r* × *c*, the result for the **min**, **max**, **sum**, and **prod** functions will be a *1* × *c* row vector, because they return the minimum, maximum, sum, or product respectively for every column. For example, assume the following matrix:

```
>> mat = randi([1 20], 3, 5)
mat =
     3    16     1    14     8
     9    20    17    16    14
    19    14    19    15     4
```

The following are the results for the **max** and **sum** functions:

```
>> max(mat)
ans =
    19    20    19    16    14
>> sum(mat)
ans =
    31    50    37    45    26
```

To find a function for every row, instead of every column, one method would be to transpose the matrix.

```
>> max(mat')
ans =
    16    20    19
>> sum(mat')
ans =
    42    76    71
```

QUICK QUESTION!

Because these functions operate columnwise, how can we get an overall result for the matrix? For example, how would we determine the overall maximum in the matrix?

Answer: We would have to get the maximum from the row vector of column maxima, in other words, ***nest the calls*** to the **max** function:

```
>> max(max(mat))
ans =
    20
```

For the **cumsum** and **cumprod** functions, again they return the cumulative sum or product of every column. The resulting matrix will have the same dimensions as the input matrix:

```
>> mat
mat =
     3    16     1    14     8
     9    20    17    16    14
    19    14    19    15     4
>> cumsum(mat)
ans =
     3    16     1    14     8
    12    36    18    30    22
    31    50    37    45    26
```

Note

that the first row in the resulting matrix is the same as the first row in the input matrix. After that, the values in the rows accumulate.

Another useful function that can be used with vectors and matrices is **diff**. The function **diff** returns the differences between consecutive elements in a vector. For example,

```
>> diff([4 7 15 32])
ans =
     3     8    17

>> diff([4 7 2 32])
ans =
     3    -5    30
```

For a vector v with a length of n, the length of **diff(v)** will be $n - 1$. For a matrix, the **diff** function will operate on each column.

```
>> mat = randi(20, 2,3)
mat =
    17     3    13
    19    19     2
>> diff(mat)
ans =
     2    16   -11
```

2.3 SCALAR AND ARRAY OPERATIONS ON VECTORS AND MATRICES

Numerical operations can be done on entire vectors or matrices. For example, let us say that we want to multiply every element of a vector *v* by 3.

In MATLAB, we can simply multiply *v* by 3 and store the result back in *v* in an assignment statement:

```
>> v= [3 7 2 1];
>> v = v*3
v =
     9    21     6     3
```

As another example, we can divide every element by 2:

```
>> v= [3 7 2 1];
>> v/2
ans =
    1.5000    3.5000    1.0000    0.5000
```

To multiply every element in a matrix by 2:

```
>> mat = [4:6; 3:-1:1]
mat =
     4     5     6
     3     2     1
>> mat * 2
 ans =
     8    10    12
     6     4     2
```

This operation is referred to as ***scalar multiplication*** (or division). We are multiplying every element in a vector or matrix by a scalar (or dividing every element in a vector or a matrix by a scalar).

QUICK QUESTION!

There is no tens function to create a matrix of all tens, so how could we accomplish that?

Answer: We can either use the **ones** function and multiply by ten, or the **zeros** function and add ten:

```
>> ones(1,5) * 10
ans =
    10    10    10    10    10
>> zeros(2) + 10
ans =
    10    10
    10    10
```

Array operations are operations that are performed on vectors or matrices term by term, or element by element. This means that the two arrays (vectors or matrices) must be of the same size to begin with. The following examples demonstrate the array addition and subtraction operators.

```
>> v1 = 2:5
v1 =
     2     3     4     5
>> v2 = [33 11 5 1]
v2 =
    33    11     5     1
>> v1 + v2
ans =
    35    14     9     6

>> mata = [5:8; 9:-2:3]
mata =
     5     6     7     8
     9     7     5     3
>> matb = reshape(1:8,2,4)
matb =
     1     3     5     7
     2     4     6     8
>> mata - matb
ans =
     4     3     2     1
     7     3    -1    -5
```

However, for any operation that is based on multiplication (which means multiplication, division, and exponentiation), a dot must be placed in front of the operator for array operations. For example, for the exponentiation operator .^ must be used when working with vectors and matrices, rather than just the ^ operator. Squaring a vector, for example, means multiplying each element by itself, so the .^ operator must be used.

```
>> v= [3 7 2 1];
>> v ^ 2
Error using ^
Incorrect dimensions for raising a matrix to a power. Check that the
matrix is square and the power is a scalar. To perform elementwise
matrix powers, use '.^'.
>> v .^ 2
ans =
     9    49     4     1
```

Similarly, the operator .* must be used for **array multiplication** and ./ or .\ for **array division**. The following examples demonstrate array multiplication and array division.

```
>> v1 = 2:5
v1 =
     2     3     4     5
```

```
>> v2 = [33 11 5 1]
v2 =
    33    11     5     1

>> v1 .* v2
ans =
    66    33    20     5

>> mata = [5:8; 9:-2:3]
mata =
     5     6     7     8
     9     7     5     3
>> matb = reshape(1:8, 2,4)
matb =
     1     3     5     7
     2     4     6     8

>> mata ./ matb
ans =
    5.0000    2.0000    1.4000    1.1429
    4.5000    1.7500    0.8333    0.3750
```

The operators .^, .*, ./, and .\ are called array operators and are used when multiplying or dividing vectors or matrices of the same size term by term. Note that matrix multiplication is a very different operation and will be covered in Section 2.5.

PRACTICE 2.3

Create a vector variable and subtract 3 from every element in it.
Create a matrix variable and divide every element by 3.
Create a matrix variable and square every element.

2.4 LOGICAL VECTORS

Logical vectors use relational expressions that result in **true**/**false** values.

2.4.1 Relational Expressions With Vectors and Matrices

Relational operators can be used with vectors and matrices. For example, let us say that there is a vector *vec*, and we want to compare every element in the vector to 5 to determine whether it is greater than 5 or not. The result would be a vector (with the same length as the original) with **logical true** or **false** values.

```
>> vec = [5 9 3 4 6 11];
>> isg = vec > 5
isg =
  1×6 logical array
   0   1   0   0   1   1
```

Note that this creates a vector consisting of all **logical true** or **false** values. Although the result is a vector of ones and zeros, and numerical operations can be done on the vector *isg*, its type is **logical** rather than **double**.

```
>> whos
  Name         Size        Bytes  Class      Attributes

  isg          1x6             6  logical
  vec          1x6            48  double
```

To determine how many of the elements in the vector *vec* were greater than 5, the **sum** function could be used on the resulting vector *isg*:

```
>> sum(isg)
ans =
     3
```

What we have done is create a ***logical vector*** *isg*. This logical vector can be used to index into the original vector. For example, if only the elements from the vector that are greater than 5 are desired:

```
>> vec(isg)
ans =
     9     6    11
```

This is called ***logical indexing***. Only the elements from *vec* for which the corresponding element in the logical vector *isg* is **logical true** are returned.

QUICK QUESTION!

Why doesn't the following work?

```
>> vec = [5 9 3 4 6 11];
>> v = [0 1 0 0 1 1];
>> vec(v)
Array indices must be positive integers or
logical values.
```

Answer: The difference between the vector in this example and *isg* is that *isg* is a vector of logicals (**logical** 1s and 0s), whereas [0 1 0 0 1 1] by default is a vector of **double** values. ***Only logical 1s and 0s can be used to index into a vector.*** So, type casting the variable *v* would work:

```
>> v = logical(v);
>> vec(v)
ans =
     9     6    11
```

To create a vector or matrix of all **logical** 1s or 0s, the functions **true** and **false** can be used.

```
>> false(2)
ans =
     0     0
     0     0
>> true(1,5)
ans =
     1     1     1     1     1
```

2.4.2 Logical Built-In Functions

There are built-in functions in MATLAB, which are useful in conjunction with **logical** vectors or matrices; two of these are the functions **any** and **all**. The function **any** returns **logical true** if any element in a vector represents **true**, and **false** if not. The function **all** returns **logical true** only if all elements represent **true**. Here are some examples.

For the following variable *vec2*, some, but not all, elements are **true**; consequently, **any** returns **true** but **all** returns **false**.

```
>> vec2 = logical([1 1 0 1])
vec2 =
     1     1     0     1
>> any(vec2)
ans =
     1
>> all(vec2)
ans =
     0
>> all(true(1,3))
ans =
     1
```

The function **find** returns the indices of a vector that meet given criteria. For example, to find all of the elements in a vector that are greater than 5:

```
>> vec = [5 3 6 7 2]
vec =
     5     3     6     7     2
>> find(vec > 5)
ans =
     3     4
```

For matrices, the **find** function will use linear indexing when returning the indices that meet the specified criteria. For example:

```
>> mata = randi(10,2,4)
mata =
     5     6     7     8
     9     7     5     3
>> find(mata == 5)
ans =
     1
     6
```

For both vectors and matrices, an empty vector will be returned if no elements match the criterion. For example,

```
>> find(mata == 11)
ans =
   0×1 empty double column vector
```

The function **isequal** is useful in comparing arrays. In MATLAB, using the equality operator with arrays will return 1 or 0 for each element; the **all** function could then be used on the resulting array to determine whether all elements were equal or not. The built-in function **isequal** also accomplishes this:

```
>> vec1 = [1 3 -4 2 99];
>> vec2 = [1 2 -4 3 99];
>> vec1 == vec2
ans =
     1     0     1     0     1
>> all(vec1 == vec2)
ans =
     0
>> isequal(vec1,vec2)
ans =
     0
```

However, one difference is that if the two arrays are not the same dimensions, the **isequal** function will return **logical** 0, whereas using the equality operator will result in an error message.

This works with character arrays, also.

```
>> ca1 = 'hello';
>> ca2 = 'howdy';
>> ca1 == ca2
ans =
     1     0     0     0     0
>> isequal(ca1, ca2)
ans =
     0
>> isequal(ca1, 'hello')
ans =
     1
```

QUICK QUESTION!

If we have a vector *vec* that erroneously stores negative values, how can we eliminate those negative values?

Answer: One method is to determine where they are and delete these elements:

```
>> vec = [11 -5 33 2 8 -4 25];
>> neg = find(vec < 0)
neg =
      2     6
>> vec(neg) = []
vec =
     11    33     2     8    25
```

Alternatively, we can just use a logical vector rather than **find**:

```
>> vec = [11 -5 33 2 8 -4 25];
>> vec(vec < 0) = []
vec =
     11    33     2     8    25
```

PRACTICE 2.4

Modify the result seen in the previous Quick Question! Instead of deleting the negative elements, retain only the positive ones. (Hint: Do it two ways, using **find** and using a logical vector with the expression *vec >= 0*.)

The following is an example of an application of several of the functions mentioned here. A vector that stores a signal can contain both positive and negative values. (For simplicity, we will assume no zeros, however.) For many applications it is useful to find the ***zero crossings***, or where the signal goes from being positive to negative or vice versa. This can be accomplished using the functions **sign**, **diff**, and **find**.

```
>> vec = [0.2 -0.1 -0.2 -0.1 0.1 0.3 -0.2];
>> sv = sign(vec)
sv =
     1    -1    -1    -1     1     1    -1
>> dsv = diff(sv)
dsv =
    -2     0     0     2     0    -2
>> find(dsv ~= 0)
ans =
     1     4     6
```

This shows that the signal crossings are between elements 1 and 2, 4 and 5, and 6 and 7.

MATLAB has **or** and operators that work elementwise for arrays:

Operator	Meaning
|	elementwise or for arrays
&	elementwise and for arrays

These operators will compare any two vectors or matrices as long as they are the same size, element by element and return a vector or matrix of the same size of **logical** 1s and 0s. The operators || and && are only used with scalars, not matrices. For example:

```
>> v1 = logical([1 0 1 1]);
>> v2 = logical([0 0 1 0]);

>> v1 & v2
ans =
     0     0     1     0
>> v1 | v2
ans =
     1     0     1     1
```

Table 2.1 Operator Precedence Rules

Operators	Precedence
parentheses: ( )	highest
transpose and power: ', ^, .^	
unary: negation (-), not (~)	
multiplication, division *,/,\,.*,./,.\	
addition, subtraction +, -	
colon :	
relational <, <=, >, >=, ==, ~=	
element-wise and &	
element-wise or |	
and && (scalars)	
or || (scalars)	lowest

```
>> v1 && v2
Operands to the logical and (&&) and or (||) operators must be
convertible to logical scalar values.
```

As with the numerical operators, it is important to know the operator precedence rules. Table 2.1 shows the rules for the operators that have been covered so far, in the order of precedence.

2.5 MATRIX OPERATIONS AND MATRIX PROPERTIES

We have seen array operations such as array multiplication. In this section, we will examine some important operations on matrices such as matrix multiplication and properties of square matrices. All of this is useful in linear algebra applications.

2.5.1 Matrix Multiplication

Matrix multiplication does *not* mean multiplying term by term; it is not an array operation. Matrix multiplication has a very specific meaning. First of all, to multiply a matrix A by a matrix B to result in a matrix C, the number of columns of A must be the same as the number of rows of B. If the matrix A has dimensions $m \times n$, that means that matrix B must have dimensions $n \times$ *something*; we will call it p.

We say that the ***inner dimensions*** (the ns) must be the same. The resulting matrix C has the same number of rows as A and the same number of columns as B (i.e., the ***outer dimensions*** $m \times p$). In mathematical notation,

$$[A]_{m \times n}\,[B]_{n \times p} = [C]_{m \times p}$$

This only defines the size of C, not how to find the elements of C.

The elements of the matrix C are defined as the sum of products of corresponding elements in the rows of A and columns of B, or in other words,

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj}.$$

In the following example, A is 2×3 and B is 3×4; the inner dimensions are both 3, so performing the matrix multiplication A*B is possible (note that B*A would not be possible). C will have as its size the outer dimensions 2×4. The elements in C are obtained using the summation just described. The first row of C is obtained using the first row of A and in succession the columns of B. For example, C(1,1) is 3*1+8*4+0*0 or 35. C(1,2) is 3*2+8*5+0*2 or 46.

$$\begin{array}{ccccc} A & & B & & C \\ \begin{bmatrix} 3 & 8 & 0 \\ 1 & 2 & 5 \end{bmatrix} & * & \begin{bmatrix} 1 & 2 & 3 & 1 \\ 4 & 5 & 1 & 2 \\ 0 & 2 & 3 & 0 \end{bmatrix} & = & \begin{bmatrix} 35 & 46 & 17 & 19 \\ 9 & 22 & 20 & 5 \end{bmatrix} \end{array}$$

In MATLAB, the * operator will perform this matrix multiplication:

```
>> A = [3 8 0; 1 2 5];
>> B = [1 2 3 1; 4 5 1 2; 0 2 3 0];
>> C = A*B
C =
    35    46    17    19
     9    22    20     5
```

PRACTICE 2.5

When two matrices have the same dimensions and are square, both array and matrix multiplication can be performed on them. For the following two matrices, perform A.*B, A*B, and B*A by hand and then verify the results in MATLAB.

$$\begin{array}{cc} A & B \\ \begin{bmatrix} 1 & 4 \\ 3 & 3 \end{bmatrix} & \begin{bmatrix} 1 & 2 \\ -1 & 0 \end{bmatrix} \end{array}$$

2.5.2 Matrix Multiplication for Vectors

Because vectors are just special cases of matrices, the matrix operations described previously (addition, subtraction, scalar multiplication, multiplication, transpose) also work on vectors, as long as the dimensions are correct.

For vectors, we have already seen that the transpose of a row vector is a column vector, and the transpose of a column vector is a row vector.

To multiply vectors, they must have the same number of elements, but one must be a row vector and the other a column vector. For example, for a column vector *c* and row vector *r*:

$$\mathrm{c} = \begin{bmatrix} 5 \\ 3 \\ 7 \\ 1 \end{bmatrix} \quad r = [6\ 2\ 3\ 4]$$

Note that r is 1×4, and c is 4×1, so

$$[\mathrm{r}]_{1 \times 4} [\mathrm{c}]_{4 \times 1} = [\mathrm{s}]_{1 \times 1}$$

or, in other words, a scalar:

$$[6 \quad 2 \quad 3 \quad 4] = \begin{bmatrix} 5 \\ 3 \\ 7 \\ 1 \end{bmatrix} = 6{*}5 + 2{*}3 + 3{*}7{*}1 = 61$$

whereas $[\mathrm{c}]_{4 \times 1}[\mathrm{r}]_{1 \times 4} = [\mathrm{M}]_{4 \times 4}$, or in other words a 4×4 matrix:

$$\begin{bmatrix} 5 \\ 3 \\ 7 \\ 1 \end{bmatrix} [6 \quad 2 \quad 3 \quad 4] = \begin{bmatrix} 30 & 10 & 15 & 20 \\ 18 & 6 & 9 & 12 \\ 42 & 14 & 21 & 28 \\ 6 & 2 & 3 & 4 \end{bmatrix}$$

In MATLAB, these operations are accomplished using the * operator, which is the matrix multiplication operator. First, the column vector *c* and row vector *r* are created.

```
>> c = [5 3 7 1]';
>> r = [6 2 3 4];
>> r*c
ans =
    61
>> c*r
ans =
    30    10    15    20
    18     6     9    12
    42    14    21    28
     6     2     3     4
```

There are also operations specific to vectors: the ***dot product*** and ***cross product***. The ***dot* product**, or ***inner product***, of two vectors *a* and *b* is written as *a* • *b* and is defined as

$$\mathrm{a_1b_1 + a_2b_2 + a_3b_3 + \ldots + a_nb_n} = \sum_{i=1}^{n} \mathrm{a_ib_i}$$

where both *a* and *b* have n elements and a_i and b_i represent elements in the vectors. In other words, this is like matrix multiplication when multiplying a row vector *a* by a column vector *b*; the result is a scalar. This can be accomplished using the * operator and transposing the second vector, or by using the **dot** function in MATLAB:

```
>> vec1 = [4 2 5 1];
>> vec2 = [3 6 1 2];
>> vec1*vec2'
ans =
    31
>> dot(vec1,vec2)
ans =
    31
```

The ***cross product*** or ***outer product*** *a* × *b* of two vectors *a* and *b* is defined only when both *a* and *b* have three elements. It can be defined as a matrix multiplication of a matrix composed from the elements from *a* in a particular manner shown here and the column vector *b*.

$$a\,x\,b = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = [\mathrm{a_2b_3 - a_3b_2, a_3b_1 - a_1b_3, a_1b_2 - a_2b_1}]$$

MATLAB has a built-in function **cross** to accomplish this.

```
>> vec1 = [4 2 5];
>> vec2 = [3 6 1];
>> cross(vec1,vec2)
ans =
   -28    11    18
```

2.5.3 Properties of Square Matrices

If an m x n matrix has the same number of rows and columns (e.g., if *m* == *n*), the matrix is ***square***. The definitions that follow in this section only apply to square matrices.

The ***main diagonal*** of a square matrix (sometimes called just the ***diagonal***) is the set of terms a_{ii} for which the row and column indices are the same, so from the upper left element to the lower right. For example, for the following matrix, the diagonal consists of 1, 6, 11, and 16.

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix}$$

A square matrix is a ***diagonal matrix*** if all values that are not on the diagonal are 0. The numbers on the diagonal, however, do not have to be all nonzero, although frequently they are. Mathematically, this is written as $a_{ij} = 0$ for i ~= j. The following is an example of a diagonal matrix:

$$\begin{bmatrix} 4 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 5 \end{bmatrix}$$

MATLAB has a function **diag** that will return the diagonal of a matrix as a column vector; transposing will result in a row vector instead.

```
>> mymat = reshape(1:16,4,4)'
mymat =
     1     2     3     4
     5     6     7     8
     9    10    11    12
    13    14    15    16
>> diag(mymat)'
ans =
     1     6    11    16
```

The **diag** function can also be used to take a vector of length *n* and create an *n* × *n* square diagonal matrix with the values from the vector on the diagonal:

```
>> v=1:4;
>> mat = diag(v)
mat =
     1     0     0     0
     0     2     0     0
     0     0     3     0
     0     0     0     4
```

Therefore, the **diag** function can be used two ways: (i) pass a matrix and it returns a vector, or (ii) pass a vector and it returns a matrix!

The ***trace*** of a square matrix is the sum of all of the elements on the diagonal. For example, for the diagonal matrix created using *v* it is 1 + 2 + 3 + 4, or 10.

In MATLAB, there is a built-in function **trace** to calculate the trace of a square matrix:

```
>> trace(mat)
ans =
     10
```

A square matrix is an ***identity*** matrix called I if $a_{ij} = 1$ for $i == j$ and $a_{ij} = 0$ for $i \sim= j$. In other words, all of the numbers on the diagonal are 1 and all others are 0. The following is a 3×3 identity matrix:

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

Note that any identity matrix is a special case of a diagonal matrix.

Identity matrices are very important and useful. MATLAB has a built-in function **eye** that will create an $n \times n$ identity matrix, given the value of n:

Note

that **i** is built into MATLAB as the square root of -1, so another name is used for the function that creates an identity matrix: **eye**, which sounds like "i" (... get it?).

```
>> eye(5)
ans =
      1      0      0      0      0
      0      1      0      0      0
      0      0      1      0      0
      0      0      0      1      0
      0      0      0      0      1
```

QUICK QUESTION!

What happens if a matrix M is multiplied by an identity matrix (of the appropriate size)?

Answer: For the size to be appropriate, the dimensions of the identity matrix would be the same as the number of columns of M. The result of the multiplication will always be the original matrix M (thus, it is similar to multiplying a scalar by 1).

```
>> M = [1 2 3 1; 4 5 1 2; 0 2 3 0]
M =
   1     2     3     1
   4     5     1     2
   0     2     3     0
>> [r, c] = size(M);
>> M * eye(c)
ans =
   1     2     3     1
   4     5     1     2
   0     2     3     0
```

A square matrix is ***symmetric*** if $a_{ij} = a_{ji}$ for all i, j. In other words, all of the values opposite the diagonal from each other must be equal to each other. In this example, there are three pairs of values opposite the diagonals, all of which are equal (the 2s, the 9s, and the 4s).

$$\begin{bmatrix} 1 & 2 & 9 \\ 2 & 5 & 4 \\ 9 & 4 & 6 \end{bmatrix}$$

PRACTICE 2.6

For the following matrices:

$$\begin{array}{ccc} A & B & C \\ \begin{bmatrix} 4 & 3 \\ 3 & 2 \end{bmatrix} & \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} & \begin{bmatrix} 1 & 0 & 0 \\ 4 & 6 & 0 \\ 3 & 1 & 3 \end{bmatrix} \end{array}$$

Which are square?
For all square matrices:

- Calculate the trace.
- Which are symmetric?
- Which are diagonal?

MATLAB has several "is" functions that determine whether or not matrices have some of the properties explained in this section (e.g., **isdiag**, **issymmetric**).

Data Science and Machine Learning Supplement

Central Tendency and Outliers

There are a lot of statistical analyses that can be performed on data sets. In this section, we will introduce some simple analyses on one variable, which are called the ***central tendency*** of the data. The idea is this: consider a sorted set of exam grades {33, 75, 77, 82, 83, 85, 85, 91, 100}. What is a "normal," "expected," or "average" exam grade? There are several ways that this could be interpreted. Perhaps the most common is the ***mean*** grade, which is found by summing the grades and dividing by the number of grades (the result of that would be 79). Another way of interpreting that would be the grade found the most often, which would be 85 (this is the ***mode***). Also, the value in the middle of the sorted list, 83, could be used (this is the ***median***). Vectors will be used to represent data sets.

The ***arithmetic mean*** of a data set is what is usually called the ***average*** of the values or, in other words, the sum of the values divided by the number of values in the data set. Mathematically, we would write this as $\frac{\sum_{i=1}^{n} x_i}{n}$.

There is a built-in function, **mean**, in MATLAB to accomplish this:

```
>> x = [9 10 10 9 8 7 3 10 9 8 5 10];
>> mean(x)
ans =
    8.1667
```

Sometimes a value that is much larger or smaller than the rest of the data (called an ***outlier***) can throw off the mean. For example, in the following, all of the numbers in the data set are in the range from 3 to 10, with the exception of the 100 in the middle. Because of this outlier, the mean of the values in this vector is actually larger than any of the other values in the vector.

```
>> xwithbig = [9 10 10 9 8 100 7 3 10 9 8 5 10];
>> mean(xwithbig)
ans =
   15.2308
```

Often, an outlier like this represents an error of some kind, perhaps in the data collection. To handle this, sometimes the minimum and maximum values from a data set are discarded before the mean is computed.

```
>> newx = xwithbig;
>> loc = find(newx == min(newx));
>> newx(loc) = [];
>> loc = find(newx == max(newx));
>> newx(loc) = []
newx =
     9   10   10    9    8    7   10    9    8    5   10
```

Instead of just removing the minimum and maximum values, sometimes the largest and smallest 1% or 2% of values are removed, especially if the data set is very large. Statistics and Machine Learning Toolbox™ has a function **trimmean**, which trims the highest and lowest *n*% of data values, where the percentage *n* is specified as an argument.

Be careful with this, however. Sometimes, outliers are not errors but are important information. In fraud detection, for example, outliers can be anomalies in the data that indicate that a security breach may have taken place.

The ***mode*** of a data set is the value that appears most frequently. The built-in function in MATLAB for this is called **mode**.

```
>> x = [9 10 10 9 8 7 3 10 9 8 5 10];
>> mode(x)
ans =
    10
```

If there is more than one value with the same (highest) frequency, the smaller value is the mode. In the following case, as 3 and 8 appear twice in the vector, the smaller value (3) is the mode:

```
>> x = [3 8 5 3 4 1 8];
>> mode(x)
ans =
     3
```

Therefore, if no value appears more frequently than any other, the mode of the vector will be the same as the minimum.

The ***median*** is defined only for a data set that has been ***sorted*** first, meaning that the values are in order. The median of a sorted set of *n* data values is defined as the value in the middle, if *n* is odd, or the average of the two values in the middle if *n* is even. For example, for the vector [1 4 5 9 12], the middle value is 5. The function in MATLAB is called **median**:

```
>> median([1 4 5 9 12 ])
ans =
     5
```

For the vector [1 4 5 9 12 33], the median is the average of the 5 and 9 in the middle:

```
>> median([1 4 5 9 12 33])
ans =
     7
```

If the vector is not in sorted order to begin with, the **sort** function can be used, but this is not necessary because the **median** function will still return the correct result (it will sort the vector automatically). For example, scrambling the order of the values in the first example will still result in a median value of 5.

```
>> median([9 4 1 5 12])
ans =
     5
```

Sometimes with actual data sets, values can be missing or incorrect. In those instances, it is common to replace the missing or incorrect data with either the mean, mode, or median of the other data values. Often, when reading data into MATLAB, missing values are replaced by the constant NaN. So, a dataset might store something like this:

```
>> dataset = [5 NaN 9 3 11 NaN];
```

The **mean** and **median** functions (as well as other functions such as **sum**, **prod**, etc.) would return NaN for this dataset. However, the argument 'omitnan' can be added to function calls using these functions in order for the NaN values to be ignored.

```
>> mean(dataset,'omitnan')
ans =
     7
```

Explore Other Interesting Features

- There are many functions that create special matrices (e.g.,. **hilb** for a Hilbert matrix, **magic**, and **pascal**).
- The **gallery** function, which can return many different types of test matrices for problems.
- The **ndims** function to find the number of dimensions of an argument.
- The **shiftdim** function.
- The **circshift** function. How can you get it to shift a row vector, resulting in another row vector?
- The **sub2ind** and **ind2sub** functions to convert from subscripted indexing to linear indexing, and vice versa.
- How to reshape a three-dimensional matrix.
- The **range** function.
- Passing 3D matrices to functions. For example, if you pass a *3x5x2* matrix to the **sum** function, what would be the size of the result?
- The **meshgrid** function can specify the x and y coordinates of points in images, or can be used to calculate functions on two variables *x* and *y*. It receives as input arguments two vectors and returns as output arguments two matrices that specify separately x and y values. ■

SUMMARY

COMMON PITFALLS

- Attempting to create a matrix that does not have the same number of values in each row.
- Confusing matrix multiplication and array multiplication. Array operations, including multiplication, division, and exponentiation, are performed term by term (so the arrays must have the same size); the operators are .*, ./, .\, and .^. For matrix multiplication to be possible, the inner dimensions must agree, and the operator is *.
- Attempting to use an array of **double** 1s and 0s to index into an array (must be **logical**, instead).
- Forgetting that for array operations based on multiplication, the dot must be used in the operator. In other words, for multiplying, dividing by,

dividing into, or raising to an exponent term by term, the operators are .*, ./, .\, and .^.

- Attempting to use || or && with arrays. Always use | and & when working with arrays; || and && are only used with scalars.

PROGRAMMING STYLE GUIDELINES

- If possible, try not to extend vectors or matrices because it is not very efficient.
- Do not use just a single index when referring to elements in a matrix; instead, use both the row and column subscripts (use subscripted indexing rather than linear indexing).
- To be general, never assume that the dimensions of any array (vector or matrix) are known. Instead, use the function **length** or **numel** to determine the number of elements in a vector, and the function **size** for a matrix:

```
len = length(vec);
[r, c] = size(mat);
```

- Use **true** instead of **logical(1)** and **false** instead of **logical(0)**, especially when creating vectors or matrices.

MATLAB Functions and Commands			
linspace	end	max	isequal
logspace	reshape	sum	dot
zeros	fliplr	prod	cross
ones	flipud	cumsum	diag
length	flip	cumprod	trace
size	rot90	diff	eye
height	repmat	any	isdiag
width	repelem	all	issymmetric
numel	min	find	

MATLAB Operators	
colon	:
transpose	'
array operators	.^, .*, ./, .\
elementwise or for matrices	|
elementwise and for matrices	&
matrix multiplication	*

Exercises

1. Create the vector *vec* in three different ways: using just square brackets, using the colon operator, and using **linspace**:

```
vec =
     5     7     9     11
```

2. Write an expression using **linspace** that will result in the same as 1: 0.5: 3
3. Which of the following will create the vector?

```
vec =
     2     4     6     8

vec = 2:2:8
vec = 2:2:9
vec = linspace(2,8,4)
vec = flip(8:-2:2)
```

4. How many elements would be in the vectors created by the following expressions?

```
linspace(3,2000)
logspace(3,2000)
```

5. Explain how the step value is obtained by the **linspace** function. First, create a few examples to reference.
6. Create a variable *myend*, which stores a random integer in the inclusive range from 5 to 9. Using the colon operator, create a vector that iterates from 1 to *myend* in steps of 3.
7. Create two row vector variables. Concatenate them together to create a new row vector variable.
8. Using the colon operator and the transpose operator, create a column vector *myvec* that has the values -1 to 1 in steps of 0.5.
9. Write an expression that refers to only the elements that have odd-numbered subscripts in a vector, regardless of the length of the vector. Test your expression on vectors that have both an odd and even number of elements.
10. Generate a 2 × 4 matrix variable *mat*. Replace the first row with 1:4. Replace the third column (you decide with which values).
11. Generate a 2 × 4 matrix variable *mat*. Verify that the number of elements is equal to the product of the number of rows and columns. Do this using **width** and **height**.
12. Which would you normally use for a matrix: **length** or **size**? Why?
13. When would you use **length** versus **size** for a vector?
14. Generate a *2* × *3* matrix of random

- real numbers, each in the range (0, 1)
- real numbers, each in the range (0, 5)
- integers, each in the inclusive range from 10 to 50

15. Create a variable *rows* that is a random integer in the inclusive range from 1 to 5. Create a variable *cols* that is a random integer in the inclusive range from 1 to 5. Create a matrix of all zeros with the dimensions given by the values of *rows* and *cols*.
16. Create a vector variable *vec*. Find as many expressions as you can that would refer to the last element in the vector, without assuming that you know how many elements it has (i.e., make your expressions general).
17. Create a matrix variable *mat*. Find as many expressions as you can that would refer to the last element in the matrix, without assuming that you know how many elements or rows or columns it has (i.e., make your expressions general).
18. Given a matrix variable *mat* that has at least three columns, show how to delete the third column (assuming that there are at least three columns).
19. Why would the following code produce an error message? Explain what each statement does or attempts to do.

    ```
    mat = [1:3; 4:6];
    mat(:,2) = [3 7 11]'
    ```

20. Explain why this code works:

    ```
    vec = 1:6;
    vec(3) = []
    ```

    But this code does not:

    ```
    mat = reshape(1:6, 2,3);
    mat(2,3) = []
    ```

21. Create a 2 × 3 matrix variable *mat*. Pass this matrix variable to each of the following functions and make sure you understand the result: **flip**, **fliplr**, **flipud**, and **rot90**. In how many different ways can you **reshape** it?
22. What is the difference between `fliplr(mat)` and `mat = fliplr(mat)`?
23. Use **reshape** to reshape the row vector 1:4 into a 2×2 matrix; store this in a variable named *mat*. Next, make 2×3 copies of *mat* using both **repelem** and **repmat**.
24. Create a three-dimensional matrix with dimensions 2 × 4 × 3 in which the first "layer" is all 0s, the second is all 1s, and the third is all 5s. Use **size** to verify the dimensions.
25. Create a vector x which consists of 20 equally spaced points in the range from –π to +π. Create a y vector which is **sin(x)**.
26. Create a *3 x 5* matrix of random integers, each in the inclusive range from -5 to 5. Get the **sign** of every element.
27. Find the sum 2+4+6+8+10 using **sum** and the colon operator.
28. Find the following sum by first creating vectors for the numerators and denominators:

    $$\frac{3}{1}+\frac{5}{2}+\frac{7}{3}+\frac{9}{4}$$

29. Create a matrix and find the product of each row and column using **prod**.
30. Write a relational expression for a vector variable that will verify that the last value in a vector created by **cumsum** is the same as the result returned by **sum**.
31. Create a vector of five random integers, each in the inclusive range from −10 to 10. Perform each of the following:
    - Subtract 3 from each element.
    - Count how many are positive.
    - Get the cumulative minimum using **cummin**.
32. Create a *3* × *5* matrix. Perform each of the following:
    - Find the maximum value in each column.
    - Find the maximum value in each row.
    - Find the maximum value in the entire matrix.
33. Find two ways to create a *3* × *5* matrix of all 100s (Hint: use **ones** and **zeros**).
34. Assume that you have two vector variables, "veca" and "vecb", and that they are both row vectors with the same number of elements. Explain the difference between the following expressions. Include in your explanation the type of the result.

```
veca == vecb
```

```
isequal(veca, vecb)
```

35. Use **doc** to determine how to get an index for **min**.
36. Create variables for these two matrices:

$$\overset{A}{\begin{bmatrix} 1 & 2 & 3 \\ 4 & -1 & 6 \end{bmatrix}} \quad \overset{B}{\begin{bmatrix} 2 & 4 & 1 \\ 1 & 3 & 0 \end{bmatrix}}$$

Perform the following operations:

```
A + B
A - B
A .* B
```

37. A vector *v* stores for several employees of the Green Fuel Cells Corporation, their hours worked one week followed for each by the hourly pay rate. For example, if the variable stores

```
>> v
v =
33.0000    10.5000    40.0000    18.0000    20.0000    7.5000
```

then that means the first employee worked 33 hours at $10.50 per hour, the second worked 40 hours at $18 an hour, and so on. Write code that will separate this into two vectors, one that stores the hours worked and another that stores the hourly rates. Then, use the array multiplication operator to create a vector, storing in the new vector the total pay for every employee.

38. Write code that would count how many elements in a matrix variable *mat* are negative numbers. Create a matrix of random numbers, some positive and some negative, first.
39. A company is calibrating some measuring instrumentation and has measured the radius and height of one cylinder eight separate times; they are in vector variables *r* and *h*. Find the volume from each trial, which is given by $\Pi r^2 h$. Also, use logical indexing first to make sure that all measurements were valid (> 0).

```
>> r = [5.499 5.498 5.5 5.5 5.52 5.51 5.5 5.48];
>> h = [11.1 11.12 11.09 11.11 11.11 11.1 11.08 11.11];
```

40. For the following matrices A, B, and C:

$$A = \begin{bmatrix} 1 & 4 \\ 3 & 2 \end{bmatrix} B = \begin{bmatrix} 2 & 1 & 3 \\ 1 & 5 & 6 \\ 3 & 6 & 0 \end{bmatrix} C = \begin{bmatrix} 3 & 2 & 5 \\ 4 & 1 & 2 \end{bmatrix}$$

- Give the result of 3*A.
- Give the result of A*C.
- Are there any other matrix multiplications that can be performed? If so, list them.

41. Create a row vector variable *r* that has four elements, and a column vector variable *c* that has four elements. Perform r*c and c*r.
42. Generate a vector of 20 random integers, each in the range from 50 to 100. Create a variable *evens* that stores all of the even numbers from the vector, and a variable *odds* that stores the odd numbers.
43. Assume that the function **diff** does not exist. Write your own expression(s) to accomplish the same thing for a vector.
44. Create a vector variable *vec*; it can have any length. Then, write assignment statements that would store the first half of the vector in one variable and the second half in another. Make sure that your assignment statements are general, and work whether *vec* has an even or odd number of elements (Hint: use a rounding function such as **fix**).
45. Create a diagonal matrix from a vector and get its trace.
46. Create a square matrix and determine whether or not it is diagonal. Also, determine whether or not it is symmetric.

Data Science and Machine Learning

47. What is the difference between the mean and the median of a data set if there are only two values in it?
48. A student missed one of four exams in a course and the professor decided to use the "average" of the other three grades for the missed exam grade. Which would be better for the student: the mean or the median if the three recorded grades were 99, 88, and 95? What if the grades were 99, 70, and 77?
49. Read in the variables from the built-in .mat file census.mat. Determine what the variables are named. Find the mean and the median values for the populations.

CHAPTER 3

Introduction to MATLAB Programming

KEY TERMS

computer program
scripts
live script
algorithm
modular program
top-down design
external file
default input device
prompting
default output device
execute/run
high-level languages
machine language
executable
compiler
source code
object code
interpreter
documentation
comments
block comment
comment blocks
input/output (I/O)
user
empty array
error message
formatting
format specifier
place holder
conversion characters
newline character
field width
leading blanks
trailing zeros
plot symbols
markers
line types
toggle
modes
writing to a file
appending to a file
reading from a file
user-defined functions
function call
argument
control
return value
function header
output arguments
input arguments
function body
function definition
local variables
scope of variables
base workspace
local functions
subfunctions

CONTENTS

We have now used the MATLAB® product interactively in the Command Window. That is sufficient when all one needs is a simple calculation. However, in many cases, quite a few steps are required before the final result can be obtained. In those cases, it is more convenient to group statements together in what is called a ***computer program***.

In this chapter, we introduce the simplest MATLAB programs, which are called ***scripts***. Examples of scripts that customize simple plots illustrate the concept.

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00003-2

Input is introduced, both from files and from the user. Output to files and to the screen is also introduced. Finally, user-defined functions that calculate and return a single value are described. These topics serve as an introduction to programming, which are expanded on in Chapter 6.

In this chapter, we create simple scripts stored in MATLAB code files, which have an extension of .m. At the end of the chapter, a new, richer script type called a ***live scripts*** is introduced. This topic is expanded in Chapter 6.

3.1 ALGORITHMS

Before writing any computer program, it is useful to first outline the steps that will be necessary. An ***algorithm*** is the sequence of steps needed to solve a problem. In a ***modular*** approach to programming, the problem solution is broken down into separate steps, and then each step is further refined until the resulting steps are small enough to be manageable tasks. This is called the ***top-down design*** approach.

As a simple example, consider the problem of calculating the area of a circle. First, it is necessary to determine what information is needed to solve the problem, which in this case is the radius of the circle. Next, given the radius of the circle, the area of the circle would be calculated. Finally, once the area has been calculated, it has to be displayed in some way. The basic algorithm then is three steps:

- Get the input: the radius.
- Calculate the result: the area.
- Display the output.

Even with an algorithm this simple, it is possible to further refine each of the steps. When a program is written to implement this algorithm, the steps would be as follows.

- Where does the input come from? Two possible choices would be from an ***external file***, or from the user (the person who is running the program) who enters the number by typing it from the keyboard. For every system, one of these will be the ***default input device*** (which means, if not specified otherwise, this is where the input comes from!). If the user is supposed to enter the radius, the user has to be told to type in the radius (and, in what units). Telling the user what to enter is called ***prompting***. Therefore, the input step actually becomes two steps: prompt the user to enter a radius, and then read it into the program.
- To calculate the area, the formula is needed. In this case, the area of the circle is π multiplied by the square of the radius. So, that means the value of the constant for π is needed in the program.

- Where does the output go? Two possibilities are: (1) to an external file, or (2) to the screen. Depending on the system, one of these will be the ***default output device***. When displaying the output from the program, it should always be as informative as possible. In other words, instead of just printing the area (just the number), it should be printed in a nice sentence format. Also, to make the output even more clear, the input should be printed. For example, the output might be the sentence: "For a circle with a radius of 1 inch, the area is 3.1416 inches squared."

For most programs, the basic algorithm consists of the three steps that have been outlined:

1. Get the input(s).
2. Calculate the result(s).
3. Display the result(s).

As can be seen here, even the simplest problem solutions can then be refined further. This is top-down design.

3.2 MATLAB SCRIPTS

Once a problem has been analyzed, and the algorithm for its solution has been written and refined, the solution to the problem is then written in a particular programming language. A computer program is a sequence of instructions, in a given language, that accomplishes a task. To ***execute*** or ***run*** a program is to have the computer actually follow these instructions sequentially.

High-level languages have English-like commands and functions, such as "print this" or "if x < 5 do something." The computer, however, can interpret commands written only in its ***machine language***. Programs that are written in high-level languages must therefore be translated into machine language before the computer can actually execute the sequence of instructions in the program. A program that does this translation from a high-level language to an ***executable*** file is called a ***compiler***. The original program is called the ***source code***, and the resulting executable program is called the ***object code***. Compilers translate from the source code to object code; this is then executed as a separate step.

By contrast, an ***interpreter*** goes through the code line-by-line, translating and executing each command as it goes. MATLAB uses what are called either *script files* or *MATLAB code files*, which have an extension on the file name of .m. These script files are interpreted rather than compiled. Therefore, the correct terminology is that these are scripts, not programs. However, the terms are used somewhat loosely by many people, and documentation in MATLAB itself refers to scripts as programs. In this book, we reserve the use of the word "program" to mean a set of scripts and functions, as described briefly in Section 3.7 and then in more detail in Chapter 6.

A script is a sequence of MATLAB instructions that is stored in a file with an extension of .m and saved. The contents of a script can be displayed in the Command Window using the **type** command. The script can be executed, or run, by simply entering the name of the file (without the .m extension).

Before creating a script, make sure the Current Folder is set to the folder in which you want to save your files.

The steps involved in creating a script depend on the version of MATLAB. The easiest method is to click on "New Script" under the HOME tab. Alternatively, one can click on the down arrow under "New" and then choose Script (see Fig. 3.1).

A new window will appear called the *Editor* (which can be docked). In the latest versions of MATLAB, this window has three tabs: "EDITOR", "PUBLISH", and "VIEW". Next, simply type the sequence of statements (note that line numbers will appear on the left).

When finished, save the file by choosing the Save down arrow under the EDITOR tab. Make sure that the extension of .m is on the file name (this should be the default). The rules for file names are the same as for variables (they must start with a letter; after that there can be letters, digits, or the underscore).

If you have entered commands in the Command Window and decide that you would like to put them into a script, an alternate method for creating a script is to select the commands in the Command History window, and then right click. This will give options for creating a script or live script and will then prepopulate the editor with those commands. As of R2021b, the editor will now display code suggestions and complete code automatically and will automatically complete syntax such as parentheses and quotation marks.

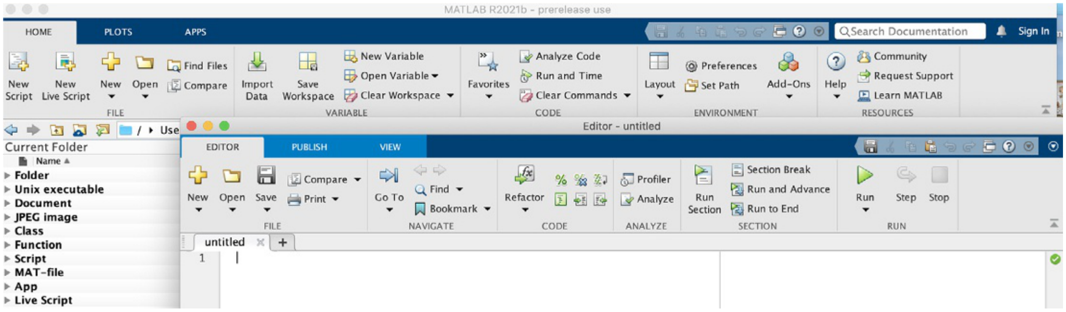


FIGURE 3.1
Toolstrip and Editor.

In our first example, we will create a script called *script1.m* that calculates the area of a circle. It assigns a value for the radius, and then calculates the area based on that radius.

In this book, scripts will be displayed in a box with the name of the file on top.

```
script1.m
```

```
radius = 5
area = pi * (radius^2)
```

There are two ways to view a script once it has been written: either open the Editor Window to view it, or use the **type** command, as shown here, to display it in the Command Window. The **type** command shows the contents of the file named *script1.m*; notice that the .m is not included:

```
>> type script1
radius = 5
area = pi * (radius^2)
```

To actually run or execute the script from the Command Window, the name of the file is entered at the prompt (again, without the .m). When executed, the results of the two assignment statements are displayed because the output was not suppressed for either statement.

```
>> script1
radius =
     5
area =
     78.5398
```

Once the script has been executed, you may find that you want to make changes to it (especially if there are errors!). To edit an existing file, there are several methods to open it. The easiest are:

- Within the Current Folder Window, double-click on the name of the file in the list of files.
- Choosing the Open down arrow will show a list of Recent Files.

3.2.1 Documentation

It is very important that all scripts be ***documented*** well so that people can understand what the script does and how it accomplishes its tasks. One way of documenting a script is to put ***comments*** in it. In MATLAB, a comment is anything from a `%` to the end of that particular line. Comments are completely ignored when the script is executed. To put in a comment, simply type the `%` symbol at the beginning of a line, or select the comment lines and then click on the Edit down arrow and click on the % symbol, and the Editor will put in the `%` symbols at the beginning of those lines for the comments.

For example, the previous script to calculate the area of a circle could be modified to have comments:

circlescript.m

```
% This script calculates the area of a circle

% First the radius is assigned
radius = 5
% The area is calculated based on the radius
area = pi * (radius^2)
```

The first comment at the beginning of the script describes what the script does; this is sometimes called a ***block comment***. Then, throughout the script, comments describe different parts of the script (not usually a comment for every line, however!). Comments do not affect what a script does, so the output from this script would be the same as for the previous version.

The **help** command in MATLAB works with scripts as well as with built-in functions. The first block of comments (defined as contiguous lines at the beginning) will be displayed. For example, for *circlescript*:

```
>> help circlescript
  This script calculates the area of a circle
```

The reason that a blank line was inserted in the script between the first two comments is that otherwise both would have been interpreted as one contiguous comment, and both lines would have been displayed with **help**. The very first comment line is called the "H1 line"; it is what the function **lookfor** searches through.

PRACTICE 3.1

Write a script to calculate the circumference of a circle ($C = 2 \pi r$). Comment the script.

Longer comments, called ***comment blocks***, consist of everything in between %{ and %}, which must be alone on separate lines. For example:

```
%{
   this is used for a really
   Really
   REALLY
   long comment
%}
```

3.3 INPUT AND OUTPUT

The previous script would be much more useful if it were more general, for example, if the value of the radius could be read from an external source rather than being assigned in the script. Also, it would be better to have the script print the output in a nice, informative way. Statements that accomplish these tasks are called ***input/output*** statements, or ***I/O*** for short. Although, for simplicity, examples of input and output statements are shown here in the Command Window, these statements make the most sense in scripts.

3.3.1 Input Function

Input statements read in values from the default or standard input device. In most systems, the default input device is the keyboard, so the input statement reads in values that have been entered by the ***user***, or the person who is running the script. To let the user know what they are supposed to enter, the script must first prompt the user for the specified values.

The simplest input function in MATLAB is called **input**. The **input** function is used in an assignment statement. To call it, a character vector is passed that is the prompt that will appear on the screen, and whatever the user types will be stored in the variable named on the left of the assignment statement. For ease of reading the prompt, it is useful to put a colon and then a space after the prompt. For example,

```
>> rad = input('Enter the radius: ')
Enter the radius: 5
rad =
     5
```

In this case, the prompt was printed and then the user entered 5.

If character or character vector input is desired, ‘s’ must be added as a second argument to the **input** function:

```
>> letter = input('Enter a char: ','s')
Enter a char: g
letter =
     'g'
```

If the user enters only spaces or tabs before hitting the Enter key, they are ignored, and an ***empty array*** is stored in the variable:

```
>> mychar = input('Enter a character: ', 's')
Enter a character:
mychar =
  0×0 empty char array
```

However, if blank spaces are entered before other characters, they are included in the variable. In the next example, the user hits the space bar four times before entering “go.” The **length** function returns the number of characters in the variable.

```
>> mystr = input('Enter a word: ', 's')
Enter a word:     go
mystr =
    '    go'
>> length(mystr)
ans =
     6
```

QUICK QUESTION!

What would be the result if the user enters blank spaces after other characters? For example, the user here entered “xyz   ” (four blank spaces):

```
>> mychar = input('Enter chars: ', 's')
Enter chars: xyz
mychar =
    'xyz    '
```

Answer: The space characters would be stored in the variable.

It is also possible for the user to type quotation marks around the entry rather than including the second argument ‘s’ in the call to the **input** function.

```
>> name = input('Enter your name: ')
Enter your name: 'Stormy'
name =
    'Stormy'
```

However, this assumes that the user would know to do this so it is better to signify that character input is desired in the **input** function itself. Also, if the ‘s’ is specified and the user enters quotation marks, these would become part of the variable.

```
>> name = input('Enter your name: ','s')
Enter your name: 'Stormy'
name =
         ''Stormy''
>> length(name)
ans =
     8
```

The ‘s’ argument in the input function reads into a character vector. To create a string, it is necessary to typecast the character vector, for example:

```
>> name = input('Enter your name: ', 's');
```

```
Enter your name: Stormy
>> stnam = string(name)
stnam = 
    "Stormy"
```

Note what happens if character input has not been specified, but the user enters a letter rather than a number.

```
>> num = input('Enter a number: ')
Enter a number: t
Error using input
Unrecognized function or variable 't'.
Enter a number: 3
num = 
     3
```

MATLAB gave an ***error message*** and repeated the prompt. However, if *t* is the name of a variable, MATLAB will take its value as the input.

```
>> t = 11;
>> num = input('Enter a number: ')
Enter a number: t
num = 
    11
```

Separate **input** statements are necessary if more than one input is desired. For example,

```
>> x = input('Enter the x coordinate: ');
>> y = input('Enter the y coordinate: ');
```

Normally in a script, the results from **input** statements are suppressed with a semicolon at the end of the assignment statements.

PRACTICE 3.2

Create a script that would prompt the user for a length, and then 'f' for feet or 'm' for meters, and store both inputs in variables. For example, when executed it would look like this (assuming the user enters 12.3 and then m):

```
Enter the length: 12.3
Is that f(eet)or m(eters)?: m
```

It is also possible to enter a vector. The user can enter any valid vector, using any valid syntax such as square brackets, the colon operator, or functions such as **linspace**.

```
>> v = input('Enter a vector: ')
Enter a vector: [3 8 22]
v = 
     3     8     22
```

3.3.2 Output Statements: disp and fprintf

Output statements display character vectors or strings and/or the results of expressions, and can allow for ***formatting***, or customizing how they are displayed. The simplest output function in MATLAB is **disp**, which is used to display the result of an expression or a string or character vector without assigning any value to the default variable *ans*. The **disp** function automatically moves down to the next line. For example,

```
>> disp('Hello')
Hello
>> disp(4^3)
      64
```

However, **disp** does not allow formatting. Formatted output can be printed to the screen using the **fprintf** function. For example,

```
>> fprintf('The value is %d, for sure!\n',4^3)
The value is 64, for sure!
>>
```

To the **fprintf** function, first a string or character vector (called the ***format specifier***) is passed that contains any text to be printed, as well as formatting information for the expressions to be printed. The format specifier can be either a string or a character vector; historically (before R2016b), it was always a character vector, so that is the way they will typically be shown, both in this book and in the MATLAB documentation. In this example, the %d is an example of format information.

The %d is sometimes called a ***place holder*** because it specifies where the value of the expression that is after the format specifier is to be printed. The character in the place holder is called the ***conversion character***, and it specifies the type of value that is being printed. There are others, but what follows is a list of the simple place holders:

```
%d    integer (it stands for decimal integer)
%f    float (real number)
%c    character (one character)
%s    string of characters (string or char vec)
```

Note

Do not confuse the % in the place holder with the symbol used to designate a comment.

The character '\n' at the end of the format specifier is a special character called the ***newline character***; what happens when it is printed is that the output that follows moves down to the next line.

QUICK QUESTION!

What do you think would happen if the newline character is omitted from the end of an **fprintf** statement?

Answer: Without it, the next prompt would end up on the same line as the output. It is still a prompt, and so an expression can be entered, but it looks messy as shown here.

```
>> fprintf('The value is %d, surely!', 4^3)
The value is 64, surely!>> 5 + 3
ans =
      8
```

Note that with the **disp** function, however, the prompt will always appear on the next line:

```
>> disp('Hi')
Hi
>>
```

Also, note that an ellipsis can be used after a string or character vector but not in the middle.

QUICK QUESTION!

How can you get a blank line in the output?

Answer: Have two newline characters in a row.

```
>> fprintf('The value is %d,\n\nOK!\n',4^3)
The value is 64,

OK!
```

This also points out that the newline character can be anywhere in the format specifier; when it is printed, the output moves down to the next line.

Note that the newline character can also be used in the prompt in the **input** statement; for example:

```
>> x = input('Enter the \nx coordinate: ');
Enter the
x coordinate: 4
```

However, the newline is the ONLY formatting character allowed in the prompt in **input**.

To print two values, there would be two place holders in the format specifier, and two expressions after the format specifier. The expressions fill in for the place holders in sequence.

```
>> fprintf('The int is %d and the char is %c\n', ...
    33 - 2, 'x')
The int is 31 and the char is x
```

A ***field width*** can also be included in the place holder in **fprintf**, which specifies how many characters total are to be used in printing. For example, %5d would indicate a field width of 5 for printing an integer and %10s would indicate a field width of 10 for a string or character vector. For floats, the number of decimal places can also be specified; for example, %6.2f means a field width of 6 (including the decimal point and the two decimal places) with two decimal places. So, the format would be xxx.xx. For floats, just the number of decimal places can also be specified; for example, %.3f indicates three decimal places, regardless of the field width.

Note that if the field width is wider than necessary, ***leading blanks*** are printed, and if more decimal places are specified than necessary, ***trailing zeros*** are printed.

```
>> fprintf('The int is %3d and the float is %6.2f\n',...
             5,4.9)
The int is   5 and the float is   4.90
```

QUICK QUESTION!

What do you think would happen if you tried to print 1234.5678 in a field width of 3 with two decimal places?

```
>> fprintf('%3.2f\n', 1234.5678)
```

Answer: It would print the entire 1234, but round the decimals to two places, that is,

1234.57

If the field width is not large enough to print the number, the field width will be increased. Basically, to cut the number off would give a misleading result, but rounding the decimal places does not change the number significantly.

QUICK QUESTION!

What would happen if you use the %d conversion character but you are trying to print a real number?

Answer: MATLAB will show the result using exponential notation

```
>> fprintf('%d\n',1234567.89)
1.234568e+006
```

Note that, if you want exponential notation, this is not the correct way to get it; instead, there are conversion characters that can be used. Use **doc** to see this option, as well as many others!

There are many other options for the format specifier. For example, the value being printed can be left-justified within the field width using a minus sign. The following example shows the difference between printing the integer 3 using %5d and using %-5d. The x's below are used to show the spacing.

```
>> fprintf('The integer is xx%5dxx and xx%-5dxx\n',3,3)
The integer is xx    3xx and xx3    xx
```

Also, strings and character vectors can be truncated by specifying "decimal places":

```
>> fprintf('The string is %s or %.2s\n', "street", "street")
The string is street or st
```

There are several special characters that can be printed in the format specifier in addition to the newline character. To print a slash, two slashes in a row are used, and also to print a single quote, two single quotes in a row are used. To print one percent sign, use two in a row. Additionally, '\t' is the tab character.

```
>> fprintf('Try this: tab\t quote '' slash \\100%%\n')
Try this: tab  quote ' slash \100%
```

3.3.2.1 Printing Vectors and Matrices

For a vector, if a conversion character and the newline character are in the format specifier, it will print in a column regardless of whether the vector itself is a row vector or a column vector.

```
>> vec = 2:5;
>> fprintf('%d\n', vec)
2
3
4
5
```

Without the newline character, it would print in a row but the next prompt would appear on the same line:

```
>> fprintf('%d', vec)
2345>>
```

However, in a script, a separate newline character could be printed to avoid this problem. It is also much better to separate the numbers with spaces.

printvec.m

```
% This demonstrates printing a vector

vec = 2:5;
fprintf('%d ',vec)
fprintf('\n')
```

```
>> printvec
2 3 4 5
>>
```

If the number of elements in the vector is known, that many conversion characters can be specified and then the newline:

```
>> fprintf('%d %d %d %d\n', vec)
2 3 4 5
>>
```

This is not very general, however, and is therefore not preferable.

For matrices, MATLAB unwinds the matrix column by column. For example, consider the following *2 x 3* matrix:

```
>> mat = [5  9  8; 4  1  10]
mat =
      5     9      8
      4     1     10
```

Specifying one conversion character and then the newline character will print the elements from the matrix in one column. The first values printed are from the first column, then the second column, and so on.

```
>> fprintf('%d\n', mat)
5
4
9
1
8
10
```

If three of the %d conversion characters are specified, the **fprintf** will print three numbers across on each line of output, but again the matrix is unwound column-by-column. It again prints first the two numbers from the first column (across on the first row of output), then the first value from the second column, and so on.

```
>> fprintf('%d %d %d\n', mat)
5  4  9
1  8  10
```

If the transpose of the matrix is printed, however, using the three %d conversion characters, the matrix is printed as it appears when created.

```
>> fprintf('%d %d %d\n', mat') % Note the transpose
5  9  8
4  1  10
```

For vectors and matrices, even though formatting cannot be specified, the **disp** function may be easier to use in general than **fprintf** because it displays the result in a straight-forward manner. For example,

```
>> mat = [15 11 14; 7 10 13]
mat =
   15     11     14
    7     10     13
>> disp(mat)
   15     11     14
    7     10     13

>> vec = 2:5
vec =
    2      3     4     5
>> disp(vec)
    2      3     4     5
```

Note that, when loops are covered in Chapter 5, formatting the output of matrices will be easier. For now, however, **disp** works well.

3.4 SCRIPTS WITH INPUT AND OUTPUT

Putting all of this together now, we can implement the algorithm from the beginning of this chapter. The following script calculates and prints the area of a circle. It first prompts the user for a radius, reads in the radius, and then calculates and prints the area of the circle based on this radius.

circleIO.m

```
% This script calculates the area of a circle
% It prompts the user for the radius

% Prompt the user for the radius and calculate
% the area based on that radius
fprintf('Note: the units will be inches.\n')
radius = input('Please enter the radius: ');
area = pi * (radius^2);

% Print all variables in a sentence format
fprintf('For a circle with a radius of %.2f inches,\n’,...
    radius)
fprintf('the area is %.2f inches squared\n',area)
```

Executing the script produces the following output:

```
>> circleIO
Note: the units will be inches.
Please enter the radius: 3.9
For a circle with a radius of 3.90 inches,
the area is 47.78 inches squared
```

Note that the output from the first two assignment statements (including the **input**) is suppressed by putting semicolons at the end. That is usually done in scripts, so that the exact format of what is displayed by the program is controlled by the **fprintf** functions.

PRACTICE 3.3

Write a script to prompt the user separately for a character and a number, and print the character in a field width of 3 and the number left justified in a field width of 8 with three decimal places. Test this by entering numbers with varying widths.

3.5 SCRIPTS TO PRODUCE AND CUSTOMIZE SIMPLE PLOTS

MATLAB has many graphing capabilities. Customizing plots is often desired, and this is easiest to accomplish by creating a script rather than typing one command at a time in the Command Window. For that reason, simple plots and how to customize them will be introduced in this chapter on MATLAB programming.

3.5.1 The Plot Function

For now, we start with a very simple graph of one point using the **plot** function.

The following script, *plotonepoint*, plots one point. To do this, first values are given for the x and y coordinates of the point in separate variables. The point is plotted using a red star by specifying ‘r*’.

This can be done from the Command Window, but it is much easier to use a script, especially when more is added to customize the plot. The following shows the contents of the script *plotonepoint* that accomplishes this. The x coordinate represents the time of day (e.g., 11:00 a.m.) and the y coordinate represents the temperature (e.g., in degrees Fahrenheit) at that time.

plotonepoint.m

```
% This is a really simple plot of just one point!

% Create coordinate variables and plot a red '*'
x = 11;
y = 48;
plot(x,y,'r*')
```

Executing this script brings up a Figure Window with the plot (see Fig. 3.2).

Notice that the point is in the middle of the plot. The axes, from 10 to 12 for the x-axis, and from 47 to 49 on the y-axis, are created by MATLAB by default. The axes can be changed using the **axis** function. There are many options for the **axis** function; for example, just calling it with no arguments returns the values used for the x- and y-axes ranges.

```
>> arang = axis
arang =
     10     12     47     49
```

The **axis** function can also be called by passing a vector consisting of four numbers; the first two are the minimum and maximum values for the x-axis, and the last two are the minimum and maximum values for the y-axis. For example, axis([9 12 35 55]) would set the x-axis from 9 to 12 and the y-axis from 35 to 55. Axes can also be turned on and off, and they can be made square

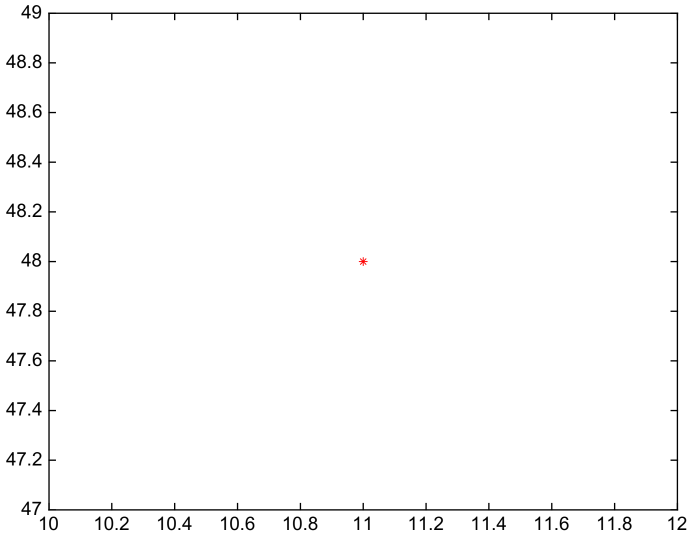


FIGURE 3.2
Plot of one data point.

or equal to each other. A subset of the data can also be shown by limiting the extent of the axes.

To plot more than one point, *x* and *y* vectors are created to store the values of the (x,y) points. For example, to plot the points (8, 31), (9, 37), (10, 46), (11, 48), representing temperatures at four different hours one morning, first an *x* vector is created that has the x values (as they range from 8 to 11 in steps of 1, the colon operator can be used) and then a *y* vector is created with the y values. The following script will create these vectors, put a title and subtitle on the plot (using **title** and **subtitle**), and put labels on the axes (using **xlabel** and **ylabel**). See Fig. 3.3. The **subtitle** function is new as of R2020b.

timesandtemps.m

```
% Create coordinate vector variables
x = 8:11;
y = [31 37 46 48];

% Plot points and add labels
plot(x,y,'b*')
title('Time and Temperatures')
subtitle('(Fahrenheit)')
xlabel('Time')
ylabel('Temperature')

% Create some space around the points
axis padded
```

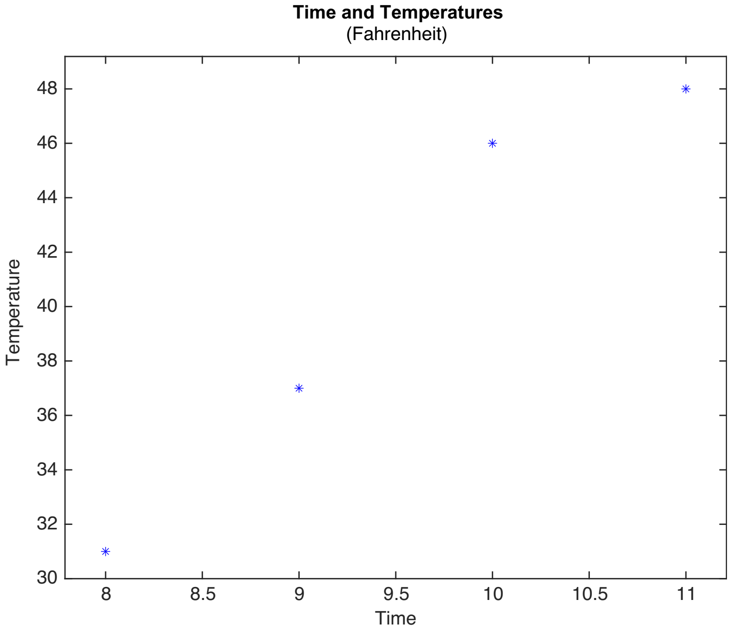


FIGURE 3.3
Plot of data points from vectors.

The **axis padded** command (new as of R2020b) is used to put space around the points. Without this, the first and last points would be on the actual axes, which make them difficult to see.

PRACTICE 3.4

Modify the script *timesandtemps* to prompt the user for the time and temperature.

In many cases, when x and y vectors are created to specify data points, the values of x range from 1 to the length of y. If that is the case, the x vector is not necessary. Therefore,

```
plot(y)
```

would be the same as

```
x = 1:length(y);
plot(x,y)
```

3.5.1.1 Customizing a Plot: Color, Line Types, Marker Types

Plots can be done in the Command Window if they are really simple. However, many times it is desired to customize the plot with labels, titles, and so on, so it makes more sense to do this in a script. Using the **doc** function for **plot** will show the many options such as the line types and colors. In the previous scripts, the character vector 'r*' specified a red star for the point type, and 'b*' specified a blue star.

The LineSpec, or line specification, can specify up to three different properties in a character vector or string, including the color, line type, and the symbol or marker used for the data points.

The possible colors are:

b	blue
g	green
r	red
c	cyan
m	magenta
y	yellow
k	black
w	white

Either the single character listed above or the full name of the color can be used in the string to specify the color.

The ***plot symbols***, or ***markers***, that can be used are:

.	point
o	circle
x	x-mark
+	plus
*	star
s	square
d	diamond
v	down triangle
^	up triangle
<	left triangle
>	right triangle
p	pentagram
h	hexagram
_	horizontal line
|	vertical line

The last two markers are new as of R2020b. If no line type is specified and no marker type is specified, a solid line is drawn between the points. ***Line types*** can also be specified by the following:

-	solid
:	dotted
-.	dash dot
—	dashed
(none)	no line

3.5.2 Simple Related Plot Functions

Other functions that are useful in customizing plots include **clf**, **figure**, **hold**, **legend**, and **grid**. Brief descriptions of these functions are given here; use **help** to find out more about them:

clf: clears the Figure Window by removing everything from it.

figure: creates a new, empty Figure Window when called without any arguments. Calling it as `figure(n)` where *n* is an integer is a way of creating and maintaining multiple Figure Windows, and of referring to each individually.

hold: is a toggle that freezes the current graph in the Figure Window, so that new plots will be superimposed on the current one. Just `hold` by itself is a ***toggle***, so calling this function once turns the hold on, and then the next time turns it off. Alternatively, the commands `hold on` and `hold off` can be used.

legend: displays strings or character vectors passed to it in a legend box in the Figure Window, in order of the plots in the Figure Window.

grid: displays grid lines on a graph. Called by itself, it is a toggle that turns the grid lines on and off. Alternatively, the commands `grid on` and `grid off` can be used.

Also, there are many plot types. We will see more in Chapter 12, but other simple plot types are **bar** charts, and straight line plots **xline** and **yline**. Introduced in R2018b, **yline** creates horizontal line(s) at specified y coordinate(s), and **xline** creates vertical line(s) at specified x coordinate(s).

For example, the following script creates two separate Figure Windows. First, it clears the Figure Window. Then, it creates an *x* vector and a y vector. In the first Figure Window, it plots the *y* values using a bar chart. In the second Figure Window, it plots the *y* values as black circles, puts **hold on** so that the next graph will be superimposed, and plots a horizontal line. It also pads the axes and uses a grid. Labels and titles are omitted in this case, as it is generic data.

plot2figs.m

```
% This creates 2 different plots, in 2 different
% Figure Windows, to demonstrate some plot features

clf
x = 1:5; % Not necessary
y = [2 11 6 9 3];
% Put a bar chart in Figure 1
figure(1)
bar(x,y)
```

```
% Plot the points and use yline in Figure 2
figure(2)
plot(x,y,'ko')
hold on
yline(5)
axis padded
grid on
```

Running this script will produce two separate Figure Windows. If there are no other active Figure Windows, the first, which is the bar chart, will be in the one titled "Figure 1" in MATLAB. The second will be in "Figure 2". See Fig. 3.4 for both plots.

PRACTICE 3.5

Modify the *plot2figs* script to add some labels.

The ability to pass a vector to a function and have the function evaluate every element of the vector can be very useful in creating plots. For example, the following script graphically displays the difference between the **sin** and **cos** functions:

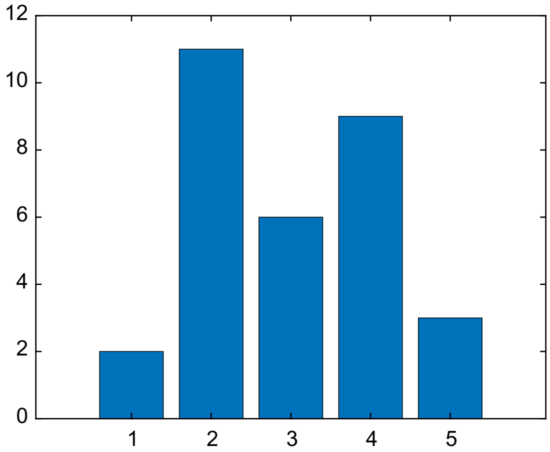


FIGURE 3.4A

Bar chart produced by script.

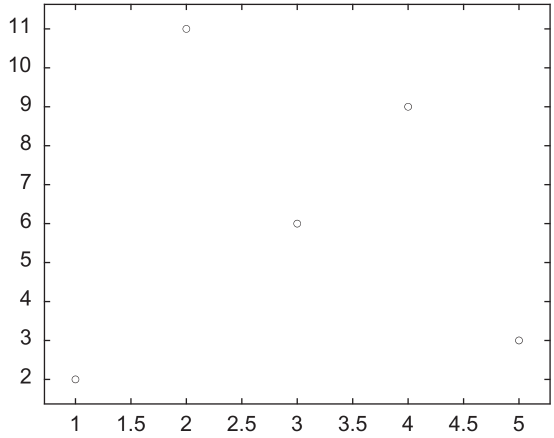


FIGURE 3.4B

Plot produced by script, with a grid.

sinncos.m

```
% This script plots sin(x) and cos(x) in the same Figure Window
% for values of x ranging from 0 to 2*pi

clf
x = 0: 2*pi/40: 2*pi;
y = sin(x);
plot(x,y)
hold on
y = cos(x);
plot(x,y)
axis padded
legend('sin', 'cos')
xlabel('x')
ylabel('sin(x) or cos(x)')
title('sin and cos on one graph')
```

The script creates an *x* vector; iterating through all of the values from 0 to 2*π in steps of 2*π/40 gives enough points to get a good graph. It then finds the sine of each *x* value, and plots these. The command **hold on** freezes this in the Figure Window so the next plot will be superimposed. Next, it finds the cosine of each *x* value and plots these points. The **legend** function creates a legend; the first character vector is paired with the first plot, and the second character vector with the second plot. Running this script produces the plot seen in Fig. 3.5.

Note that instead of using **hold on**, both functions could have been plotted using one call to the **plot** function:

```
plot(x,sin(x),x,cos(x))
```

PRACTICE 3.6

Write a script that plots **exp(x)** and **log(x)** for values of x ranging from 0 to 3.5.

3.6 INTRODUCTION TO FILE INPUT/OUTPUT (LOAD AND SAVE)

We have seen the use of **load** and **save** to read from/write to MAT-files. This section is different; we will be working with data files that only store data, not variables with their names and values.

In many cases, input to a script will come from a data file that has been created by another source. Also, it is useful to be able to store output in an external file that can be manipulated and/or printed later. In this section, the simplest

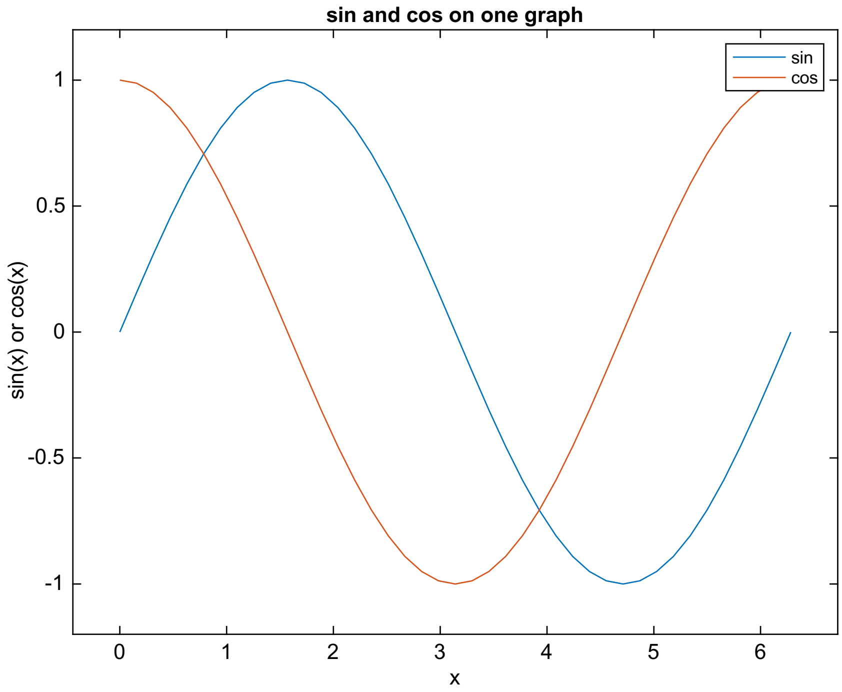


FIGURE 3.5

Plot of **sin** and **cos** in one Figure Window with a legend.

methods used to read from an external data file and also to write to an external data file will be demonstrated.

There are basically three different operations, or ***modes*** on files. Files can be:

- read from
- written to
- appended to

Writing to a file means writing to a file from the beginning. ***Appending to a file*** is also writing, but starting at the end of the file rather than the beginning. In other words, appending to a file means adding to what was already there.

There are many different file types, which use different filename extensions. For now, we will keep it simple and just work with .dat or .txt files when working with data, or text, files. There are several methods for reading from files and writing to files; we will, for now, use the **load** function to read and the **save** function to write to files. More file types and functions for manipulating them will be discussed in Chapter 9.

3.6.1 Writing Data to a File

The **save** command can be used to write data from a matrix to a data file, or to append to a data file. The format is:

```
save filename matrixvariablename -ascii
```

The "-ascii" qualifier is used when creating a text or data file. For example, the following creates a matrix and then saves the values from the matrix variable to a data file called *testfile.dat*:

```
>> mymat = rand(2,3)
mymat =
    0.4565    0.8214    0.6154
    0.0185    0.4447    0.7919

>> save testfile.dat mymat -ascii
```

This creates a file called "testfile.dat" that stores the numbers:

```
0.4565    0.8214    0.6154
0.0185    0.4447    0.7919
```

Note
that if the file already exists, the **save** command will overwrite the file; **save** always writes from the beginning of a file.

The **type** command can be used to display the contents of the file; note that scientific notation is used:

```
>> type testfile.dat

  4.5646767e-001  8.2140716e-001  6.1543235e-001
  1.8503643e-002  4.4470336e-001  7.9193704e-001
```

3.6.2 Appending Data to a Data File

Once a text file exists, data can be appended to it. The format is the same as the preceding, with the addition of the qualifier "-append". For example, the following creates a new random matrix and appends it to the file that was just created:

```
>> mat2 = rand(3,3)
mymat =
    0.9218    0.4057    0.4103
    0.7382    0.9355    0.8936
    0.1763    0.9169    0.0579
>> save testfile.dat mat2 -ascii -append
```

This results in the file "testfile.dat" containing the following:

```
   0.4565    0.8214    0.6154
   0.0185    0.4447    0.7919
   0.9218    0.4057    0.4103
   0.7382    0.9355    0.8936
   0.1763    0.9169    0.0579
```

Note that, although technically any size matrix could be appended to this data file, to be able to read it back into a matrix later, there would have to be the same number of values on every row (or, in other words, the same number of columns).

PRACTICE 3.7

Prompt the user for the number of rows and columns of a matrix, create a matrix with that many rows and columns of random integers, and write it to a file.

3.6.3 Reading From a File

Reading from a file is accomplished using **load**. Once a file has been created (as in the preceding), it can be read into a matrix variable. If the file is a data file, the **load** command will read from the file "filename.ext" (e.g., the extension might be .dat) and create a matrix with the same name as the file. For example, if the data file "testfile.dat" had been created as shown in the previous section, this would read from it, and store the result in a matrix variable called *testfile*:

```
>> clear
>> load testfile.dat
>> who
Your variables are:
testfile
>> testfile
testfile =
    0.4565    0.8214    0.6154
    0.0185    0.4447    0.7919
    0.9218    0.4057    0.4103
    0.7382    0.9355    0.8936
    0.1763    0.9169    0.0579
```

The **load** command works only if there are the same number of values in each line, so that the data can be stored in a matrix, and the **save** command only writes from a matrix to a file. If this is not the case, lower-level file I/O functions must be used; these will be discussed in Chapter 9.

3.6.3.1 Example: Load From a File and Plot the Data

As an example, a file called "timetemp.dat" stores two lines of data. The first line is the times of day, and the second line is the recorded temperature at each of those times. The first value of 0 for the time represents midnight. For example, the contents of the file might be:

```
0      3      6      9      12     15     18     21
55.5   52.4   52.6   55.7   75.6   77.7   70.3   66.6
```

The following script loads the data from the file into a matrix called *timetemp*. It then separates the matrix into vectors for the time and temperature, and then plots the data using black star (*) symbols.

timetempprob.m

```
% This reads time and temperature data for an afternoon
% from a file and plots the data

load timetemp.dat

% The times are in the first row, temps in the second row
time = timetemp(1,:);
temp = timetemp(2,:);

% Plot the data and label the plot
plot(time,temp,'k*')
xlabel('Time')
ylabel('Temperature')
title('Temperatures one afternoon')
axis padded
```

Running the script produces the plot seen in Fig. 3.6.

To create the data file, the Editor in MATLAB can be used; it is not necessary to create a matrix and **save** it to a file. Instead, just enter the numbers in a new script file, and Save As *timetemp.dat*, making sure that the Current Folder is set.

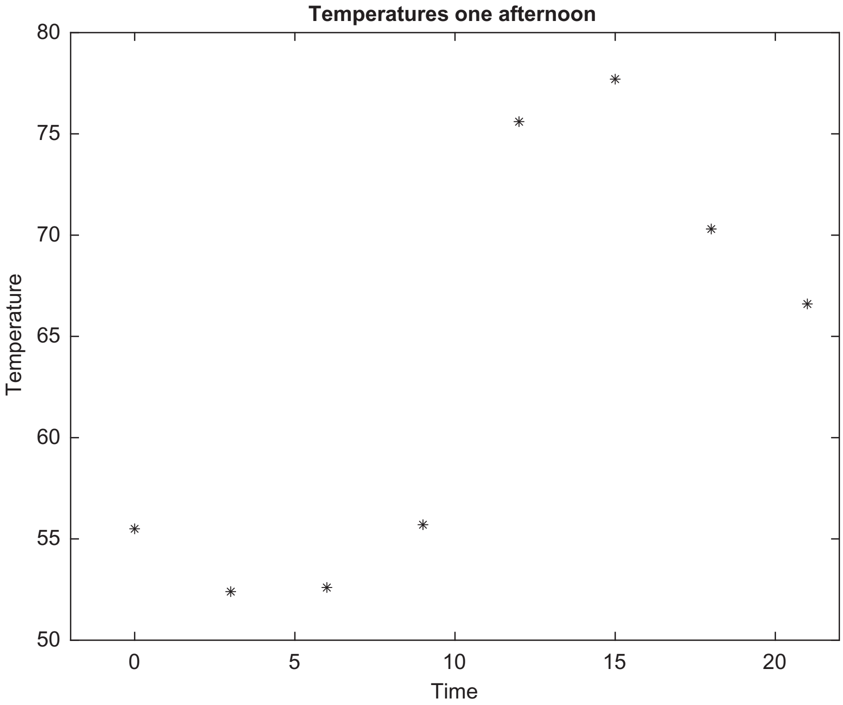


FIGURE 3.6

Plot of temperature data from a file.

PRACTICE 3.8

The sales (in billions) for two separate divisions of the ABC Corporation for each of the four quarters of 2021 are stored in a file called "salesfigs.dat":

```
1.2 1.4 1.8 1.3
2.2 2.5 1.7 2.9
```

- First, create this file (just type the numbers in the Editor, and Save As "salesfigs.dat").
- Then, write a script that will
  - load the data from the file into a matrix.
  - separate this matrix into two vectors.
  - create the plot seen in Fig. 3.7 (which uses black circles and stars as the plot symbols).

QUICK QUESTION!

Sometimes files are not in the format that is desired. For example, a file "expresults.dat" has been created that has some experimental results, but the order of the values is reversed in the file:

```
4    53.4
3    44.3
2    50.0
1    55.5
```

How could we create a new file that reverses the order?

Answer: We can **load** from this file into a matrix, use the **flipud** function to "flip" the matrix up to down, and then **save** this matrix to a new file:

```
>> load expresults.dat
>> expresults
expresults =
    4.0000      53.4000
    3.0000      44.3000
    2.0000      50.0000
    1.0000      55.5000
>> correctorder = flipud(expresults)
correctorder =
    1.0000      55.5000
    2.0000      50.0000
    3.0000      44.3000
    4.0000      53.4000
>> save neworder.dat correctorder - ascii
```

3.7 USER-DEFINED FUNCTIONS THAT RETURN A SINGLE VALUE

We have already seen the use of many functions in MATLAB. We have used many built-in functions such as **sin**, **fix**, **abs**, and **double**. In this section, ***user-defined functions*** will be introduced. These are functions that the programmer defines, and then uses, in either the Command Window or in a script.

There are several different types of functions. For now, we will concentrate on the kind of function that calculates and returns a single result. Other types of functions will be introduced in Chapter 6.

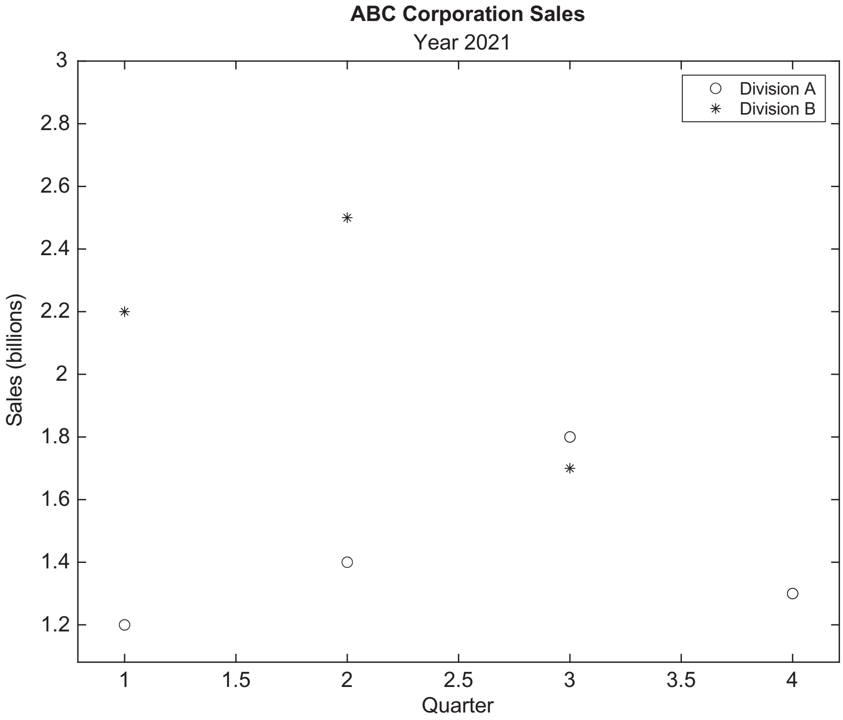


FIGURE 3.7

Plot of sales data from file.

First, let us review some of what we already know about functions, including the use of built-in functions. Although by now, the use of these functions is straightforward, explanations will be given in some detail here in order to compare to and contrast with the use of user-defined functions.

The **length** function is an example of a built-in function that calculates a single value; it returns the length of a vector. As an example,

```
length(vec)
```

is an expression that represents the number of elements in the vector *vec*. This expression could be used in the Command Window or in a script. Typically, the value returned from this expression might be assigned to a variable:

```
>> vec = 1:3:10;
>> lv = length(vec)
lv =
     4
```

Alternatively, the length of the vector could be printed:

```
>> fprintf('The length of the vector is %d\n', length(vec))
The length of the vector is 4
```

The ***function call*** to the **length** function consists of the name of the function, followed by the ***argument*** in parentheses. The function receives as input the argument and returns a result. What happens when the call to the function is encountered is that ***control*** is passed to the function itself (in other words, the function begins executing). The argument(s) are also passed to the function.

The function executes its statements and does whatever is necessary (the actual contents of the built-in functions are not generally known or seen by the user) to determine the number of elements in the vector. Because the function is calculating a single value, this result is then ***returned*** and it becomes the value of the expression. Control is also passed back to the expression that called it in the first place, which then continues (e.g., in the first example, the value would then be assigned to the variable *lv* and in the second example, the value was printed).

3.7.1 Function Definitions

There are different ways to organize scripts and functions, but, for now, every function that we write will be stored in a separate file. Like scripts, function files have an extension of .m. Although to enter function definitions in the Editor, it is possible to choose the New down arrow and then Function, it will be easier for now to type in the function by choosing New Script (this ignores the defaults that are provided when you choose Function). Also, as of R2021b, "Refactor" in the Editor allows code to be converted to a function.

A function in MATLAB that returns a single result consists of the following.

- The ***function header*** (the first line), comprised of:
  - the reserved word **function**.
  - the name of the *output argument* followed by the assignment operator (=), as the function *returns* a result.
  - the name of the function (*important*: This should be the same as the name of the file in which this function is stored to avoid confusion).
  - the *input arguments* in parentheses, which correspond to the arguments that are passed to the function in the function call.
- A comment that describes what the function does (this is printed when **help** is used).
- The ***body*** of the function, which includes all statements and eventually must put a value in the output argument.
- **end** at the end of the function (note that this is not necessary in many cases in current versions of MATLAB, but it is considered good style anyway).

The general form of a ***function definition*** for a function that calculates and returns one value looks like this:

```
functionname.m
```

```
function outputargument = functionname(input arguments)
% Comment describing the function

Statements here; these must include putting a value in the output
argument

end % of the function
```

For example, the following is a function called *calcarea* that calculates and returns the area of a circle; it is stored in a file called *calcarea.m*.

```
calcarea.m
```

```
function area = calcarea(rad)
% calcarea calculates the area of a circle
% Format of call: calcarea(radius)
% Returns the area

area = pi * rad * rad;
end
```

A radius of a circle is passed to the function to the input argument *rad*; the function calculates the area of this circle and stores it in the output argument *area*.

In the function header, we have the reserved word **function**, then the output argument *area* followed by the assignment operator =, then the name of the function (the same as the name of the file), and then the input argument *rad*, which is the radius. As there is an output argument in the function header, somewhere in the body of the function we must put a value in this output argument. This is how a value is returned from the function. In this case, the function is simple and all we have to do is assign to the output argument *area* the value of the built-in constant **pi** multiplied by the square of the input argument *rad*.

The function can be displayed in the Command Window using the **type** command.

```
>> type calcarea

     function area = calcarea(rad)
     % calcarea calculates the area of a circle
     % Format of call: calcarea(radius)
     % Returns the area

     area = pi * rad * rad;
     end
```

3.7.2 Calling a Function

The following is an example of a call to this function in which the value returned is stored in the default variable *ans*:

```
>> calcarea(4)
ans =
   50.2655
```

Technically, calling the function is done with the name of the file in which the function resides. To avoid confusion, it is easiest to give the function the same name as the file name, so that is how it will be presented in this book. In this example, the function name is *calcarea* and the name of the file is *calcarea.m*. The result returned from this function can also be stored in a variable in an assignment statement; the name could be the same as the name of the output argument in the function itself, but that is not necessary. Therefore, for example, either of these assignments would be fine:

```
>> area = calcarea(5)
area =
   78.5398

>> myarea = calcarea(6)
myarea =
  113.0973
```

The output could also be suppressed when calling the function:

```
>> mya = calcarea(5.2);
```

The value returned from the *calcarea* function could also be printed using either **disp** or **fprintf**:

```
>> disp(calcarea(4))
   50.2655
>> fprintf('The area is %.1f\n', calcarea(4))
The area is 50.3
```

Note that the printing is not done in the function itself; rather, the function returns the area and then an output statement can print or display it.

QUICK QUESTION!

Could we pass a vector of radii to the *calcarea* function?

Answer: This function was written assuming that the argument was a scalar, so calling it with a vector instead would produce an error message. This is because the * was used for multiplication in the function, but .* must be used when multiplying vectors term by term. Changing this in the function would allow either scalars or vectors to be passed to this function:

```
calcareaii.m
```

```
function area = calcareaii(rad)
% calcareaii returns the area of a circle
% The input argument can be a vector of
radii
% Format: calcareaii(radiiVector)

area = pi * rad .* rad;
end
```

```
>> calcareaii(1:3)
ans =
    3.1416    12.5664    28.2743

>> calcareaii(4)
ans =
    50.2655
```

Note that the .* operator is only necessary when multiplying the radius vector by itself. Multiplying by **pi** is scalar multiplication, so the .* operator is not needed there. We could have also used:

```
area = pi * rad .^ 2;
```

Using **help** with either of these functions displays the contiguous block of comments under the function header (the block comment). It is useful to put the format of the call to the function in this block comment:

```
>> help calcarea
  calcarea calculates the area of a circle
  Format of call: calcarea(radius)
  Returns the area
```

Suggested corrections for invalid filenames in the Command Window work for user-defined files.

```
>> clacarea(3)
Undefined function or variable 'clacarea'.
Did you mean:
>> calcarea(3)
```

Many organizations have standards regarding what information should be included in the block comment in a function. These can include:

- Name of the function
- Description of what the function does
- Format of the function call
- Description of input arguments
- Description of output argument
- Description of variables used in function
- Programmer name and date written
- Information on revisions

Although this is excellent programming style, for the most part in this book these will be omitted simply to save space. Also, documentation in MATLAB suggests that the name of the function should be in all uppercase letters in the beginning of the block comment. However, this can be somewhat misleading in that MATLAB is case-sensitive and typically lowercase letters are used for the actual function name.

3.7.3 Calling a User-Defined Function From a Script

Now, we will modify our script that prompts the user for the radius and calculates the area of a circle to call our function *calcarea* to calculate the area of the circle rather than doing this in the script.

circleCallFn.m

```
% This script calculates the area of a circle
% It prompts the user for the radius
radius = input('Please enter the radius: ');
% It then calls our function to calculate the
% area and then prints the result
area = calcarea(radius);
fprintf('For a circle with a radius of %.2f,',radius)
fprintf(' the area is %.2f\n',area)
```

Running this will produce the following:

```
>> circleCallFn
Please enter the radius: 5
For a circle with a radius of 5.00, the area is 78.54
```

3.7.3.1 Simple Programs

In this book, a script that calls function(s) is what we will call a MATLAB program. In the previous example, the program consisted of the script *circleCallFn* and the function it calls, *calcarea*. A simple program, consisting of a script that calls a function to calculate and return a value, looks like the format shown in Fig. 3.8.

It is also possible for a function to call another (whether built-in or user-defined).

3.7.4 Passing Multiple Arguments

In many cases it is necessary to pass more than one argument to a function. For example, the volume of a cone is given by

$$V=\frac{1}{4}\pi r^2 h$$

where r is the radius of the circular base and h is the height of the cone. Therefore, a function that calculates the volume of a cone needs both the radius and the height:

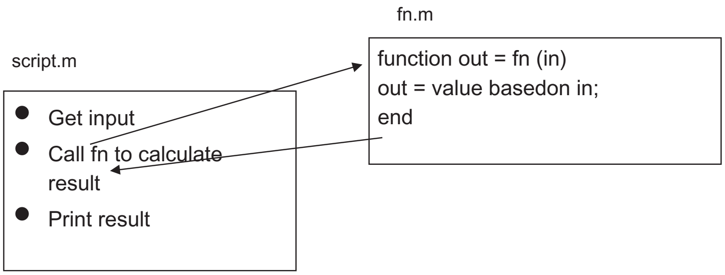


FIGURE 3.8
General form of a simple program.

conevol.m

```
function outarg = conevol(radius, height)
% conevol calculates the volume of a cone
% Format of call: conevol(radius, height)
% Returns the volume

outarg = (pi/3) * radius .^ 2 .* height;
end
```

Because the function has two input arguments in the function header, two values must be passed to the function when it is called. The order makes a difference. The first value that is passed to the function is stored in the first input argument (in this case, *radius*) and the second value in the function call is passed to the second input argument in the function header.

This is very important: the arguments in the function call must correspond one-to-one with the input arguments in the function header.

Here is an example of calling this function. The result returned from the function is simply stored in the default variable *ans*.

```
>> conevol(4,6.1)
ans =
   102.2065
```

In the next example, the result is instead printed with a format of two decimal places.

```
>> fprintf('The cone volume is %.2f\n',conevol(3, 5.5))
The cone volume is 51.84
```

Note that by using the array exponentiation and multiplication operators, it would be possible to pass arrays for the input arguments, as long as the dimensions are the same.

QUICK QUESTION!

Nothing is technically wrong with the following function, but what about it does not make sense?

fun.m

```
function out = fun(a,b,c)
out = a*b;
end
```

Answer: Why pass the third argument if it is not used?

PRACTICE 3.9

Write a script that will prompt the user for the radius and height, call the function *conevol* to calculate the cone volume, and print the result in a nice sentence format. Therefore, the program will consist of a script and the *conevol* function that it calls.

PRACTICE 3.10

For a project, we need some material to form a rectangle. Write a function *calcrectarea* that will receive the length and width of a rectangle in inches as input arguments and will return the area of the rectangle. For example, the function could be called as shown, in which the result is stored in a variable and then the amount of material required is printed, rounded up to the nearest square inch.

```
>> ra = calcrectarea(3.1, 4.4)
ra =
   13.6400

>> fprintf('We need %d sq in.\n', ceil(ra))
We need 14 sq in.
```

3.7.5 Functions With Local Variables

The functions discussed thus far have been very simple. However, in many cases the calculations in a function are more complicated, and may require the use of extra variables within the function; these are called ***local variables***.

For example, a closed cylinder is being constructed of a material that costs a certain dollar amount per square foot. We will write a function that will calculate and return the cost of the material, rounded up to the nearest square foot, for a cylinder with a given radius and a given height. The total surface area for the closed cylinder is

$$SA = 2\pi rh + 2\pi r^2$$

For a cylinder with a radius of 32 inches, height of 73 inches, and cost per square foot of the material of $4.50, the calculation would be given by the following algorithm.

- Calculate the surface area SA = 2*π*32*73 + 2*π*32*32 inches squared.
- Convert the SA from square inches to square feet = SA/144.
- Calculate the total cost = SA in square feet * cost per square foot.
- The function includes local variables to store the intermediate results.

cylcost.m

```
function outcost = cylcost(radius, height, cost)
% cylcost calculates the cost of constructing a closed
%   cylinder
% Format of call: cylcost(radius, height, cost)
% Returns the total cost

% The radius and height are in inches
% The cost is per square foot

% Calculate surface area in square inches
surf_area = 2 * pi * radius .* height + 2 * pi * radius .^ 2;

% Convert surface area in square feet and round up
surf_areasf = ceil(surf_area/144);

% Calculate cost
outcost = surf_areasf .* cost;
end
```

The following shows examples of calling the function:

```
>> cylcost(32,73,4.50)
ans =
  661.5000

>> fprintf('The cost would be $%.2f\n', cylcost(32,73,4.50))
The cost would be $661.50
```

3.7.6 Introduction to Scope

It is important to understand the ***scope of variables***, which is where they are valid. More will be described in Chapter 6, but, basically, variables used in a script are also known in the Command Window and vice versa. All variables used in a function, however, are local to that function. Both the Command Window and scripts use a common workspace, the ***base workspace***. Functions, however, have their own workspaces. This means that when a script is executed, the variables can subsequently be seen in the Workspace Window and can be used from the Command Window. This is not the case with functions, however.

3.8 LOCAL FUNCTIONS IN SCRIPTS

In Section 3.7.3, a program was described as a script that calls a function; both the script and the function were stored in separate code files. Figure 3.8 illustrated this organization. However, it is possible to include functions within a script file, at the end of the script file. Functions that are contained within a script code file are ***local functions*** to that script and can only be called from within the script code file. They are sometimes called ***subfunctions***. All local functions, like other user-defined functions, have their own workspaces. Even though a local function is contained in a script, the script uses the base workspace whereas local functions use their own workspaces.

The following script code file includes a local function:

```
testlocfn.m
```

```
x = 33;
y = 11;

a = locfn(x);
fprintf('a is %d\n', a)
fprintf('x is %d\n', x)

function out = locfn(in)
x = in + 5;
out = x;
end
```

The script will create the variables *x*, *y*, and *a* in the base workspace. Although the function is executing, it will have *in*, *x*, and *out* in its workspace, but that workspace only exists while the function is executing. Therefore, the value of *x* that is printed from the script is the value assigned in the script in the base workspace.

```
>> testlocfn
a is 38
x is 33
```

An advantage of having a local function is that it cuts down on the number of code files. If a function is only going to be called from a script (and it is not desired to call it from the Command Window or from another function), then it is easier to include it in the same code file as the script. Another use for a local function is to have an easy way of testing the function when the function is first being written; later when finished the function could be placed in its own code file. The disadvantage of a local function is that it can only be called from within the script code file. This means that it can be called from within the script, or from another local function within the script. The order of the local functions does not matter if there are multiple local functions, but they must appear after the script code.

3.9 COMMANDS AND FUNCTIONS

Some of the commands that we have used (e.g., **format**, **type**, **save**, and **load**) are just shortcuts for function calls. If all of the arguments to be passed to a function are strings or character vectors, and the function does not return any values, it can be used as a command. For example, the following produce the same results:

```
>> type script1

radius = 5
area = pi * (radius^2)

>> type('script1')

radius = 5
area = pi * (radius^2)
```

Using **load** as a command creates a variable with the same name as the file. If a different variable name is desired, it is easiest to use the functional form of **load**. For example,

```
>> type pointcoords.dat

3.3     1.2
4       5.3

>> points = load('pointcoords.dat')
points =
    3.3000    1.2000
    4.0000    5.3000
```

This stores the result in a variable *points* rather than *pointcoords*.

3.10 INTRODUCTION TO LIVE SCRIPTS

An alternate type of script is called a ***live script*** and is created using the ***Live Editor***. A live script is much more dynamic than a simple script; it can embed equations, images, and hyperlinks in addition to formatted text. Instead of having graphs in separate windows, the graphics are shown next to the code that created them. It is also possible to put the graphs inline, under the code. Equations can be entered in LaTeX format.

The scripts that we have seen so far have been simple scripts, stored in files that have an extension of .m. Live scripts are instead stored using the .mlx file format.

There are several ways to create a live script. The simplest is to click on New Live Script, or on New, then Live Script. A simple script can also be transformed into a live script by choosing Save As and then Live Script. Right clicking on a set of commands from the Command History window also pops up an option to save as a Live Script. The Live Script toolstrip is shown in Fig. 3.9.

Note

Notice that there are sections for "Text", "Code", "Section", and "Run", among others.

An example of a live script is shown in Fig. 3.10. In this untitled live script, there is text that includes an equation, then code, more text which includes an equation, and then more code. To the right, there are plots created by the code blocks. To create this Live Script, the following steps are to be taken:

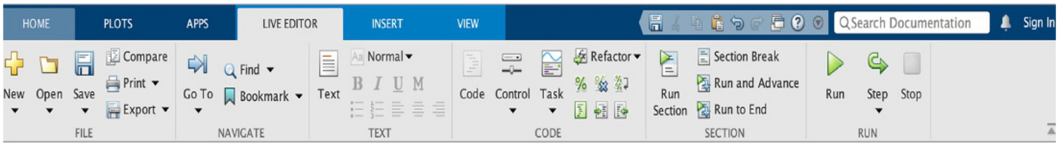
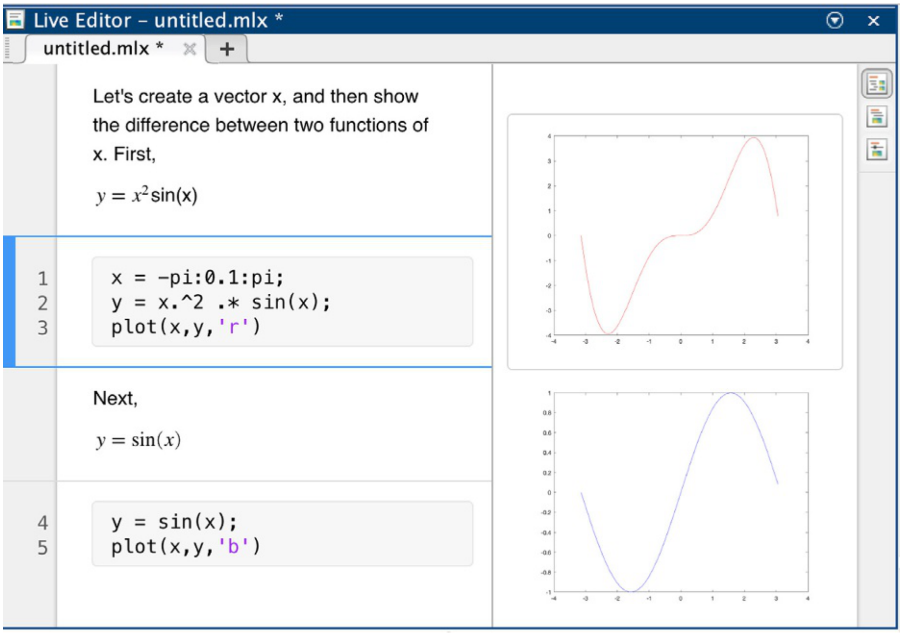


FIGURE 3.9
Live Editor Toolstrip.



Let's create a vector x, and then show the difference between two functions of x. First,

$y = x^2\sin(x)$

```
x = -pi:0.1:pi;
y = x.^2 .* sin(x);
plot(x,y,'r')
```

Next,

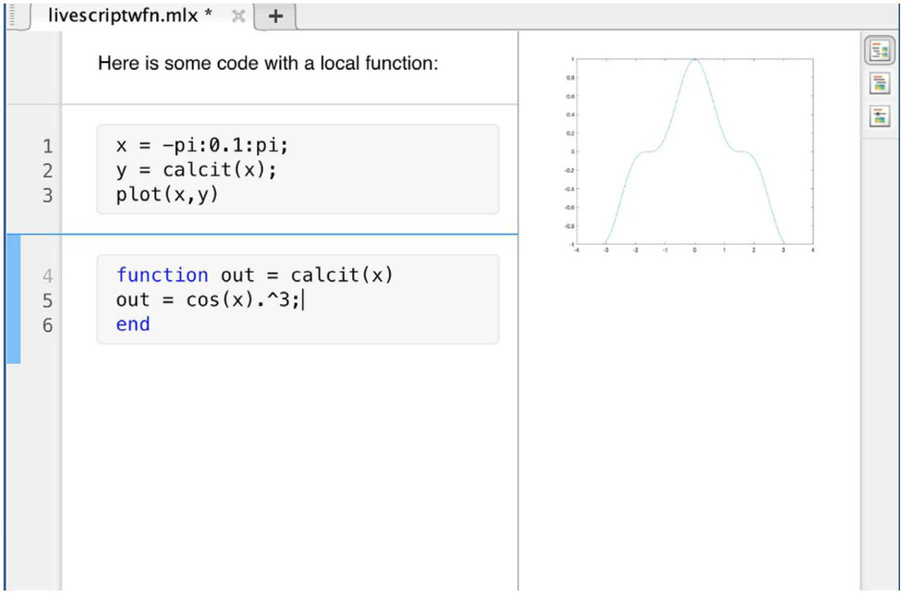
$y = \sin(x)$

```
y = sin(x);
plot(x,y,'b')
```

FIGURE 3.10
Live script with plots.

- Once in the Live Editor, the default section is a Code section, so click on Text to make it text instead. Enter the text “Let’s create…”.
- For the equation, click on the Insert tab and then Equation, and enter the equation.
- Click on Section Break.
- Again, the default section type is code, which is what we want. Enter the lines of code.
- Click on Section Break, then Text.
- Enter the text including the equation.
- Click on Section Break.
- Enter the code.
- Then, to run the code and produce the plots, click on the Run Button.

All of the code from the live script can be executed by choosing the Run button. Alternatively, individual sections can be executed by clicking on the bar to the



Here is some code with a local function:

```
x = -pi:0.1:pi;
y = calcit(x);
plot(x,y)
```

```
function out = calcit(x)
out = cos(x).^3;
end
```

FIGURE 3.11
Function in Live Script.

left of the section (as in the highlighted bar to the left of the first code section in Fig. 3.10). Also, by default the results of the code sections are shown to the right. To the right of that, there are three icons that can be used to modify the display: "Output on Right", "Output Inline", and "Hide Code". This live script could then be saved, for example as sintest.mlx.

Functions can be included in Live Scripts. When a function is entered into a code section of a live script, a section break is automatically created before the function, as seen in Fig. 3.11. The function must appear after all of the script code.

Once a live script has been completed, it can be shared with others as an .mlx file, or it can be converted to a PDF or HTML format. To do this, click on the down arrow under "Save", and then either "Export to PDF" or "Export to HTML".

Live scripts can also be converted to code files with the .m extension by choosing Save As and then choosing MATLAB Code file from the drop-down menu for the Format.

Using the **type** command on a live script will show just the code sections. The entire contents of the .mlx file can be seen from the Live Editor.

```
>> type sintest.mlx

x = -pi:0.01:pi;
y = x.^2.*sin(x);
```

```
    plot(x,y,'r')
    y = sin(x);
    plot(x,y,'b')
```

More on live scripts, including tasks that can be utilized and that can auto-generate code, will be seen in Section 6.6.

PRACTICE 3.11

Create a live script with text, equations, and code to produce at least one plot.

Data Science and Machine Learning Supplement

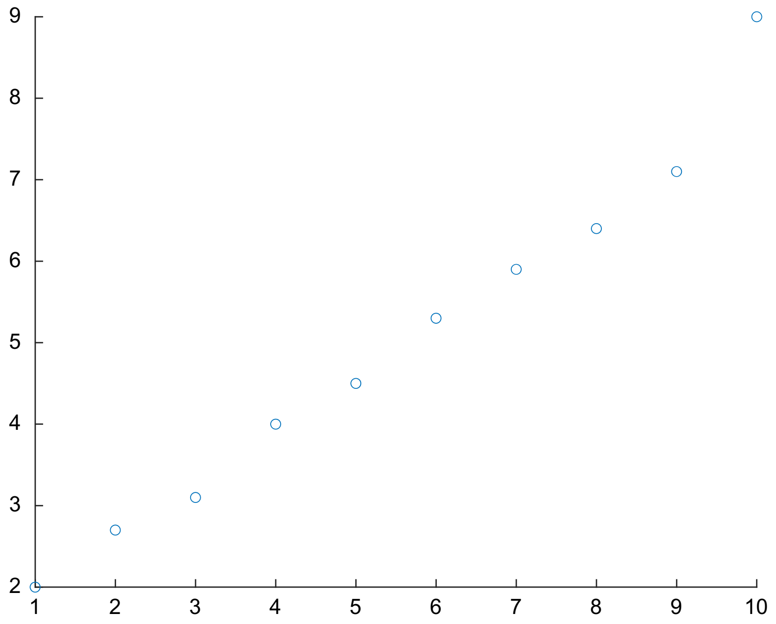
Correlation Between Two Vectors

Previously, we have explored some analyses on a single vector variable. It is also important to examine the correlation between two (or more) vector variables.

One method of visualizing the correlation between two vector variables is to plot them. We could use **plot** for this, or a **scatter** plot. With a scatterplot, the x-axis represents one variable and the y-axis is the other variable. Note that the variables must have the same length.

Here is an example:

```
    >> x = 1:10;
    >> y = [2, 2.7, 3.1, 4, 4.5, 5.3, 5.9, 6.4, 7.1, 9];
    >> scatter(x,y)
```



We can see that there is a high correlation between these two vectors. When x rises, so does y; this is called ***positive correlation***. If, on the other hand, y falls when x rises, this would be called a ***negative correlation***.

A ***correlation coefficient*** measures the association between two vectors. The values range from −1 to +1. Negative numbers indicate negatively correlated vectors, and positive numbers indicate positively correlated vectors. A correlation coefficient of 0 means that there is no correlation between the vectors. If the numbers in the x and y vectors are identical, for example, they would be perfectly correlated and have a correlation coefficient of 1. A correlation coefficient matrix shows the vectors on the rows and columns, and the correlation coefficients of the vectors. The function **corrcoef** accomplishes this:

```
>> corrcoef(x,y)
ans =
    1.0000    0.9872
    0.9872    1.0000
```

The x vector is represented by the first row and first column, and the y vector is the second row and the second column. So, on the first row the number 1.0000 in the upper left is the correlation between x and x, the number 0.9872 is the correlation between x and y. On the second row, the 0.9872 is the correlation between y and x, and the number 1.0000 on the bottom right is the correlation between y and y. Of course, x is perfectly correlated with x and y is perfectly correlated with y, which is why those values are 1. A correlation coefficient of 0.9872 (which is redundantly displayed twice) shows that x and y are also positively correlated.

This shows that the two vectors are highly correlated. It is very important, however, to separate correlation from ***causality*** when working with data sets. For example, if we are working with patient data, we might have vectors that represent different characteristics of the patients (these are called ***features***), such as age, weight, blood type, whether or not they have heart problems, etc. We would have this information for all patients, so all of the feature vectors would have the same length. Finding correlations is of great interest in Machine Learning, but correlations may or may not indicate causality. For example, we might find a high correlation between weight and heart problems, and this may be an indication that weight can be a cause of heart problems (or vice versa!). It may also just be pure coincidence, however.

Normalizing Data

To make sure that one numerical feature vector does not dominate over others by having much larger numbers, it may be wise to ***normalize*** the data. Normalizing takes the original range of values and converts it to a particular range, frequently from 0 to 1. To accomplish this, one can subtract the minimum value from each number and divide by the original range (the minimum subtracted from the maximum). In the following example, two feature vectors are simulated using random integers in different ranges, and then both are normalized.

```
>> feat1 = randi([1, 10], 1,8)
feat1 =
     3     10     2     9     6     10     1     5
>> normf1 = (feat1-min(feat1))/(max(feat1)-min(feat1))
normf1 =
    0.2222   1.0000   0.1111   0.8889   0.5556   1.0000 0   0.4444
>> feat2 = randi([1, 100], 1, 8)
feat2 =
    11     97     1     78     82     87     9     40
>> normf2 = (feat2-min(feat2))/(max(feat2)-min(feat2))
normf2 =
    0.1042   1.0000   0 0.8021   0.8438   0.8958   0.0833   0.4062
```

Now the two feature vectors have the same range of values, so one will not take on more importance than the other when running a ML algorithm.

Explore Other Interesting Features

Note that this chapter serves as an introduction to several topics, most of which will be covered in more detail in future chapters. Before getting to those chapters, the following are some things you may wish to explore.

- The **help** command can be used to see short explanations of built-in functions. At the end of this, a doc page link is also listed. These documentations pages frequently have much more information, and useful examples. They can also be reached by typing "doc fnname" where fnname is the name of the function.
- Look at formatSpec on the doc page on the **fprintf** function for more ways in which expressions can be formatted, e.g., padding numbers with zeros and printing the sign of a number.
- Use the Search Documentation to find the conversion characters used to print other types, such as unsigned integers and exponential notation.

SUMMARY

COMMON PITFALLS

- Spelling a variable name different ways in different places in a script or function.
- Forgetting to add the second 's' argument to the **input** function when character input is desired.

- Not using the correct conversion character when printing.
- Confusing **fprintf** and **disp.** Remember that only **fprintf** can format.

PROGRAMMING STYLE GUIDELINES

- Especially for longer scripts and functions, start by writing an algorithm.
- Use comments to document scripts and functions, as follows:
  - a block of contiguous comments at the top to describe a script
  - a block of contiguous comments under the function header for functions
  - comments throughout any code file (script or function) to describe each section
- Make sure that the "H1" comment line has useful information.
- Use your organization's standard style guidelines for block comments.
- Use mnemonic identifier names (names that make sense, e.g., radius instead of xyz) for variable names and for file names.
- Make all output easy to read and informative.
- Put a newline character at the end of every format specifier printed by fprintf so that the next output or the prompt appears on the line below.
- Put informative labels on the x- and y-axes, and a title on all plots.
- Keep functions short, typically no longer than one page in length.
- Suppress the output from all assignment statements in functions and scripts.
- Functions that return a value do not normally print the value; it should simply be returned by the function.
- Use the array operators .*, ./, .\, and .^ in functions so that the input arguments can be arrays and not just scalars.

MATLAB Reserved Words

function	end

MATLAB Functions and Commands

type	plot	clf	bar
input	xlabel	figure	load
disp	ylabel	hold	save
fprintf	title	legend	
display	axis	grid	

MATLAB Operators

comment %	comment block %{, %}

Exercises

1. Using the top-down design approach, write an algorithm for making a sandwich.
2. Write a simple script that will calculate the volume of a hollow sphere,

   $$\frac{4\pi}{3}\left(r_0^3 - r_i^3\right)$$

   where r_i is the inner radius and r_o is the outer radius. Assign a value to a variable for the inner radius, and also assign a value to another variable for the outer radius. Then, using these variables, assign the volume to a third variable. Include comments in the script. Use **help** to view the block comment in your script.
3. Write a script that will prompt the user for a number and print it twice, once with three decimal places, and then with one decimal place.
4. Write a script that will prompt the user for a number, and will print the square of the user's number in the following format:

   ```
   Enter a number: 11.1
   Your number squared is 123.21
   ```

5. Experiment, in the Command Window, with using the **fprintf** function for real numbers. Make a note of what happens for each. Use **fprintf** to print the real number 12345.6789

   - without specifying any field width
   - in a field width of 10 with four decimal places
   - in a field width of 10 with two decimal places
   - in a field width of 6 with four decimal places
   - in a field width of 2 with four decimal places

6. Experiment, in the Command Window, with using the **fprintf** function for integers. Make a note of what happens for each. Use **fprintf** to print the integer 12345

   - without specifying any field width
   - in a field width of 5
   - in a field width of 8
   - in a field width of 3

7. When would you use **disp** instead of **fprintf**? When would you use **fprintf** instead of **disp**?
8. Explain exactly why these two sets of code (the one **disp** statement and the two **fprintf** statements) produce the same output.

   ```
   disp('And away we go!!')
   ```

   ```
   fprintf('And ')
   fprintf('away we go!!\n')
   ```

9. Write a script that will prompt the user for a character and will print it twice; once left-justified in a field width of 5, and again right-justified in a field width of 3.
10. A power company charges 6.6 cents per kilowatt hour (KWH) for providing electricity. Write a script "power_charge" that will prompt the user for the number of KWH used in a given month, and will print the charge for the month in dollars, in the following format. (The conversion is 100 cents in one dollar.) Here is an example of running the script.

```
>> power_charge
How many KWH this month: 200
Your charge for 200 KWH will be $13.20.
```

11. Why do we always suppress all assignment statements in scripts?
12. Write a script that assigns values for the x coordinate and then y coordinate of a point, and then plots this using a green +.
13. Plot **sin(x)** for x values ranging from 0 to π (in separate Figure Windows):

    - using 10 points in this range
    - using 100 points in this range

    Do this using a Live Script.
14. A data file "nums.dat" stores some numbers on one line. Write a script that will read from this file, and plot only the positive numbers (>= 0), using black stars. Put labels on the axes, and a title and subtitle on the plot.
15. Create a plot that uses both the **xline** and **yline** functions.
16. When would it be important to use **legend** in a plot?
17. Atmospheric properties such as temperature, air density, and air pressure are important in aviation. Create a file that stores temperatures in degrees Kelvin at various altitudes. The altitudes are in the first column and the temperatures in the second. For example, it may look like this:

```
1000        288
2000        281
3000        269
```

18. Create a *3* × *6* matrix of random integers, each in the range from 50 to 100. Write this to a file called *randfile.dat*. Then, create a new matrix of random integers, but this time make it a *2* × *6* matrix of random integers, each in the range from 50 to 100. Append this matrix to the original file. Then, read the file in (which will be to a variable called *randfile*) just to make sure that worked!
19. Write a script that would create a 5×5 matrix of random integers. From this, create another matrix variable which is the "middle" 3×3 part of the original matrix. Write this new matrix to a file.
20. A part is being turned on a lathe. The diameter of the part is supposed to be 20,000 mm. The diameter is measured every 10 minutes and the results are stored in a file called *partdiam.dat*. Create a data file to simulate this. The file will store the time in minutes and the diameter at each time. Plot the data.
21. List some differences between a script and a function.

22. Write a function that converts inches to feet. Note that 12 inches = 1 foot.
23. Write a *fives* function that will receive two arguments for the number of rows and columns and will return a matrix with that size of all fives.
24. Write a function *perim* that receives the radius r of a circle, and calculates and returns the perimeter P of the circle ($P = 2\,\Pi\, r$). Include a block comment.
25. Write a function *isdivby4* that will receive an integer input argument, and will return **logical** 1 for **true** if the input argument is divisible by 4, or **logical false** if it is not.
26. A Pythagorean triple is a set of positive integers (a,b,c) such that $a^2 + b^2 = c^2$. Write a function *ispythag* that will receive three positive integers (a, b, c in that order) and will return **logical** 1 for **true** if they form a Pythagorean triple, or 0 for **false** if not.
27. A function can return a vector as a result. Write a function *vecout* that will receive one integer argument and will return a vector that increments from the value of the input argument to its value plus 5, using the colon operator. For example,

    ```
    >> vecout(4)
    ans =
         4     5     6     7     8     9
    ```

28. The conversion depends on the temperature and other factors, but an approximation is that 1 inch of rain is equivalent to 6.5 inches of snow. Write a script that prompts the user for the number of inches of rain, calls a function to return the equivalent amount of snow, and prints this result. Write the function, as well. Do this two ways: in a separate code file, and as a local function.
29. A spherical sector is a part of a sphere, consisting of a spherical cap (which is a part of the sphere created by putting a plane through the sphere), and the cone that begins at the center of the sphere and extends to the base of the cap. The volume V of a spherical sector is given by:

    $$V = \frac{2\pi r^2 h}{3}$$

    where r is the radius of the sphere, and h is the height of the spherical cap. Write a program that consists of a live script with a function.
    The script:

    - prompts the user for the values of the radius and the height
    - calls a function to calculate the volume
    - prints the volume in a nice sentence format with three decimal places

    The function calculates the volume, given the radius and height. For simplicity, ignore units.
30. Many mathematical models in engineering use the exponential function. The general form of the exponential decay function is:

    $$y(t) = Ae^{-\tau t}$$

where A is the initial value at $t=0$, and τ is the time constant for the function. Write a script to study the effect of the time constant. To simplify the equation, set A equal to 1. Prompt the user for two different values for the time constant, and for beginning and ending values for the range of a t vector. Then, calculate two different y vectors using the above equation and the two-time constants, and graph both exponential functions on the same graph within the range the user specified. Use a local function to calculate y. Make one plot red. Be sure to label the graph and both axes. What happens to the decay rate as the time constant gets larger?

Data Science and Machine Learning

31. Write a script that will prompt the user for the results of a classification model (the values of TP, TN, FP, and FN). Calculate and print the accuracy in a nice sentence format. Recall that the accuracy is the sum of the correctly classified (TP + TN) divided by the total number (sum of all).
32. Write a function that will receive a vector as an input argument, and will normalize the vector and return the resulting normalized vector.
33. Examine the correlation between vectors 1:4 and 6:9, and then also between the vectors 1:4 and 9:−1:6. Explain the correlation coefficients.

CHAPTER 4

Selection Statements

KEY TERMS

selection statements
branching statements
condition
action
temporary variable
error-checking
throwing an error
nesting statements
cascading if-else
"is" functions

CONTENTS

In the scripts and functions we have seen thus far, every statement was executed in sequence. This is not always desirable, and in this chapter, we see how to make choices as to whether statements are executed or not, and how to choose between or among statements. The statements that accomplish this are called ***selection*** or ***branching*** statements.

The MATLAB® software has two basic statements that allow us to make choices: the **if** statement and the **switch** statement. The **if** statement has optional **else** and **elseif** clauses for branching. The **if** statement uses expressions that are logically **true** or **false**. These expressions use relational and logical operators. MATLAB also has "is" functions that test whether an attribute is **true** or not; these can be used with the selection statements.

4.1 THE IF STATEMENT

The **if** statement chooses whether another statement, or group of statements, is executed or not. The general form of the **if** statement is:

```
if condition
    action
end
```

A ***condition*** is a relational expression that is conceptually, or logically, **true** or **false**. The ***action*** is a statement, or a group of statements, that will be executed if the condition is **true**. When the **if** statement is executed, first the condition is evaluated. If the value of the condition is **true**, the action will be executed; if

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00004-4

not, the action will not be executed. The action can be any number of statements until the reserved word **end**; the action is naturally bracketed by the reserved words **if** and **end**. (Note that this is different from the **end** that is used as an index into a vector or matrix.) The action is usually indented to make it easier to see.

For example, the following **if** statement checks to see whether the value of a variable is negative. If it is, the value is changed to a zero; otherwise, nothing is changed.

```
if num < 0
     num = 0
end
```

If statements can be entered in the Command Window, although they generally make more sense in scripts or functions. In the Command Window, the **if** line would be entered, followed by the Enter key, the action, the Enter key, and finally **end** and Enter. The results will follow immediately. For example, the preceding **if** statement is shown twice here.

```
>> num = -4;
>> if num < 0
      num = 0
   end
 num =
       0

>> num = 5;
>> if num < 0
      num = 0
   end
>>
```

The first time the value of the variable is negative so the action is executed and the variable is modified, but, in the second case, the variable is positive so the action is skipped.

Note
that the output from the assignment is not suppressed, so the result of the action will be shown if the action is executed.

This may be used, for example, to make sure that the square root function is not used on a negative number. The following script prompts the user for a number and prints the square root. If the user enters a negative number the **if** statement changes it to zero before taking the square root.

sqrtifexamp.m

```
% Prompt the user for a number and print its sqrt

num=input('Please enter a number: ');

% If the user entered a negative number, change it
if num<0
    num = 0;
end
fprintf('The sqrt of %.1f is %.1f\n',num,sqrt(num))
```

Here are two examples of running this script:

```
>> sqrtifexamp
Please enter a number: -4.2
The sqrt of 0.0 is 0.0

>> sqrtifexamp
Please enter a number: 1.44
The sqrt of 1.4 is 1.2
```

In this case, the action of the **if** statement was a single assignment statement. The action can be any number of valid statements. For example, we may wish to print a note to the user to say that the number entered was being changed. Also, instead of changing it to zero we will use the absolute value of the negative number entered by the user.

Note that in the script the output from the assignment statement is suppressed.

sqrtifexampii.m

```
% Prompt the user for a number and print its sqrt

num=input('Please enter a number: ');

% If the user entered a negative number, tell
% the user and change it
if num < 0
    disp('OK, we''ll use the absolute value')
    num=abs(num);
end
fprintf('The sqrt of %.1f is %.1f\n',num,sqrt(num))
```

Note that as seen in this example, two single quotes in the **disp** statement are used to print one single quote.

```
>> sqrtifexampii
Please enter a number: -25
OK, we'll use the absolute value
The sqrt of 25.0 is 5.0
```

PRACTICE 4.1

Write an **if** statement that would print "Hey, you get overtime!" if the value of a variable *hours* is greater than 40. Test the **if** statement for values of *hours* less than, equal to, and greater than 40. Will it be easier to do this in the Command Window or in a script?

QUICK QUESTION!

Assume that we want to create a vector of increasing integer values from *mymin* to *mymax*. We will write a function *createvec* that receives two input arguments, *mymin* and *mymax*, and returns a vector with values from *mymin* to *mymax* in steps of one. First, we would make sure that the value of *mymin* is less than the value of *mymax*. If not, we would need to exchange their values before creating the vector. How would we accomplish this?

Answer: To exchange values, a third variable, a temporary variable, is required. For example, let us say that we have two variables, *a* and *b*, storing the values:

Continued

QUICK QUESTION!—CONT'D

```
a=3;
b=5;
```

To exchange values, we could *not* just assign the value of *b* to *a*, as follows:

```
a=b;
```

If that were done, then the value of *a* (the 3), is lost! Instead, we need to assign the value of *a* first to a ***temporary variable*** so that the value is not lost. The algorithm would be:

- assign the value of *a* to *temp*
- assign the value of *b* to *a*
- assign the value of *temp* to *b*

```
>> temp=a;
>> a=b
a =
    5
>> b=temp
b =
    3
```

Now, for the function. An **if** statement is used to determine whether or not the exchange is necessary.

createvec.m

```
function outvec=createvec(mymin, mymax)
% createvec creates a vector that iterates from a
% specified minimum to a maximum
% Format of call: createvec(minimum, maximum)
% Returns a vector

% If the "minimum" isn't smaller than the "maximum",
% exchange the values using a temporary variable
if mymin > mymax
    temp=mymin;
    mymin=mymax;
    mymax=temp;
end

% Use the colon operator to create the vector
outvec=mymin:mymax;
end
```

Examples of calling the function are:

```
>> createvec(4,6)
ans =
     4     5     6

>> createvec(7,3)
ans =
     3     4     5     6     7
```

4.1.1 Representing Logical True and False

It has been stated that conceptually true expressions have the **logical** value of 1, and expressions that are conceptually false have the **logical** value of 0.

Representing the concepts of **logical true** and **false** in MATLAB is slightly different: the concept of false is represented by the value of 0, but the concept of true can be represented by *any nonzero value* (not just 1). This can lead to some strange **logical** expressions. Consider the following **if** statement:

```
>> if 5
      disp('Yes, this is true!')
   end
 Yes, this is true!
```

As 5 is a nonzero value, the condition is **true**. Therefore, when this **logical** expression is evaluated, it will be **true**, so the **disp** function will be executed and "Yes, this is true" is displayed. Of course, this is a pretty bizarre **if** statement, one that hopefully would never be encountered!

However, a simple mistake in an expression can lead to a similar result. For example, let us say that the user is prompted for a choice of 'Y' or 'N' for a yes/no question.

```
letter=input('Choice (Y/N): ','s');
```

In a script we might want to execute a particular action if the user responded with 'Y'. Most scripts would allow the user to enter either lowercase or uppercase; for example, either 'y' or 'Y' to indicate "yes". The proper expression that would return **true** if the value of *letter* was 'y' or 'Y' would be

```
letter == 'y' || letter == 'Y'
```

However, if by mistake this was written as:

```
letter == 'y' || 'Y'   %Note: incorrect!!
```

this expression would ALWAYS be **true**, regardless of the value of the variable *letter*. This is because 'Y' is a nonzero value, so it is a **true** expression. The first part of the expression, on the left side of the or operator, may be **false**, but as the second expression (on the right side of the or operator; the 'Y') is **true** the entire expression would be **true**, regardless of the value of the variable *letter*.

Note

we might also want to use letter(1) in case the user entered the entire word 'yes' or 'no'.

4.2 THE IF-ELSE STATEMENT

The **if** statement chooses whether or not an action is executed. Choosing between two actions, or choosing from among several actions, is accomplished using **if-else**, nested **if-else**, and **switch** statements.

The **if-else** statement is used to choose between two statements, or sets of statements. The general form is:

```
if condition
    action1
else
    action2
end
```

First, the condition is evaluated. If it is **true**, then the set of statements designated as "action1" is executed, and that is the end of the **if-else** statement. If, instead, the condition is **false**, the second set of statements designated as "action2" is executed, and that is the end of the **if-else** statement. The first set of statements ("action1") is called the action of the **if** clause; it is what will be executed if the expression is **true**. The second set of statements ("action2") is called the action of the **else** clause; it is what will be executed if the expression is **false**. One of these actions, and only one, will be executed; which one depends on the value of the condition.

For example, to determine and print whether a random number in the range from 0 to 1 is less than 0.5, an **if-else** statement could be used:

```
if rand<0.5
   disp('It was less than .5!')
else
   disp('It was not less than .5!')
end
```

PRACTICE 4.2

Write a script *printsindegorrad* that will:

- prompt the user for an angle
- prompt the user for (r)adians or (d)egrees, with radians as the default
- if the user enters 'd', the **sind** function will be used to get the sine of the angle in degrees; otherwise, the **sin** function will be used. Which sine function to use will be based solely on whether the user entered a 'd' or not ('d' means degrees, so **sind** is used; otherwise, for any other character the default of radians is assumed so **sin** is used)
- print the result

Here are examples of running the script:

```
>> printsindegorrad
Enter the angle: 45
(r)adians (the default) or (d)egrees: d
The sin is 0.71

>> printsindegorrad
Enter the angle: pi
(r)adians (the default) or (d)egrees: r
The sin is 0.00
```

One application of an **if-else** statement is to check for errors in the inputs to a script (this is called ***error-checking***). For example, an earlier script prompted the user for a radius, and then used that to calculate the area of a circle. However, it did not check to make sure that the radius was valid (e.g., a positive number). Here is a modified script that checks the radius:

checkradius.m

```
% This script calculates the area of a circle
% It error-checks the user's radius
radius=input('Please enter the radius: ');
if radius <= 0
    fprintf('Sorry; %.2f is not a valid radius\n',radius)
else
    area=calcarea(radius);
    fprintf('For a circle with a radius of %.2f,',radius)
    fprintf(' the area is %.2f\n',area)
end
```

Examples of running this script when the user enters invalid and then valid radii are shown as follows:

```
>> checkradius
Please enter the radius: -4
Sorry; -4.00 is not a valid radius

>> checkradius
Please enter the radius: 5.5
For a circle with a radius of 5.50, the area is 95.03
```

The **if-else** statement in this example chooses between two actions: printing an error message, or using the radius to calculate the area and then printing out the result. Note that the action of the **if** clause is a single statement, whereas the action of the **else** clause is a group of three statements.

MATLAB also has an **error** function that can be used to display an error message; the terminology is that this is ***throwing an error***. In the previous script, the if clause could be modified to use the **error** function rather than **fprintf**; the result will be displayed in red as with the error messages generated by MATLAB. Also, very importantly, when an error message is thrown, the script stops executing. This is illustrated by the following modified script:

checkraderror.m

```
radius=input('Please enter the radius: ');
if radius <=0
   error('Sorry; %.2f is not a valid radius\n',radius)
else
   area=pi * radius .^ 2;
   fprintf('For a circle with a radius of %.2f,',radius)
   fprintf(' the area is %.2f\n',area)
end
disp("And that is it!")
```

```
>> checkraderror
Please enter the radius: -5
Error using checkraderror (line 3)
Sorry; -5.00 is not a valid radius

>> checkraderror
Please enter the radius: 4.5
For a circle with a radius of 4.50, the area is 63.62
And that is it!
```

If the entered radius is not valid, an error message is thrown and nothing else is executed. However, if the radius is valid, it is used to calculate and print the error; also, the **disp** statement is executed after the **if-else** statement ends.

4.3 NESTED IF-ELSE STATEMENTS

The **if-else** statement is used to choose between two actions. To choose from more than two actions, the **if-else** statements can be ***nested***, meaning one statement inside of another. For example, consider implementing the following continuous mathematical function *y* = *f(x)*:

```
y = 1    if   x<-1
y = x^2  if   -1 ≤ x ≤ 2
y = 4    if   x>2
```

The value of *y* is based on the value of *x*, which could be in one of three possible ranges. Choosing which range could be accomplished with three separate **if** statements as follows:

```
if x<-1
   y=1;
end
if x>=-1 && x <=2
   y=x^2;
end
if x>2
   y=4;
end
```

Note that the && in the expression of the second if statement is necessary. Writing the expression as $-1<=x<=2$ would be incorrect; recall from Chapter 1 that that expression would always be **true**, regardless of the value of the variable *x*.

As the three possibilities are mutually exclusive, the value of *y* can be determined by using three separate **if** statements. However, this is not very efficient code: all three **logical** expressions must be evaluated, regardless of the range in which *x* falls. For example, if *x* is less than −1, the first expression is **true** and 1 would be assigned to *y*. However, the two expressions in the next two **if** statements are still evaluated. Instead of writing it this way, the statements can be nested so that the entire **if-else** statement ends when an expression is found to be **true**:

```
if x<-1
   y=1;
else
   % If we are here, x must be >=-1
   % Use an if-else statement to choose
   %  between the two remaining ranges
   if x<=2
      y=x^2;
   else
      % No need to check
      % If we are here, x must be >2
      y=4;
   end
end
```

By using a nested **if-else** to choose from among the three possibilities, not all conditions must be tested as they were in the previous example. In this case, if *x* is less than −1, the statement to assign 1 to *y* is executed, and the **if-else** statement is completed so no other conditions are tested. If, however, *x* is not less than −1, then the **else** clause is executed. If the **else** clause is executed, then we already know that *x* is greater than or equal to −1 so that part does not need to be tested.

Instead, there are only two remaining possibilities: either *x* is less than or equal to 2, or it is greater than 2. An **if-else** statement is used to choose between those two possibilities. So, the action of the **else** clause was another **if-else** statement. Although it is long, all of the above code is one **if-else** statement, a nested **if-else** statement. The actions are indented to show the structure of the statement. Nesting **if-else** statements in this way can be used to choose from among 3, 4, 5, 6, ... the possibilities are practically endless!

This is actually an example of a particular kind of nested **if-else** called a ***cascading* if-else** statement. This is a type of nested **if-else** statement in which the conditions and actions cascade in a stair-like pattern.

Not all nested **if-else** statements are cascading. For example, consider the following (which assumes that a variable *x* has been initialized):

```
if x >= 0
   if x < 4
       disp('a')
   else
       disp('b')
   end
else
   disp('c')
end
```

4.3.1 The elseif Clause

To choose from among more than two actions, the **elseif** clause can be used. For example, if there are n choices (where n > 3 in this example), the following general form would be used:

```
if condition1
    action1
elseif condition2
    action2
elseif condition3
    action3
% etc: there can be many of these
else
    actionn    % the nth action
end
```

The actions of the **if**, **elseif**, and **else** clauses are naturally bracketed by the reserved words **if**, **elseif**, **else**, and **end**.

For example, a previous example could be written using the **elseif** clause, rather than nesting **if-else** statements:

This could be implemented in a function that receives a value of *x* and returns the corresponding value of *y*:

```
calcy.m
```

```
function y=calcy(x)
% calcy calculates y as a function of x
% Format of call: calcy(x)
% y = 1       if   x<-1
% y = x^2     if   -1 <=x<=2
% y = 4       if   x>2

if x < -1
    y = 1;
elseif x<=2
    y=x^2;
else
    y=4;
end
end
```

Note

that in this example we only need one **end** for the nested **if-else**.

```
>> x=1.1;
   >> y=calcy(x)
  y =
     1.2100
```

Therefore, there are three ways of accomplishing the original task: using three separate **if** statements, using nested **if-else** statements, and using an **if** statement with **elseif** clauses, which are the simplest.

QUICK QUESTION!

How could you write a function to determine whether an input argument is a scalar, a vector, or a matrix?

Answer: To do this, the **size** function can be used to find the dimensions of the input argument. If both the number of rows and columns is equal to 1, then the input argument is a scalar. If, however, only one dimension is 1, the input argument is a vector (either a row or column vector). If neither dimension is 1, the input argument is a matrix. These three options can be tested using a nested **if-else** statement. In this example, the word 'scalar', 'vector' or 'matrix' is returned from the function.

findargtype.m

```
function outtype=findargtype(inputarg)
% findargtype determines whether the input
%   argument is a scalar, vector, or matrix
%
Format of call: findargtype(inputArgument)
% Returns a character vector

[r c] = size(inputarg);
if r == 1 && c == 1
    outtype='scalar';
elseif r == 1 || c == 1
    outtype='vector';
else
    outtype='matrix';
end
end
```

Note that there is no need to check for the last case: if the input argument is not a scalar or a vector, it must be a matrix! Examples of calling this function are:

```
>> findargtype(33)
ans =
    'scalar'

>> disp(findargtype(2:5))
vector

>> findargtype(zeros(2,3))
ans =
    'matrix'
```

PRACTICE 4.3

Modify the function *findargtype* to return either 'scalar', 'row vector', 'column vector', or 'matrix', depending on the input argument.

PRACTICE 4.4

Modify the original function *findargtype* to use three separate **if** statements instead of a nested **if-else** statement.

Another example demonstrates choosing from more than just a few options. The following function receives an integer quiz grade, which should be in the range from 0 to 10. The function then returns a corresponding letter grade, according to the following scheme: a 9 or 10 is an 'A', an 8 is a 'B', a 7 is a 'C', a 6 is a 'D', and anything below that is an 'F'. As the possibilities are mutually exclusive, we could implement the grading scheme using separate **if** statements. However, it is more efficient to have one **if-else** statement with multiple **elseif** clauses. Also, the function returns the letter 'X' if the quiz grade is not valid. The function assumes that the input is an integer.

letgrade.m

```
function grade=letgrade(quiz)
% letgrade returns the letter grade corresponding
%   to the integer quiz grade argument
% Format of call: letgrade(integerQuiz)
% Returns a character

% First, error-check
if quiz<0 || quiz >10
    grade='X';

% If here, it is valid so figure out the
%  corresponding letter grade
elseif quiz == 9 || quiz == 10
    grade='A';
elseif quiz == 8
    grade='B';
elseif quiz == 7
    grade='C';
elseif quiz == 6
    grade='D';
else
    grade='F';
end
end
```

Three examples of calling this function are:

```
>> quiz=8;
>> lettergrade=letgrade(quiz)
lettergrade =
    'B'
>> quiz=4;
>> letgrade(quiz)
ans =
    'F'

>> lg=letgrade(22)
lg =
    'X'
```

In the part of this **if** statement that chooses the appropriate letter grade to return, all of the **logical** expressions are testing the value of the variable *quiz* to see if it is equal to several possible values, in sequence (first 9 or 10, then 8, then 7, etc.). This part can be replaced by a **switch** statement.

4.4 THE SWITCH STATEMENT

A **switch** statement can often be used in place of a nested **if-else** or an **if** statement with many **elseif** clauses. **Switch** statements are used when an expression is tested to see whether it is *equal to* one of several possible values.

The general form of the **switch** statement is:

```
switch switch_expression
  case caseexp1
    action1
  case caseexp2
    action2
  case caseexp3
    action3
  % etc: there can be many of these
  otherwise
    actionother
end
```

The **switch** statement starts with the reserved word **switch** and ends with the reserved word **end**. The *switch_expression* is compared, in sequence, to the **case** expressions (*caseexp1*, *caseexp2*, etc.). If the value of the *switch_expression* matches *caseexp1*, for example, then *action1* is executed and the **switch** statement ends. If the value matches *caseexp3*, then *action3* is executed, and in general if the value matches *caseexpi* where *i* can be any integer from 1 to n, then *actioni* is executed. If the value of the *switch_expression* does not match any of the **case** expressions, the action after the word **otherwise** is executed (*actionother*) if there is an **otherwise** (if not, no action is executed). It is not necessary to have an **otherwise** clause, although it is frequently useful. The *switch_expression* must be either a scalar or a character vector.

For the previous example, the **switch** statement can be used as follows:

switchletgrade.m

```
function grade=switchletgrade(quiz)
% switchletgrade returns the letter grade corresponding
%   to the integer quiz grade argument using switch
% Format of call: switchletgrade(integerQuiz)
% Returns a character

% First, error-check
if quiz<0 || quiz >10
    grade='X';
else
    % If here, it is valid so figure out the
    % corresponding letter grade using a switch
    switch quiz
        case 10
            grade='A';
        case 9
            grade='A';
        case 8
            grade='B';
        case 7
            grade='C';
        case 6
            grade='D';
        otherwise
            grade='F';
    end
end
end
```

Here are two examples of calling this function:

```
>> quiz=22;
>> lg=switchletgrade(quiz)
lg =
    'X'

>> switchletgrade(9)
ans =
    'A'
```

Note

that it is assumed that the user will enter an integer value. If the user does not, either an error message will be printed or an incorrect result will be returned. Methods for remedying this will be discussed in Chapter 5.

As the same action of printing ‘A’ is desired for more than one grade, these can be combined as follows:

```
switch quiz
     case {10,9}
         grade='A';
     case 8
         grade='B';
       % etc.
```

The curly braces around the **case** expressions 10 and 9 are necessary.

In this example, we error-checked first using an **if-else** statement. Then, if the grade was in the valid range, a **switch** statement was used to find the corresponding letter grade.

Sometimes the **otherwise** clause is used for the error message rather than first using an **if-else** statement. For example, if the user is supposed to enter only a 1, 3, or 5, the script might be organized as follows:

switcherror.m

```
% Example of otherwise for error message

choice=input('Enter a 1, 3, or 5: ');

switch choice
    case 1
        disp('It''s a one!!')
    case 3
        disp('It''s a three!!')
    case 5
        disp('It''s a five!!')
    otherwise
        disp('Follow directions next time!!')
end
```

Note

that the order of the case expressions does not matter, except that this is the order in which they will be evaluated.

In this example, actions are taken if the user correctly enters one of the valid options. If the user does not, the **otherwise** clause handles printing an error message. Note the use of two single quotes within the string to print one quote.

```
>> switcherror
Enter a 1, 3, or 5: 4
Follow directions next time!!
```

MATLAB has a built-in function called **menu** that will display a Figure Window with pushbuttons for the options. The first string passed to the **menu** function is the heading (an instruction), and the rest are labels that appear on the pushbuttons. The function returns the number of the button that is pushed. For example,

```
>> mypick=menu('Pick a pizza','Cheese','Shroom','Sausage');
```

will display the Figure Window seen in Fig. 4.1 and store the result of the user's button push in the variable *mypick*.

There are three buttons, the equivalent values of which are 1, 2, and 3. For example, if the user pushes the "Sausage" button, *mypick* would have the value 3:

```
>> mypick
mypick =
     3
```

Note that the strings 'Cheese', 'Shroom', and 'Sausage' are just labels on the buttons. The actual value of the button push in this example would be 1, 2, or 3, so that is what would be stored in the variable *mypick*.

A script that uses this **menu** function would then use either an **if-else** statement or a **switch** statement to take an appropriate action based on the button pushed. For example, the following script simply prints which pizza to order, using a **switch** statement.

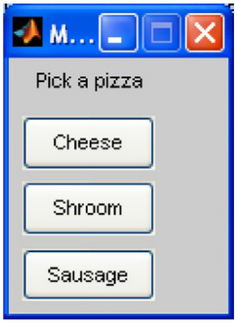


FIGURE 4.1
Menu Figure Window.

pickpizza.m

```
%This script asks the user for a type of pizza
% and prints which type to order using a switch

mypick=menu('Pick a pizza','Cheese','Shroom','Sausage');
switch mypick
    case 1
        disp('Order a cheese pizza')
    case 2
        disp('Order a mushroom pizza')
    case 3
        disp('Order a sausage pizza')
    otherwise
        disp('No pizza for us today')
end
```

This is an example of running this script and clicking on the “Sausage” button:

```
>> pickpizza
Order a sausage pizza
```

QUICK QUESTION!

How could the **otherwise** action get executed in this **switch** statement?

Answer: If the user clicks on the red “X” on the top of the menu box to close it instead of on one of the three buttons, the value returned from the **menu** function will be 0, which will cause the **otherwise** clause to be executed. This could also have been accomplished using a **case** 0 label instead of **otherwise**.

Instead of using a **switch** statement in this script, an alternative method would be to use an **if-else** statement with **elseif** clauses.

PRACTICE 4.5

Write a function that will receive one number as an input argument. It will use the **menu** function to display 'Choose a function' and will have buttons labeled 'fix', 'floor', and 'abs'. Using a **switch** statement, the function will then calculate and return the requested function (e.g., if 'abs' is chosen, the function will return the absolute value of the input argument). Choose a fourth function to return if the user clicks on the red 'X' instead of pushing a button.

The **menu** function is no longer recommended. An alternative, which is not quite as simple, is the **listdlg** function.

4.5 THE “IS” FUNCTIONS IN MATLAB

There are a lot of functions that are built into MATLAB that test whether something is **true**; these functions have names that begin with the word “is”. For example, we have already seen the use of the **isequal** function to compare arrays for equality. As another example, the function called **isletter** returns **logical** 1 if the character argument is a letter of the alphabet, or 0 if it is not:

```
>> isletter('h')
ans =
     1
>> isletter('4')
ans =
     0
```

The **isletter** function will return **logical true** or **false** so that it can be used in a condition in an **if** statement. For example, here is code that would prompt the user for a character, and then print whether it is a letter:

```
mychar=input('Please enter a char: ','s');
if isletter(mychar)
   disp('Is a letter')
else
   disp('Not a letter')
end
```

When used in an **if** statement, it is not necessary to test the value to see whether the result from **isletter** is equal to 1 or 0; this is redundant. In other words, in the condition of the **if** statement,

```
isletter(mychar)
```

and

```
isletter(mychar) == 1
```

would produce the same results.

QUICK QUESTION!

How can we write our own function *myisletter* to accomplish the same result as **isletter**?

Answer: The function would compare the character's position within the character encoding.

myisletter.m

```
function outlog=myisletter(inchar)
% myisletter returns true if the input argument
% is a letter of the alphabet or false if not
% Format of call: myisletter(inputCharacter)
% Returns logical 1 or 0

outlog=inchar >='a' && inchar <='z' ...
       || inchar >='A' && inchar <='Z';
end
```

Note that it is necessary to check for both lowercase and uppercase letters.

Another useful "is" function is **isnumeric**.

```
>> isnumeric(4.5)
ans =
   1
>> isnumeric(5:7)
ans =
   1
```

The function **isempty** returns **logical true** if a variable is empty, **logical false** if it has a value, or an error message if the variable does not exist. Therefore, it can be used to determine whether a variable has a value yet or not. For example,

```
>> clear
>> isempty(evec)
Unrecognized function or variable 'evec'.

>> evec=[];
>> isempty(evec)
ans =
      1

>> evec=[evec 5];
>> isempty(evec)
ans =
      0
```

The **isempty** function will also determine whether or not a string or character vector variable is empty. This can be used to determine whether the user entered a character vector in an **input** function. In the following example, when prompted the user simply hit the Return key.

```
>> cv=input('Please enter a char vec: ','s');
Please enter a char vec:
>> isempty(cv)
ans =
      1
```

PRACTICE 4.6

Prompt the user for a character vector, and then print either the character vector that the user entered or an error message if the user did not enter anything.

The **isa** function can be used to determine whether the first argument is a particular type.

```
>> num = 11;
>> isa(num, 'int16')
ans =
      0
>> isa(num,'double')
ans =
      1
```

The function **iskeyword** will determine whether or not a character vector or string is the name of a keyword in MATLAB, and therefore something that cannot be used as an identifier name. By itself (with no arguments), it will return the list of all keywords.

Note
that the names of functions like "sin" are not keywords, so their values can be overwritten if used as an identifier name.

```
>> iskeyword('sin')
ans =
     0
>> iskeyword('switch')
ans =
     1

>> iskeyword
ans =
    'break'
    'case'
    'catch'

     % etc.
```

There are many other "is" functions; the complete list can be found in the Documentation.

Data Science and Machine Learning Supplement

Working with NaN Values

As we have seen in Chapter 2, when reading data into MATLAB, missing values are often replaced by the constant NaN. Usually, there would not be very many, but a data set might look like the following, where NaN represents missing data:

```
>> dataset=[5  NaN  9  3  11  NaN];
```

Before working with such a data set, it is useful to ***clean*** the data by replacing the NaN values with something else, frequently the mean, median, or mode of the rest of the data. So, it is necessary to determine where the NaN values are. The equality operator does not work with NaN, e.g.:

```
>> dataset == NaN
ans =
  1*6 logical array
   0    0    0    0    0    0
```

However, there is an "is" function, **isnan**, that returns 1 for true for every element that stores NaN, and 0 for false for all other elements.

```
>> wherenan=isnan(dataset)
wherenan =
  1*6 logical array
   0    1    0    0    0    1
```

Using logical indexing, we could then replace the NaN values in the vector with, for example, the mean of the non-NaN values:

```
>> restmean=mean(dataset, 'omitnan')
restmean =
     7
>> dataset(wherenan)=restmean
dataset =
     5     7     9     3     11     7
```

Binning/Bucketing

Binning, or ***bucketing***, involves taking real numbers and lumping them together into what are called ***bins***, or ***buckets***, or ***categories***. For example, data used to evaluate housing markets might store information on the size of the kitchen in square feet. However, for the analysis it may not be necessary to know the exact size in square feet. It may be sufficient to just categorize each kitchen as “small”, “medium”, or “large”. For this example, we will assume that a small kitchen is 100 square feet or less, a medium-sized kitchen is in the range from 100 to 300 square feet, and anything larger than that is a large kitchen. To illustrate this, we will create a variable that stores a kitchen size, and then use a nested **if-else** statement to put it in the correct category.

```
kitchensize=randi([50, 600]);
if kitchensize <=100
   kitchenbin="small";
elseif kitchensize >100 && kitchensize <=300
   kitchenbin="medium";
else
   kitchenbin="large";
end
fprintf('A kitchen with size %.1f is %s\n', ...
        kitchensize, kitchenbin)
```

Decision Trees

A ***decision tree*** is a particular type of ML algorithm that is generally used for classification problems. The decision tree is basically a set of questions for which there are only two possible answers. The questions are called ***nodes***. The very first question that starts everything off is called the ***root node***. Each node ***splits*** the tree into two ***branches*** (also called ***edges***). A node that does not have any splits coming out of it is called a ***terminal node***, or ***end node***, or ***leaf node***. Because each node splits into two branches, these splits are accomplished using **if-else** statements. A diagram depicting a decision tree can be seen in Fig. 15.1.

■ Explore Other Interesting Features

There are many other “is” functions. As more concepts are covered in the book, more and more of these functions will be introduced. Others you may want to explore now include **isvarname**, and functions that will tell you whether an argument is a particular type or not (**ischar**, **isfloat**, **isinteger**, **islogical**, **isstr**, **isreal**).

There are “is” functions to determine the type of an array: **isvector**, **isrow**, **iscolumn**, **ismatrix**.

The **try/catch** functions are a particular type of **if-else** used to find and avoid potential errors. They may be a bit complicated to understand at this point, but keep them in mind for the future! ■

SUMMARY

COMMON PITFALLS

- Using = instead of == for equality in conditions
- Putting a space in the keyword **elseif**
- Not using quotes when comparing a string variable to a string, such as

  ```
  letter == y
  ```

  instead of

  ```
  letter == 'y'
  ```

- Not spelling out an entire **logical** expression. An example is typing

  ```
  radius || height <=0
  ```

  instead of

  ```
  radius <=0 || height <=0
  ```

  or typing

  ```
  letter == 'y' || 'Y'
  ```

  instead of

  ```
  letter == 'y' || letter == 'Y'
  ```

  Note that these are logically incorrect but would not result in error messages. Note also that the expression "`letter == 'y' || 'Y'`" will ALWAYS be **true**, regardless of the value of the variable *letter*, as `'Y'` is a nonzero value and therefore a **true** expression.
- Not correctly checking for a range of values (e.g., using $1 < x < 5$ instead of using $1 < x$ && $x < 5$)
- Writing conditions that are more complicated than necessary, such as

  ```
  if (x<5) == 1
  ```

  instead of just

  ```
  if (x<5)
  ```

  (The "==1" is redundant.)
- Using an **if** statement instead of an **if-else** statement for error-checking; for example,

  ```
  % Wrong method
  if error occurs
       print error message
  end

  continue rest of code
  ```

instead of

```
% Correct method
if error occurs
     print error message
else
     continue rest of code
end
```

In the first example, the error message would be printed but then the program would continue anyway. Of course, if you throw an **error** message instead of printing, it would not matter.

PROGRAMMING STYLE GUIDELINES

- Use indentation to show the structure of a script or function. In particular, the actions in an **if** statement should be indented.
- When the **else** clause is not needed, use an **if** statement rather than an **if-else** statement. The following is an example:

```
if unit == 'i'
   len=len * 2.54;
else
   len=len; % this does nothing so skip it!
end
```

- Instead, just use:

```
if unit == 'i'
   len=len * 2.54;
end
```

- Do not put unnecessary conditions on **else** or **elseif** clauses. For example, the following prints one thing if the value of a variable *number* is equal to 5, and something else if it is not.

```
if number == 5
   disp('It is a 5')
elseif number ~= 5
   disp('It is not a 5')
end
```

The second condition, however, is not necessary. Either the value is 5 or not, so just the **else** would handle this:

```
if number == 5
   disp('It is a 5')
else
   disp('It is not a 5')
end
```

MATLAB Reserved Words

if
switch
else
elseif
case
otherwise

MATLAB Functions and Commands

error
menu
listdlg
isletter
isnumeric
isempty
isa
iskeyword

Exercises

1. Write a script that tests whether the user can follow instructions. It prompts the user to enter an ‘x’. If the user enters anything other than an ‘x’, it prints an error message – otherwise, the script does nothing.
2. Write a function *nexthour* that receives one integer argument, which is an hour of the day, and returns the next hour. This assumes a 12-hour clock; so, for example, the next hour after 12 would be 1. Here are two examples of calling this function.

```
>> fprintf('The next hour will be %d.\n’,nexthour(3))
The next hour will be 4.
>> fprintf('The next hour will be %d.\n’,nexthour(12))
The next hour will be 1.
```

3. Write a script that will begin by asking the user’s name. Then, it asks the user to enter a number, and then a smaller number. If the user follows directions, and enters a smaller number, the script prints the difference between the larger and smaller numbers. If, however, the user does not follow directions, the script tells the user that (using the user’s name). You may assume that the user enters numbers both times.
4. When would you use just an **if** statement and not an **if-else**?
5. Write a statement that will store **logical true** in a variable named *isit* if the value of a variable *x* is in the range from 0 to 10, or **logical false** if not. Do this with just one assignment statement, with no **if** or **if-else** statement!
6. For planes, the taper ratio is the wing tip length divided by the wing root length (e.g., 66”/200”). Write a script that will:
   - prompt the user for the wing tip length and the wing root length
   - call a function to calculate and return the taper ratio
   - print the taper ratio

   However, the script should print an error message if either input value is not a positive number. So, the script will either print an error message, or it will calculate and print the taper ratio (since it does not make sense to calculate the taper ratio using invalid input(s)). Also write the function that calculates and returns the taper ratio. Write the entire program, using separate code files for the script and the function.

7. A data file "parttolerance.dat" stores, on one line, a part number, and the minimum and maximum values for the valid range that the part could weigh. Write a script "parttol" that will read these values from the file, prompt the user for a weight, and print whether or not that weight is within range. Create a sample data file; for example, the file might store the following:

```
>> type parttolerance.dat
123 44.205 44.287
```

8. Write a live script that will prompt the user for a character. It will create an x-vector that has 50 numbers, equally spaced between -2π and 2π, and then a y-vector which is cos(x). If the user entered the character 'r', it will plot these vectors with red *s – otherwise, for any other character it will plot the points with green +s.
9. Simplify this statement:

```
if number >100
   number=100;
else
   number=number;
end
```

10. Explain why the "if val < 4" in the line "elseif val < 4" is not necessary, and show how this statement could be simplified:

```
if val>=4
   disp('ok')
elseif val<4
   disp('smaller')
end
```

11. Explain why the following code always prints "In middle", regardless of what the user enters (although you may assume that the user enters an integer). Then, modify the **if** statement so that it will print "In middle" if the user's integer is in the range from 0 to 50, or "Out of range" if not.

```
val=input('Enter an integer: ');
if 0<val<50
   disp('In middle')
else
   disp('Out of range')
end
```

12. Write a function *myabs* that calculates and returns the absolute value of the input argument (without using the **abs** function). Do this using an **if-else** statement.
13. Rewrite the myabs function from Problem 12, this time using an **if** statement (not an **if-else**).
14. Given the following function:

divit.m

```
function myout=divit(myin)
myout=1/myin;
end
```

Write a script *divornot* that will prompt the user for a number (assume the user does enter a number). The script will then print "cannot call function" if the user enters a 0, or it will pass the user's number to the function and print the result.

15. Modify your script for Problem 14 to throw an **error** if the user enters a 0.
16. In chemistry, the pH of an aqueous solution is a measure of its acidity. The pH scale ranges from 0 to 14, inclusive. A solution with a pH of 7 is said to be *neutral*, a solution with a pH greater than 7 is *basic*, and a solution with a pH less than 7 is *acidic*. Write a script that will prompt the user for the pH of a solution, and will print whether it is neutral, basic, or acidic. If the user enters an invalid pH, an error message will be printed.
17. In a script, the user is supposed to enter either a 'y' or 'n' in response to a prompt. The user's input is read into a character variable called *letter*. The script will print "OK, continuing" if the user enters either a 'y' or 'Y' or it will print "OK, halting" if the user enters a 'n' or 'N' or "Error" if the user enters anything else. Write the script using a single nested **if-else** statement (**elseif** clause is permitted).
18. Write the script from the previous exercise using a **switch** statement instead.
19. In aerodynamics, the Mach number is a critical quantity. It is defined as the ratio of the speed of an object (e.g., an aircraft) to the speed of sound. If the Mach number is less than 1, the flow is subsonic; if the Mach number is equal to 1, the flow is transonic; and if the Mach number is greater than 1, the flow is supersonic. Write a script that will prompt the user for the speed of an aircraft and the speed of sound at the aircraft's current altitude and will print whether the condition is subsonic, transonic, or supersonic.
20. Write a script that will generate one random integer, and will print whether the random integer is an even or an odd number. (Hint: an even number is divisible by 2, whereas an odd number is not; so check the remainder after dividing by 2.)
21. The Beaufort Wind Scale is used to characterize the strength of winds. The scale uses integer values and goes from a force of 0, which is no wind, up to 12, which is a hurricane. The following script first generates a random force value. Then, it prints a message regarding what type of wind that force represents, using a **switch** statement. You are to re-write this **switch** statement as one nested **if-else** statement that accomplishes exactly the same thing. You may use **else** and/or **elseif** clauses.
22. Write a script *areaMenu* that will print a list consisting of "cylinder", "circle", and "rectangle". It prompts the user to choose one, and then prompts the

user for the appropriate quantities (e.g., the radius of the circle) and then prints its area. If the user enters an invalid choice, the script simply prints an error message. The script should use a nested **if-else** statement to accomplish this.

23. Modify the *areaMenu* script to use a **switch** statement to decide which area to calculate.
24. Modify the areaMenu script to use the **menu** function instead of printing a menu.
25. Write a script that will prompt the user for a character vector and then print whether it was empty or not.
26. Simplify this statement:

```
if iskeyword('else') == 1
    disp('Cannot use as a variable name')
end
```

27. Write a script to test the **isnumeric** function.
28. Store a value in a variable and then use **isa** to test to see whether or not it is the type **double**.
29. Write a function called "makemat" that will receive two row vectors as input arguments, and from them create and return a matrix with two rows. You may not assume that the length of the vectors is known. Also, the vectors may be of different lengths. If that is the case, add 0's to the end of one vector first to make it as long as the other. For example, a call to the function might be:

```
>>makemat(1:4, 2:7)
ans =

    1     2     3     4     0     0

    2     3     4     5     6     7
```

Data Science and Machine Learning

30. Create a matrix that contains some NaN values, for example:

```
mat =
    14   NaN    13    15
     3     7   NaN    13
```

Write code that will replace the NaN constants with the median of the rest of the numbers in the matrix, for example:

```
mat =
     14    13    13    15
      3     7    13    13
```

Be careful about this! Note that the median of the non-NaN values is 13 because the median of the sorted vector storing the numbers from the matrix, [3 7 13 13 14 15], is 13.

31. True or False: the equality operator can be used to determine whether elements in a vector store the constant NaN, or not.

CHAPTER 5

Loop Statements and Vectorizing Code

KEY TERMS

looping statements
counted loops
conditional loops
action
vectorized code
iterate
loop or iterator variable
echo printing
running sum
running product
preallocate
nested loop
outer loop
inner loop
infinite loop
factorial
counting
error-checking
efficient code

CONTENTS

Consider the problem of calculating the area of a circle with a radius of 0.3 cm. A MATLAB® program certainly is not needed to do that; you would use your calculator instead, and punch in π*0.3 ^{2}. However, if a table of circle areas is desired, for radii ranging from 0.1 cm to 100 cm in steps of 0.05 (e.g., 0.1, 0.15, 0.2, etc.), it would be very tedious to use a calculator and write it all down. One of the great uses of programming languages and software packages such as MATLAB is the ability to repeat a process such as this.

This chapter will cover statements in MATLAB that allow other statement(s) to be repeated. The statements that do this are called ***looping statements***, or ***loops***. There are two basic kinds of loops in programming: ***counted loops*** and ***conditional loops***. A counted loop is a loop that repeats statements a specified number of times (so, ahead of time it is known how many times the statements are to be repeated). In a counted loop, for example, you might say "repeat these statements 10 times". A conditional loop also repeats statements, but ahead of time it is not known *how many* times the statements will need to be repeated. With a conditional loop, for example, you might say "repeat these statements until this condition becomes false". The statement(s) that are repeated in any loop are called the ***action*** of the loop.

There are two different loop statements in MATLAB: the **for** statement and the **while** statement. In practice, the **for** statement is used as the counted loop, and

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the **while** is usually used as the conditional loop. To keep it simple, that is how they will be presented here.

In many programming languages, looping through the elements in a vector or matrix is a very fundamental concept. In MATLAB, however, as it is written to work with vectors and matrices, looping through elements is usually not necessary. Instead, ***vectorized code*** is used, which means replacing the loops through arrays with the use of built-in functions and operators. Both methods will be described in this chapter. The earlier sections will focus on "the traditional programming concepts", using loops. These will be contrasted with "the efficient methods", using vectorized code. Loops are still relevant and necessary in MATLAB in other contexts, just not normally when working with vectors or matrices.

5.1 THE FOR LOOP

The **for** statement, or the **for** loop, is used when it is necessary to repeat statement(s) in a script or function and when it *is* known ahead of time how many times the statements will be repeated. The statements that are repeated are called the action of the loop. For example, it may be known that the action of the loop will be repeated five times. The terminology used is that we ***iterate*** through the action of the loop five times.

The variable that is used to iterate through values is called a ***loop variable*** or an ***iterator variable***. For example, the variable might iterate through the integers 1 through 5 (e.g., 1, 2, 3, 4, and then 5). Although, in general, variable names should be mnemonic, it is common in many languages for an iterator variable to be given the name *i* (and if more than one iterator variable is needed, *i*, *j*, *k*, *l*, etc.). This is historical and is because of the way integer variables were named in Fortran. However, in MATLAB both **i** and **j** are built-in functions that return the value $\sqrt{-1}$, so using either as a loop variable will override that value. If that is not an issue, then it is okay to use *i* as a loop variable.

The general form of the **for** loop is:

```
for loopvar=range
    action
end
```

where *loopvar* is the loop variable, "range" is the range of values through which the loop variable is to iterate, and the action of the loop consists of all statements up to the **end**. Just like with **if** statements, the action is indented to make it easier to see. The range can be specified using any vector, but normally the easiest way to specify the range of values is to use the colon operator.

As an example, we will print a column of numbers from 1 to 5.

The loop could be entered in the Command Window, although, like **if** and **switch** statements, loops will make more sense in scripts and functions. In the Command Window, the results would appear after the **for** loop:

```
>> for i=1:5
       fprintf('i is %d\n’,i)
   end
i is 1
i is 2
i is 3
i is 4
i is 5
```

What the **for** statement accomplished was to print the value of *i* and then the newline character for every value of *i*, from 1 through 5 in steps of 1. The first thing that happens is that *i* is initialized to have the value 1. Then, the action of the loop is executed, which is the **fprintf** statement that prints "i is" and then the value of *i* (1), and then the newline character to move the cursor down. Then, *i* is incremented to have the value of 2. Next, the action of the loop is executed, which prints 2 and the newline. Then, *i* is incremented to 3 and that is printed; then, *i* is incremented to 4 and that is printed; and then, finally, *i* is incremented to 5 and that is printed. The final value of *i* is 5; this value can be used once the loop has finished.

QUICK QUESTION!

How could you print this column of integers (using the traditional programming method):

```
  0
 50
100
150
200
```

Answer: In a loop, you could print these values starting at 0, incrementing by 50 and ending at 200. Each is printed using a field width of 3.

```
>> for i=0:50:200
       fprintf('%3d\n',i)
   end
```

5.1.1 For Loops That Do Not Use the Iterator Variable in the Action

In the previous example, the value of the loop variable was used in the action of the **for** loop: it was printed. It is not always necessary to actually use the value of the loop variable, however. Sometimes the variable is simply used to iterate, or repeat, an action a specified number of times. For example,

```
for i=1:3
    fprintf('I will not chew gum\n')
end
```

produces the output:

```
I will not chew gum
I will not chew gum
I will not chew gum
```

The variable *i* is necessary to repeat the action three times, even though the value of *i* is not used in the action of the loop.

QUICK QUESTION!

What would be the result of the following **for** loop?

```
for i=4:2:8
    fprintf('I will not chew gum\n')
end
```

Answer: Exactly the same output as above! It does not matter that the loop variable iterates through the values 4, then 6, then 8 instead of 1, 2, 3. Because the loop variable is not used in the action, this is just another way of specifying that the action should be repeated three times. Of course, using 1:3 makes more sense!

PRACTICE 5.1

Write a **for** loop that will print a column of five *'s.

5.1.2 Input in a for Loop

The following script repeats the process of prompting the user for a number, and ***echo printing*** the number (which means simply printing it back out). A **for** loop specifies how many times this is to occur. This is another example in which the loop variable is not used in the action, but, instead, just specifies how many times to repeat the action.

forecho.m

```
% This script loops to repeat the action of
% prompting the user for a number and echo-printing it

for iv=1:3
    inputnum=input('Enter a number: ');
    fprintf('You entered %.1f\n',inputnum)
end
```

```
>> forecho
Enter a number: 33
You entered 33.0
Enter a number: 1.1
You entered 1.1
Enter a number: 55
You entered 55.0
```

In this example, the loop variable *iv* iterates through the values 1 through 3, so the action is repeated three times. The action consists of prompting the user for a number and echo-printing it with one decimal place.

5.1.3 Finding Sums and Products

A very common application of a **for** loop is to calculate sums and products. For example, instead of just echo printing the numbers that the user enters, we could calculate the sum of the numbers. To do this, we need to add each value to a ***running sum***. A running sum keeps changing, as we keep adding to it. First, the sum has to be initialized to 0.

As an example, we will write a script *sumnnums* that will sum the *n* numbers entered by the user; *n* is a random integer that is generated. In a script to calculate the sum, we need a loop or iterator variable *i*, and also a variable to store the running sum. In this case we will use a variable *runsum* as the running sum. Every time through the loop, the next value that the user enters is added to the value of *runsum*. This script will print the end result, which is the sum of all of the numbers, stored in the variable *runsum*.

sumnnums.m

```
% sumnnums calculates the sum of the n numbers
% entered by the user

n=randi([3 10]);
runsum=0;
for i=1:n
    inputnum=input('Enter a number: ');
    runsum=runsum+inputnum;
end
fprintf('The sum is %.2f\n', runsum)
```

Here is an example in which 3 is generated to be the value of the variable *n*; the script calculates and prints the sum of the numbers the user enters, 4 + 3.2 + 1.1, or 8.3:

```
>> sumnnums
Enter a number: 4
Enter a number: 3.2
Enter a number: 1.1
The sum is 8.30
```

Another very common application of a **for** loop is to find a ***running product***. With a product, the running product must be initialized to 1 (as opposed to a running sum, which is initialized to 0).

PRACTICE 5.2

Write a script *prodnnums* that is similar to the *sumnnums* script but will calculate and print the product of the numbers entered by the user.

5.1.4 Preallocating Vectors

When numbers are entered by the user, it is often necessary to store them in a vector. There are two basic methods that could be used to accomplish this. One method is to start with an empty vector and extend the vector by adding each number to it as the numbers are entered by the user. Extending a vector, however, is very inefficient. What happens is that every time a vector is extended, a new "chunk" of memory must be found that is large enough for the new vector, and all of the values must be copied from the original location in memory to the new one. This can take a long time to execute.

A better method is to ***preallocate*** the vector to the correct size and then change the value of each element to be the numbers that the user enters. This method involves referring to each index in the result vector, and placing each number into the next element in the result vector. This method is far superior, if it is known ahead of time how many elements the vector will have. One common method is to use the **zeros** function to preallocate the vector to the correct length.

The following is a script that accomplishes this and prints the resulting vector. The script generates a random integer *n* and repeats the process *n* times. Because it is known that the resulting vector will have *n* elements, the vector can be preallocated.

forgenvec.m

```
% forgenvec creates a vector of length n
% It prompts the user and puts n numbers into a vector

n=randi([2 5]);
numvec=zeros(1,n);
for iv=1:n
    inputnum=input('Enter a number: ');
    numvec(iv)=inputnum;
end
fprintf('The vector is: \n')
disp(numvec)
```

Next is an example of executing this script.

```
>> forgenvec
Enter a number: 44
Enter a number: 2.3
Enter a number: 11
The vector is:
   44.0000    2.3000    11.0000
```

The number could also be read directly into *numvec(iv)*. The variable *inputnum* is not necessary.

Note

It is very important to notice that the loop variable iv is used as the index into the vector.

QUICK QUESTION!

If you need to just print the sum or average of the numbers that the user enters, would you need to store them in a vector variable?

Answer: No. You could just add each to a running sum as you read them in a loop.

QUICK QUESTION!

What if you wanted to calculate how many of the numbers that the user entered were greater than the average?

Answer: Yes, then you would need to store them in a vector because you would have to go back through them to count how many were greater than the average (or, alternatively, you could go back and ask the user to enter them again!).

5.1.3 For Loop Example: subplot

A function that is very useful with all types of plots is **subplot**, which creates a matrix of plots in the current Figure Window. Three arguments are passed to it in the form **subplot(r,c,n)**, where *r* and *c* are the dimensions of the matrix in the Figure Window and *n* is the number of the particular plot within this matrix. The plots are numbered rowwise starting in the upper left corner. In many cases, it is useful to create a **subplot** in a **for** loop so the loop variable can iterate through the integers 1 through *n*.

For example, if it is desired to have three plots next to each other in one Figure Window, the function would be called as **subplot(1,3,n).** The matrix dimensions in the Figure Window would be *1*×*3* in this case, and from left to right the individual plots would be numbered 1, 2, and then 3 (these would be the values of *n*). The first two arguments would always be 1 and 3, because they specify the dimensions of the matrix within the Figure Window.

When the **subplot** function is called in a loop, the first two arguments will always be the same as they give the dimensions of the matrix. The third argument will iterate through the numbers assigned to the elements of the matrix. When the **subplot** function is called, it makes the specified element the "active" plot; then, any plot function can be used, complete with formatting such as axis labeling and titles within that element. Note that the **subplot** function just specifies the dimensions of the matrix in the Figure Window, and which is the "active" element; **subplot** itself does not plot anything.

For example, the following **subplot** shows the difference, in one Figure Window, between using 20 points and 40 points to plot **sin(x)** between 0 and 2*π. The **subplot** function creates a *1* × *2* row vector of plots in the

Figure Window, so that the two plots are shown side by side. The loop variable *i* iterates through the values 1 and then 2.

The first time through the loop, when *i* has the value 1, 20 * 1 or 20 points are used, and the value of the third argument to the **subplot** function is 1. The second time through the loop, 40 points are used and the third argument to **subplot** is 2. The **sgtitle** function (introduced in R2018b) is used to put a title on the entire Figure Window. The resulting Figure Window with both plots is shown in Fig. 5.1.

subplotex.m

```
% Demonstrates subplot using a for loop
for i=1:2
    x=linspace(0,2*pi,20*i);
    y=sin(x);
    subplot(1,2,i)
    plot(x,y,'ko')
    xlabel('x')
    ylabel('sin(x)')
    title('sin plot')
end
sgtitle('sin plot with varying # of points'
```

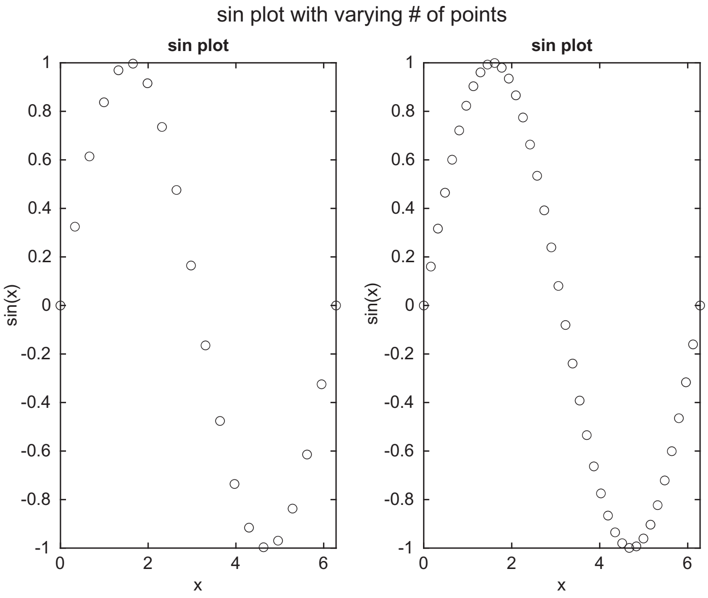

FIGURE 5.1

Subplot to demonstrate a plot using 20 points and 40 points

Note

that once string manipulating functions have been covered in Chapter 7, it will be possible to have customized titles (e.g., showing the number of points).

5.2 NESTED FOR LOOPS

The action of a loop can be any valid statement(s). When the action of a loop is another loop, this is called a ***nested loop***.

The general form of a nested **for** loop is as follows:

```
for loopvarone = rangeone              ← outer loop

    % actionone includes the inner loop

    for loopvartwo = rangetwo          ← inner loop
        actiontwo
    end
end
```

The first **for** loop is called the ***outer loop***; the second **for** loop is called the ***inner loop***. The action of the outer loop consists (in part; there could be other statements) of the entire inner loop.

As an example, a nested **for** loop will be demonstrated in a script that will print a box of stars (*). Variables in the script will specify how many rows and columns to print. For example, if *rows* has the value 3 and *columns* has the value 5, a *3* × *5* box would be printed. Because lines of output are controlled by printing the newline character, the basic algorithm is as follows.

- For every row of output:
  - Print the required number of stars
  - Move the cursor down to the next line (print '\n')

printstars.m

```
% Prints a box of stars
% How many will be specified by two variables
% for the number of rows and columns

rows=3;
columns=5;
% loop over the rows
for i=1:rows
    % for every row loop to print *'s and then one \n
    for j=1:columns
        fprintf('*')
    end
    fprintf('\n')
end
```

Executing the script displays the output:

```
>> printstars
*****
*****
*****
```

The variable *rows* specifies the number of rows to print, and the variable *columns* specifies how many stars to print in each row. There are two loop variables: *i* is the loop variable over the rows and *j* is the loop variable over the columns. As the number of rows is known and the number of columns is known (given by the variables *rows* and *columns*), **for** loops are used. There is one **for** loop to loop over the rows, and another to print the required number of stars for every row.

The values of the loop variables are not used within the loops, but are used simply to iterate the correct number of times. The first **for** loop specifies that the action will be repeated "rows" times. The action of this loop is to print stars and then the newline character. Specifically, the action is to loop to print *columns* stars (e.g., five stars) across on one line. Then, the newline character is printed after all five stars to move the cursor down to the next line.

In this case, the outer loop is over the rows, and the inner loop is over the columns. The outer loop must be over the rows because the script is printing a certain number of rows of output. For each row, a loop is necessary to print the required number of stars; this is the inner **for** loop.

When this script is executed, first the outer loop variable *i* is initialized to 1. Then, the action is executed. The action consists of the inner loop and then printing the newline character. So, while the outer loop variable has the value 1, the inner loop variable *j* iterates through all of its values. As the value of *columns* is 5, the inner loop will print a single star five times. Then, the newline character is printed and then the outer loop variable *i* is incremented to 2. The action of the outer loop is then executed again, meaning the inner loop will print five stars, and then the newline character will be printed. This continues, and, in all, the action of the outer loop will be executed *rows* times.

Notice that the action of the outer loop consists of two statements (the **for** loop and an **fprintf** statement). The action of the inner loop, however, is only a single **fprintf** statement.

The **fprintf** statement to print the newline character must be separate from the other **fprintf** statement that prints the star character. If we simply had

```
fprintf('*\n')
```

as the action of the inner loop (without the separate **fprintf**), this would print a long column of 15 stars, not a *3* × *5* box.

QUICK QUESTION!

How could this script be modified to print a triangle of stars instead of a box such as the following:

```
*
**
***
```

Answer: In this case, the number of stars to print in each row is the same as the row number (e.g., one star is printed in row 1, two stars in row 2, and so on). The inner **for** loop does not loop to *columns* but to the value of the row loop variable (so we do not need the variable *columns*):

printtristars.m

```
% Prints a triangle of stars
% How many will be specified by a variable
% for the number of rows
rows=3;
for i=1:rows
    % inner loop just iterates to the value of i
    for j=1:i
        fprintf('*')
    end
    fprintf('\n')
end
```

In the previous examples, the loop variables were just used to specify the number of times the action is to be repeated. In the next example, the actual values of the loop variables will be printed.

printloopvars.m

```
% Displays the loop variables
for i=1:3
    for j=1:2
        fprintf('i=%d, j=%d\n',i,j)
    end
    fprintf('\n')
end
```

Executing this script would print the values of both *i* and *j* on one line every time the action of the inner loop is executed. The action of the outer loop consists of the inner loop and printing a newline character, so there is a separation between the actions of the outer loop:

```
>> printloopvars
i=1, j=1
i=1, j=2

i=2, j=1
i=2, j=2

i=3, j=1
i=3, j=2
```

Again, *i* goes through all of its values from 1 to 3. For each value of *i*, *j* goes through both of its values (1 and 2).

Now, instead of just printing the loop variables, we can use them to produce a multiplication table, by multiplying the values of the loop variables.

The following function *multtable* calculates and returns a matrix which is a multiplication table. Two arguments are passed to the function, which are the number of rows and columns for this matrix.

```
multtable.m
```

```
function outmat=multtable(rows, columns)
% multtable returns a matrix which is a
% multiplication table
% Format: multtable(nRows, nColumns)

% Preallocate the matrix
outmat=zeros(rows,columns);
for i=1:rows
    for j=1:columns
        outmat(i,j)=i*j;
    end
end
end
```

In the following example of calling this function, the resulting matrix has three rows and five columns:

```
>> multtable(3,5)
ans=
      1     2     3      4      5
      2     4     6      8     10
      3     6     9     12     15
```

Note that this is a function that returns a matrix. It preallocates the matrix to zeros, and then replaces each element. Because the number of rows and columns are known, **for** loops are used. The outer loop loops over the rows, and the inner loop loops over the columns. The action of the nested loop calculates i*j for all values of *i* and *j*. ***Just like with vectors, it is again important to notice that the loop variables are used as the indices into the matrix.***

First, when *i* has the value 1, *j* iterates through the values 1 through 5, so first we are calculating 1*1, then 1*2, then 1*3, then 1*4, and, finally, 1*5. These are the values in the first row (first in element outmat(1,1), then outmat(1,2), then outmat(1,3), then outmat(1,4), and finally outmat(1,5)). Then, when *i* has the value 2, the elements in the second row of the output matrix are calculated, as *j* again iterates through the values from 1 through 5. Finally, when *i* has the value 3, the values in the third row are calculated (3*1, 3*2, 3*3, 3*4, and 3*5).

PRACTICE 5.3

For each of the following (they are separate), determine what would be printed. Then, check your answers by trying them in MATLAB.

```
mat=[7 11 3; 3:5];
[r, c]=size(mat);
for i=1:r
    fprintf('The sum is %d\n', sum(mat(i,:)))
end
```

```
for i=1:2
    fprintf('%d: ', i)
    for j= 1:4
        fprintf('%d ', j)
    end
    fprintf('\n')
end
```

Another more complicated example is matrix multiplication. Recall from Chapter 2 that the number of columns of a matrix A must be the same as the number of rows of a matrix B to multiply A times B, and the elements of the result matrix C are defined as the sum of products of corresponding elements in the rows of A and columns of B, or in other words,

$$[\mathrm{A}]_{m \times n}\,[\mathrm{B}]_{n \times p} = [\mathrm{C}]_{m \times p}$$

$$\mathrm{c_{ij}} = \sum_{k=1}^{n} a_{ik} b_{kj}.$$

Therefore, to accomplish this, it is necessary to loop through all of the elements of C (one loop over the rows and one loop over the columns), and for each element loop through the values of k to calculate the summation. In other words, three nested loops are required. The following function implements this algorithm. It first checks the dimensions of the input matrices to make sure that matrix multiplication is possible (and if not, it returns an empty vector). If it is possible, it loops to create the output matrix C.

mymatmult.m

```
function C=mymatmult(A,B)
% mymatmult performs matrix multiplication
% It returns an empty vector if the matrix
% multiplication cannot be performed
% Format: mymatmult(matA, matB)

[m, n]=size(A);
[nb, p]=size(B);
```

```
if n ~= nb
    C=[];
else
    % Preallocate C
    C=zeros(m,p);
    % Outer 2 loops iterate through the elements in C
    % which has dimensions m by p
    for i=1:m
        for j=1:p
            % Inner loop performs the sum for each
            % element in C
            mysum=0;
            for k=1:n
                mysum=mysum+A(i,k)*B(k,j);
            end
            C(i,j)=mysum;
        end
    end
end
```

5.2.1 Combining Nested For Loops and If Statements

The statements inside of a nested loop can be any valid statements, including any selection statement. For example, there could be an **if** or **if-else** statement as the action, or part of the action, in a loop.

As an example, assume there is a file called "datavals.dat" containing results recorded from an experiment. However, some were recorded erroneously. The numbers are all supposed to be positive. The following script reads from this file into a matrix. It prints the sum from each row of only the positive numbers. We will not assume how many lines are in the file nor how many numbers per line (although we will assume that there are the same number of numbers on every line, so we can use **load**).

sumonlypos.m

```
% Sums only positive numbers from file
% Reads from the file into a matrix and then
%   calculates and prints the sum of only the
%   positive numbers from each row

load datavals.dat
[r c]=size(datavals);

for row=1:r
    runsum=0;
    for col=1:c
        if datavals(row,col) >= 0
            runsum=runsum+datavals(row,col);
        end
    end
    fprintf('The sum for row %d is %d\n',row,runsum)
end
```

For example, *if* the file contains:

```
33   -11    2
 4     5    9
22     5   -7
 2    11    3
```

the output from the program would look like this:

```
>> sumonlypos
The sum for row 1 is 35
The sum for row 2 is 18
The sum for row 3 is 27
The sum for row 4 is 16
```

The file is loaded, and the data are stored in a matrix variable. The script finds the dimensions of the matrix and then loops through all of the elements in the matrix by using a nested loop; the outer loop iterates through the rows and the inner loop iterates through the columns. This is important; as an action is desired for every row, the outer loop has to be over the rows. For each element an **if** statement determines whether the element is positive or not. It only adds the positive values to the row sum. As the sum is found for each row, the *runsum* variable is initialized to 0 for every row, meaning inside of the outer loop.

QUICK QUESTION!

Would it matter if the order of the loops was reversed in this example, so that the outer loop iterates over the columns and the inner loop over the rows?

Answer: Yes, as we want a sum for every row the outer loop must be over the rows.

QUICK QUESTION!

What would you have to change in order to calculate and print the sum of only the positive numbers from each column instead of each row?

Answer: You would reverse the two loops, and change the sentence to say "The sum of column…". That is all that would change. The elements in the matrix would still be referenced as datavals(row,col). The row index is always given first, then the column index – regardless of the order of the loops.

PRACTICE 5.4

Write a function *mymatmin* that finds the minimum value in each column of a matrix argument and returns a vector of the column minimums. Use the traditional programming method. An example of calling the function follows:

```
>> mat=randi(20,3,4)
mat=
    15     19     17      5
     6     14     13     13
     9      5      3     13

>> mymatmin(mat)
ans=
     6      5      3      5
```

QUICK QUESTION!

Would the function *mymatmin* in Practice 5.4 also work for a vector argument?

Answer: Yes, it should, as a vector is just a subset of a matrix. In this case, one of the loop actions would be executed only one time (for the rows if it is a row vector or for the columns if it is a column vector).

5.3 WHILE LOOPS

The **while** statement is used as the conditional loop in MATLAB; it is used to repeat an action when ahead of time it is *not known how many* times the action will be repeated. The general form of the **while** statement is:

```
while condition
    action
end
```

The action, which consists of any number of statement(s), is executed as long as the condition is **true**.

The way it works is that first the condition is evaluated. If it is logically **true**, the action is executed. Therefore, to begin with, the **while** statement is just like an **if** statement. However, at that point the condition is evaluated again. If it is still **true**, the action is executed again. Then, the condition is evaluated again. If it is still **true**, the action is executed again. Then, the condition is....eventually, this has to stop! Eventually, something in the action has to change something in the condition so it becomes **false**. The condition must eventually become **false** to avoid an ***infinite loop***. (If this happens, Ctrl-C will exit the loop.)

As an example of a conditional loop, we will write a function that will find the first ***factorial*** that is greater than the input argument *high*. For an integer n, the factorial of n, written as n!, is defined as $n! = 1 * 2 * 3 * 4 * \ldots * n$. To calculate a factorial, a **for** loop would be used. However, in this case we do not know the value of n, so we have to keep calculating the next factorial until a level is reached, which means using a **while** loop.

The basic algorithm is to have two variables: one that iterates through the values 1,2, 3, and so on, and one that stores the factorial of the iterator at each step. We start with 1 and 1 factorial, which is 1. Then, we check the factorial. If it is not greater than *high*, the iterator variable will then increment to 2 and find its factorial (2). If this is not greater than *high*, the iterator will then increment to 3 and the function will find its factorial (6). This continues until we get to the first factorial that is greater than *high*.

Therefore, the process of incrementing a variable and finding its factorial is repeated until we get to the first value greater than *high*. This is implemented using a **while** loop:

factgthigh.m

```
function facgt=factgthigh(high)
% factgthigh returns the first factorial > input
% Format: factgthigh(inputInteger)

i=0;
fac=1;
while fac <= high
    i=i+1;
    fac=fac*i;
end
facgt=fac;
end
```

Note
that the variable *fac* is not necessary. The output argument *facgt* could be used to calculate the running product.

An example of calling the function, passing 5000 for the value of the input argument *high*, follows:

```
>> factgthigh(5000)
ans=
        5040
```

The iterator variable *i* is initialized to 0, and the running product variable *fac*, which will store the factorial of each value of *i*, is initialized to 1. The first time the **while** loop is executed, the condition is **true**: 1 is less than or equal to 5000. So, the action of the loop is executed, which is to increment *i* to 1 and *fac* becomes 1 (1 * 1).

After the execution of the action of the loop, the condition is evaluated again. As it will still be **true**, the action is executed: *i* is incremented to 2 and *fac* will get the value 2 (1*2). The value 2 is still <= 5000, so the action will be executed again: *i* will be incremented to 3 and *fac* will get the value 6 (2 * 3). This continues, until the first value of *fac* is found that is greater than 5000. As soon as *fac* gets to this value, the condition will be **false** and the **while** loop will end. At that point the factorial is assigned to the output argument, which returns the value.

The reason that *i* is initialized to 0 rather than 1 is that the first time the loop action is executed, *i* becomes 1 and *fac* becomes 1, so we have 1 and 1!, which is 1.

5.3.1 Multiple Conditions in a While Loop

In the *factgthigh* function, the condition in the **while** loop consisted of one expression, which tested whether the variable *fac* was less than or equal to the variable *high*. In many cases, however, the condition will be more complicated than that and could use either the **or** operator || or the **and** operator &&. For example, it may be that it is desired to stay in a **while** loop as long as a variable *x* is in a particular range:

```
while x >= 0 && x <= 100
```

As another example, continuing the action of a loop may be desired as long as at least one of two variables is in a specified range:

```
while x < 50 || y < 100
```

5.3.2 Input in a While Loop

Sometimes a **while** loop is used to process input from the user as long as the user is entering data in a correct format. The following script repeats the process of prompting the user, reading in a positive number, and echo printing it, as long as the user correctly enters positive numbers when prompted. As soon as the user types in a negative number, the script will print “OK” and end.

whileposnum.m

```
% Prompts the user and echo prints the numbers entered
% until the user enters a negative number

inputnum=input('Enter a positive number: ');
while inputnum >= 0
    fprintf('You entered a %d.\n\n',inputnum)
    inputnum=input('Enter a positive number: ');
end
fprintf('OK!\n')
```

When the script is executed, the input/output might look like this:

```
>> whileposnum
Enter a positive number: 6
You entered a 6.

Enter a positive number:-2
OK!
```

Note that the prompt is repeated in the script: once before the loop, and then again at the end of the action. This is done so that every time the condition is evaluated, there is a new value of *inputnum* to check. If the user enters a negative number the first time, no values would be echo-printed:

```
>> whileposnum
Enter a positive number:-33
OK!
```

As we have seen previously, MATLAB will give an error message if a character is entered rather than a number.

Note

This example illustrates a very important feature of while loops: it is possible that the action will not be executed at all, if the value of the condition is false the first time it is evaluated.

```
>> whileposnum
Enter a positive number: a
Error using input
Unrecognized function or variable 'a'.
Error in whileposnum (line 4)
inputnum=input('Enter a positive number: ');
Enter a positive number:-4
OK!
```

However, if the character is actually the name of a variable, it will use the value of that variable as the input. For example:

```
>> a=5;
>> whileposnum
Enter a positive number: a
You entered a 5.

Enter a positive number:-4
OK!
```

5.3.2.1 *Extending a Vector*

If it is desired to store all of the positive numbers that the user enters, we would store them one at a time in a vector. However, as we do not know ahead of time how many elements we will need, we cannot preallocate to the correct size. The two methods of extending a vector one element at a time are shown here. We can start with an empty vector and concatenate each value to the vector, or we can increment an index.

```
numvec=[];
inputnum=input('Enter a positive number: ');
while inputnum >= 0
    numvec=[numvec inputnum];
    inputnum=input('Enter a positive number: ');
end

% OR:
i=0;
inputnum=input('Enter a positive number: ');
while inputnum >= 0
    i=i+1;
    numvec(i)=inputnum;
    inputnum=input('Enter a positive number: ');
end
```

Keep in mind that both of these are inefficient and should be avoided if the vector can be preallocated.

5.3.3 Counting in a While Loop

Although **while** loops are used when the number of times the action will be repeated is not known ahead of time, it is often useful to know how many times the action was, in fact, repeated. In that case, it is necessary to ***count*** the number of times the action is executed. The following variation on the previous script counts the number of positive numbers that the user successfully enters.

countposnum.m

```
% Prompts the user for positive numbers and echo prints as
% long as the user enters positive numbers

% Counts the positive numbers entered by the user
counter=0;
inputnum=input('Enter a positive number: ');
while inputnum >= 0
    fprintf('You entered a %d.\n\n',inputnum)
    counter=counter+1;
    inputnum=input('Enter a positive number: ');
end
fprintf('Thanks, you entered %d positive numbers.\n',counter)
```

The script initializes a variable *counter* to 0. Then, in the **while** loop action, every time the user successfully enters a number, the script increments the counter variable. At the end of the script it prints the number of positive numbers that were entered.

```
>> countposnum
Enter a positive number: 4
You entered a 4.

Enter a positive number: 11
You entered a 11.

Enter a positive number:-4
Thanks, you entered 2 positive numbers.
```

PRACTICE 5.5

Write a script *avenegnum* that will repeat the process of prompting the user for negative numbers until the user enters a zero or positive number, as just shown. Instead of echo-printing them, however, the script will print the average (of just the negative numbers). If no negative numbers are entered, the script will print an error message instead of the average. Use the traditional programming method. Examples of executing this script follow:

```
>> avenegnum
Enter a negative number: 5
No negative numbers to average.
```

```
>> avenegnum
Enter a positive number:-8
Enter a positive number:-3
Enter a positive number:-4
Enter a positive number: 6
The average was-5.00
```

5.3.4 Error-Checking User Input in a While loop

In most applications, when the user is prompted to enter something, there is a valid range of values. If the user enters an incorrect value, rather than having the program carry on with an incorrect value, or just printing an error message, the program should repeat the prompt. The program should keep prompting the user, reading the value, and checking it until the user enters a value that is in the correct range. This is a very common application of a conditional loop: looping until the user correctly enters a value in a program. This is called ***error-checking***.

For example, the following script prompts the user to enter a positive number and loops to print an error-message and repeat the prompt until the user finally enters a positive number.

readonenum.m

```
% Loop until the user enters a positive number

inputnum=input('Enter a positive number: ');
while inputnum < 0
    inputnum=input('Invalid! Enter a positive number: ');
end
fprintf('Thanks, you entered a %.1f \n',inputnum)
```

An example of running this script follows:

```
>> readonenum
Enter a positive number:-5
Invalid! Enter a positive number:-2.2
Invalid! Enter a positive number: 44
Thanks, you entered a 44.0
```

QUICK QUESTION!

How could we vary the previous example so that the script asks the user to enter positive numbers *n* times, where *n* is an integer defined to be 3?

Answer: Every time the user enters a value, the script checks and in a **while** loop keeps telling the user that it is invalid until a valid positive number is entered. By putting the error-check in a **for** loop that repeats n times, the user is forced eventually to enter three positive numbers, as shown in the following.

readnnums.m

```
% Loop until the user enters n positive numbers
n=3;
fprintf('Please enter %d positive numbers\n\n',n)
for i=1:n
    inputnum=input('Enter a positive number: ');
    while inputnum < 0
        inputnum=input('Invalid! Enter a positive number: ');
    end
    fprintf('Thanks, you entered a %.1f \n',inputnum)
end
```

```
>> readnnums
Please enter 3 positive numbers

Enter a positive number: 5.2
Thanks, you entered a 5.2
Enter a positive number: 6
Thanks, you entered a 6.0
Enter a positive number:-7.7
Invalid! Enter a positive number: 5
Thanks, you entered a 5.0
```

5.3.4.1 Error-Checking for Integers

Because MATLAB uses the type **double** by default for all numbers, to check to make sure that the user has entered an integer, the program has to convert the input value to an integer type (e.g., **int32**) and then check to see whether that is equal to the original input. The following examples illustrate the concept.

If the value of the variable *num* is a real number, converting it to the type **int32** will round it, so the result is not the same as the original value.

```
>> num = 3.3;
>> inum = int32(num)
inum =
        3

>> num == inum
ans =
    0
```

If, however, the value of the variable *num* is an integer, converting it to an integer type will not change the value.

```
>> num = 4;
>> inum = int32(num)
inum =
          4

>> num == inum
ans =
     1
```

The following script uses this idea to error-check for integer data; it loops until the user correctly enters an integer.

```
readoneint.m
```

```
% Error-check until the user enters an integer
inputnum=input('Enter an integer: ');
num2=int32(inputnum);
while num2 ~= inputnum
    inputnum=input('Invalid! Enter an integer: ');
    num2=int32(inputnum);
end
fprintf('Thanks, you entered a %d \n',inputnum)
```

Examples of running this script are:

```
>> readoneint
Enter an integer: 9.5
Invalid! Enter an integer: 3.6
Invalid! Enter an integer:-11
Thanks, you entered a-11

>> readoneint
Enter an integer: 5
Thanks, you entered a 5
```

Note

this assumes that the user enters something. Use the **isempty** function to be sure.

Putting these ideas together, the following script loops until the user correctly enters a positive integer. There are two parts to the condition, as the value must be positive and must be an integer.

```
readoneposint.m
```

```
% Error checks until the user enters a positive integer
inputnum=input('Enter a positive integer: ');
num2=int32(inputnum);
while num2 ~= inputnum || num2 < 0
    inputnum=input('Invalid! Enter a positive integer: ');
    num2=int32(inputnum);
end
fprintf('Thanks, you entered a %d \n',inputnum)
```

```
>> readoneposint
Enter a positive integer: 5.5
Invalid! Enter a positive integer:-4
Invalid! Enter a positive integer: 11
Thanks, you entered a 11
```

PRACTICE 5.6

Modify the script *readoneposint* to read *n* positive integers, instead of just one.

5.4 LOOPS WITH VECTORS AND MATRICES; VECTORIZING

In most programming languages when performing an operation on a vector, a **for** loop is used to loop through the entire vector, using the loop variable as the index into the vector. In general, in MATLAB, assuming there is a vector variable *vec*, the indices range from 1 to the length of the vector, and the **for** statement loops through all of the elements performing the same operation on each one:

```
for i=1:length(vec)
    % do something with vec(i)
end
```

In fact, this is one reason to store values in a vector. Typically, values in a vector represent "the same thing", so, typically in a program the same operation would be performed on every element.

Similarly, for an operation on a matrix, a nested loop would be required, and the loop variables over the rows and columns are used as the subscripts into the matrix. In general, assuming a matrix variable mat, we use size to return separately the number of rows and columns, and we use these variables in the for loops. If an action is desired for every row in the matrix, the nested for loop would look like this:

```
[r, c]=size(mat);
for row=1:r
   for col=1:c
      % do something with mat(row,col)
   end
end
```

For example, if we desire to sum all of the elements in each row, the outer loop would be over the rows. If, instead, an action is desired for every column in the matrix, the outer loop would be over the columns. (Note, however, that the reference to a matrix element always refers to the row index first and then the column index.)

```
[r, c]=size(mat);
for col=1:c
   for row=1:r
      % do something with mat(row,col)
   end
end
```

In some cases, the order of the loops does not matter. For example, if we wanted an overall sum of all elements in the matrix, the outer loop could be over the rows or columns.

Typically, looping through vectors or matrices is not necessary in MATLAB! Although **for** loops are very useful for many other applications in MATLAB, they are not typically used for operations on vectors or matrices; instead, the efficient method is to use built-in functions and/or operators. This is called vectorized code. The use of loops and selection statements with vectors and matrices is a basic programming concept with many other languages, and so both "the traditional programming method" and "the efficient method" are highlighted in this section and, to some extent, throughout the rest of this book.

5.4.1 Vectorizing Sums and Products

For example, let us say that we want to perform a scalar multiplication, in this case multiplying every element of a vector *v* by 3, and store the result back in *v*, where *v* is initialized as follows:

```
>> v = [3 7 2 1];
```

THE TRADITIONAL METHOD

To accomplish this, we can loop through all of the elements in the vector and multiply each element by 3. In the following, the output is suppressed in the loop, and then the resulting vector is shown:

```
>> for i=1:length(v)
       v(i)=v(i)*3;
   end
>> v
  v=
     9    21    6    3
```

THE EFFICIENT METHOD

```
>> v=v*3
```

It is important to understand that although MATLAB has this efficient method, many other languages do not and a loop must be used. This also shows what is "under the hood," for example, how the efficient method in MATLAB is actually accomplished.

How could we calculate the factorial of n, n! = 1 * 2 * 3 * 4 *… * n?

THE TRADITIONAL METHOD

The basic algorithm is to initialize a running product to 1 and multiply the running product by every integer from 1 to n. This is implemented in a function:

myfact.m

```
function runprod=myfact(n)
% myfact returns n!
% Format of call: myfact(n)

runprod=1;
for i=1:n
    runprod=runprod*i;
end
end
```

Any positive integer argument could be passed to this function, and it will calculate the factorial of that number. For example, if 5 is passed, the function will calculate and return 1*2*3*4*5, or 120:

```
>> myfact(5)
ans=
    120
```

Again, it is important to understand the traditional method using a loop, but MATLAB has a built-in function to do this.

THE EFFICIENT METHOD

MATLAB has a built-in function, **factorial**, that will find the factorial of an integer *n*. The **prod** function could also be used to find the product of the vector 1:5.

```
>> factorial(5)
ans=
    120
>> prod(1:5)
ans=
    120
```

QUICK QUESTION!

MATLAB has a **cumsum** function that will return a vector of all of the running sums of an input vector. However, many other languages do not, so how could we write our own?

Answer: Essentially, there are two programming methods that could be used to simulate the **cumsum** function. One method is to start with an empty vector and extend the vector by adding each running sum to it as the running sums are calculated. A better method is to preallocate the vector to the correct size and then change the value of each element to be successive running sums.

myveccumsum.m

```
function outvec=myveccumsum(vec)
% myveccumsum imitates cumsum for a
vector
% It preallocates the output vector
% Format: myveccumsum(vector)

outvec=zeros(size(vec));
runsum=0;
for i=1:length(vec)
    runsum=runsum+vec(i);
    outvec(i)=runsum;
end
end
```

An example of calling the function follows:

```
>> myveccumsum([5 9 4])
ans=
     5    14    18
```

PRACTICE 5.7

Write a function that imitates the **cumprod** function. Use the method of preallocating the output vector.

QUICK QUESTION!

How would we sum each individual column of a matrix?

Answer: The traditional programming method would require a nested loop in which the outer loop is over the columns. The function will sum each column and return a row vector containing the results.

matcolsum.m

```
function outsum=matcolsum(mat)
% matcolsum finds the sum of every column in a matrix
% Returns a vector of the column sums
% Format: matcolsum(matrix)

[row, col]=size(mat);

% Preallocate the vector to the number of columns
outsum=zeros(1,col);

% Every column is being summed so the outer loop
% has to be over the columns
for i=1:col
    % Initialize the running sum to 0 for every column
    runsum=0;
    for j=1:row
        runsum=runsum+mat(j,i);
    end
    outsum(i)=runsum;
end
end
```

Note that the output argument will be a row vector containing the same number of columns as the input argument matrix. Also, as the function is calculating a sum for each column, the *runsum* variable must be initialized to 0 for every column, so it is initialized inside of the outer loop.

```
>> mat=[3:5; 2 5 7]
mat=
     3     4     5
     2     5     7

>> matcolsum(mat)
ans=
     5     9    12
```

Of course, the built-in **sum** function in MATLAB would accomplish the same thing, as we have already seen.

PRACTICE 5.8

Modify the function *matcolsum*. Create a function *matrowsum* to calculate and return a vector of all of the row sums instead of column sums. For example, calling it and passing the *mat* variable above would result in the following:

```
>> matrowsum(mat)
ans=
    12    14
```

5.4.2 Vectorizing Loops with Selection Statements

In many applications, it is useful to determine whether numbers in a matrix are positive, zero, or negative. This requires a nested loop to loop over the elements in the matrix, and for each, use a nested **if-else** statement to determine the outcome.

THE TRADITIONAL METHOD

A function *signum* follows that will accomplish this:

```
signum.m
```

```
function outmat=signum(mat)
% signum imitates the sign function
% Format: signum(matrix)

[r, c]=size(mat);
for i=1:r
    for j=1:c
        if mat(i,j) > 0
            outmat(i,j)=1;
        elseif mat(i,j)== 0
            outmat(i,j)=0;
        else
            outmat(i,j)=-1;
        end
    end
end
end
```

Here is an example of using this function:

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

>> signum(mat)
ans=
     0    1    -1
    -1    0     1
```

THE EFFICIENT METHOD

Close inspection reveals that the function accomplishes the same task as the built-in **sign** function!

```
>> sign(mat)
ans=
     0    1    -1
    -1    0     1
```

QUICK QUESTION!

Does the order of the loops matter in the signum function?

Answer: No.

QUICK QUESTION!

Determine what the following function accomplishes:

xxx.m

```
function logresult=xxx(vec)
% QQ for you-what does this do?

logresult=false;
i=1;
while i <= length(vec) && logresult== false
    if vec(i) ~= 0
       logresult=true;
    end
    i=i+1;
end
end
```

Answer: The output produced by this function is the same as the **any** function for a vector. It initializes the output argument to **false**. It then loops through the vector and, if any element is nonzero, changes the output argument to **true**. It loops until either a nonzero value is found or it has gone through all elements.

QUICK QUESTION!

Determine what the following function accomplishes.

yyy.m

```
function logresult=yyy(mat)
% QQ for you - what does this do?

counter=0;
[r, c]=size(mat);
for i=1:r
    for j=1:c
        if mat(i,j) ~= 0
           counter=counter+1;
        end
    end
end

logresult=counter== numel(mat);
end
```

Answer: The output produced by this function is the same as the **all** function. It loops through all elements of a matrix (the order of the loops does not matter) and counts how many elements are nonzero. Then, it compares that number to the total number of elements in the matrix.

As another example, we will write a function that will receive a vector and an integer as input arguments and will return a logical vector that stores **logical true** only for elements of the vector that are greater than the integer and **false** for the other elements.

THE TRADITIONAL METHOD

The function receives two input arguments: the vector, and an integer *n* with which to compare. It loops through every element in the input vector, and stores in the result vector either **true** or **false** depending on whether vec(i) > n is **true** or **false**.

testvecgtn.m

```
function outvec=testvecgtn(vec,n)
% testvecgtn tests whether elements in vector
% are greater than n or not
% Format: testvecgtn(vector, n)

% Preallocate the vector to logical false
outvec=false(size(vec));
for i=1:length(vec)
    % If an element is > n, change to true
    if vec(i) > n
        outvec(i)=true;
    end
end
end
```

```
>> ov=testvecgtn([44 2 11-3 5 8], 6)
ov=
     1     0     1     0     0     1
>> class(ov)
ans=
     logical
```

Note that as the vector was preallocated to **false**, the **else** clause is not necessary.

THE EFFICIENT METHOD

As we have seen, the relational operator > will automatically create a **logical** vector.

testvecgtnii.m

```
function outvec=testvecgtnii(vec,n)
% testvecgtnii tests whether elements in vector
% are greater than n or not with no loop
% Format: testvecgtnii(vector, n)

outvec=vec > n;
end
```

Because the focus of this book is the programming concepts, it is important to understand the fundamental, traditional concepts of loops and selection statements. However, it is also useful to know how to use MATLAB efficiently.

PRACTICE 5.9

Call the function *testvecgtnii*, passing a vector and a value for n. Use MATLAB code to count how many values in the vector were greater than n.

5.4.3 Tips for Writing Efficient Code

To be able to write ***efficient code*** in MATLAB, including vectorizing, there are several important features to keep in mind:

- Scalar and array operations
- Logical vectors
- Built-in functions
- Preallocation of vectors

There are many functions in MATLAB that can be utilized instead of code that uses loops and selection statements. These functions have been demonstrated already but it is worth repeating them to emphasize their utility:

- **sum** and **prod**: find the sum or product of every element in a vector or column in a matrix
- **cumsum** and **cumprod**: return a vector or matrix of the cumulative (running) sums or products
- **min** and **max**: find the minimum value in a vector or in every column of a matrix
- **any**, **all**, **find**: work with logical expressions
- "is" functions, such as **isletter** and **isequal**: return **logical** values

In almost all cases, code that is faster to write by the programmer is also faster for MATLAB to execute. So, "efficient code" means that it is both efficient for the programmer and for MATLAB.

PRACTICE 5.10

Vectorize the following (re-write the code efficiently):

```
i=0;
for inc=0: 0.5: 3
    i=i+1;
    myvec(i)=sqrt(inc);
end
```

```
[r c]=size(mat);
newmat=zeros(r,c);
for i=1:r
    for j=1:c
        newmat(i,j)=sign(mat(i,j));
    end
end
```

MATLAB has a built-in function **checkcode** that can detect potential problems within scripts and functions. Consider, for example, the following script that extends a vector within a loop:

badcode.m

```
for j=1:4
    vec(j)=j
end
```

The function **checkcode** will flag this, as well as the good programming practice of suppressing output within scripts:

```
>> checkcode('badcode')
L 2 (C 5-7): The variable 'vec' appears to change size on every loop
iteration (within a script). Consider preallocating for speed.
L 2 (C 12): Terminate statement with semicolon to suppress output
(within a script).
```

The same information is shown in Code Analyzer Reports, which can be produced within MATLAB for one file (script or function) or for all code files within a folder. Clicking on the down arrow for the Current Folder, and then choosing Reports and then Code Analyzer Report will check the code for all files within the Current Folder. When viewing a file within the Editor, click on the down arrow and then Show Code Analyzer Report for a report on just that one file.

5.5 TIMING

MATLAB has built-in functions that determine how long it takes code to execute. One set of related functions is **tic**/**toc**. These functions are placed around code and will print the time it took for the code to execute. Essentially, the function **tic** turns a timer on, and then **toc** evaluates the timer and prints the result. Here is a script that illustrates these functions.

forticitoc.m

```
tic
mysum=0;
for i=1:20000000
    mysum=mysum+i;
end
toc
```

```
>> *forticitoc*
Elapsed time is 0.087294 seconds.
```

Note that when using timing functions such as **tic**/**toc**, be aware that other processes running in the background (e.g., any web browser) will affect the speed of your code.

Here is an example of a script that demonstrates how much preallocating a vector speeds up the code.

tictocprealloc.m

```
% This shows the timing difference between
% preallocating a vector vs. not

clear
disp('No preallocation')
tic
for i=1:10000
    x(i)=sqrt(i);
end
toc

disp('Preallocation')
tic
y=zeros(1,10000);
for i=1:10000
    y(i)=sqrt(i);
end
toc
```

```
>> tictocprealloc
No preallocation
Elapsed time is 0.005070 seconds.
Preallocation
Elapsed time is 0.000273 seconds.
```

QUICK QUESTION!

Preallocation can speed up code, but to preallocate it is necessary to know the desired size. What if you do not know the eventual size of a vector (or matrix)? Does that mean that you have to extend it rather than preallocating?

Answer: If you know the maximum size that it could possibly be, you can preallocate to a size that is larger than necessary and then delete the "unused" elements. To do that, you would have to count the number of elements that are actually used. For example, if you have a vector *vec* that has been preallocated and a variable *counter* that stores the number of elements that were actually used, this will trim the unnecessary elements:

```
vec=vec(1:counter)
```

MATLAB also has a Profiler that will generate detailed reports on execution time of codes. In newer versions of MATLAB, from the Editor click on Run and Time; this will bring up a report in the Profile Viewer. Choose the function name to see a very detailed report, including a Code Analyzer Report. From the Command Window, this can be accessed using **profile on** and **profile off**, and **profile viewer**.

```
>> profile on
>> tictocprealloc
No preallocation
Elapsed time is 0.003656 seconds.
Preallocation
Elapsed time is 0.001949 seconds.
>> profile viewer
>> profile off
```

Data Science and Machine Learning Supplement

Split Validation and Cross Validation

Once a labeled data set has been cleaned up (replacing missing data values, for example), it is necessary to break the data into ***training*** and ***testing*** sets. The training data is used to train the model by using the labels. The model "predicts" the labels and compares the results to the actual labels. Once the desired accuracy is obtained, the model is then tested using the test data set. Frequently, the training set is approximately 80% of the original data, and the remaining 20% is reserved for the test data set.

For the training, the training data set is also often split into an initial training set and a validation set. An 80/20 split is common for this, also. The validation set is also sometimes called the holdout set, as it consists of data that were held out of the original training. This process of splitting the training data set to validate the model is called split validation.

Split validation is not always possible, however. For example, if the data set is fairly small, splitting the training data into two data sets is not a viable option. In this case, a different process called cross validation can be used. One type of cross validation, called k-fold validation, involves splitting the training data into k sets and then iterating until each set has been used as the validation set. For example, for a 4-fold validation, the algorithm would look like this:

- Break the data into four sets (of the same size).
- Loop four times using an iterator variable i. Each time in the loop:
  - Use data set i as the validation set.
  - Use all others as the training set.
  - Train, validate, and get results.
- Average the results.

Each iteration through the loop is called a *fold*.

In summary, first the data are split into training and testing data sets. Then, a validation method is chosen. If split validation is used, the training set is split into an initial training set and a validation set. The model is trained using the initial training set, and then the validation set is used to predict labels and compare the predictions to the actual labels. If k-fold validation is chosen, this validation is done in a loop, each time using a different subset of the training set as the validation set. Once the training and validation have been completed using the training set, and the results are known, the testing set is then used to test the model. The testing set has not been used at all in the training process. Again, the model predicts the labels for the testing set, and compares to the actual labels.

Randomizing Data

When working with classification algorithms, before data sets can be split for either validation method, the data need to be randomized. The reason for this is to remove possibly hidden biases in the data, to make sure that the training and test sets are representative of the entire data set. For example, sometimes labeled data are grouped by the categories, or labels. This means that the last 20% might be all in one category, so it would certainly not be able to test for all categories. Having data that are sorted chronologically or alphabetically could also introduce biases. So, the first step is to randomly “scramble” the original data set. In MATLAB, this can be done with the **randperm** function. The function randperm(n) randomly permutates the integers from 1 through n and returns the resulting vector.

```
>> randperm(6)
ans=
     3     5     4     2     1     6
```

Therefore, to randomize the rows of a matrix, a random permutation of the integers from 1 through the number of rows is obtained, and then this is used to index into the rows. It is a good idea to set the seed for the random number generators first.

```
>> rng('shuffle')
>> dataset=randi([1, 100], 5, 6)
dataset=
    81    15    15    41    24    50
    44    14    86     8    42    49
    92    87    63    24     5    34
    19    58    36    13    91    91
    27    55    52    19    95    37
>> [r, c]=size(dataset);
>> dataset=dataset(randperm(r), :)
dataset=
    81    15    15    41    24    50
    19    58    36    13    91    91
```

```
        92    87    63    24     5    34
        27    55    52    19    95    37
        44    14    86     8    42    49
```

This is an example of vectorized code. Loops are not necessary to accomplish this task in MATLAB.

Visualizing Data Correlations

Let us examine the columns of the following matrix:

```
>> mat
mat=
    4.0000    2.0000    9.1000     1.0000
    4.0000    2.7000    8.0000     2.0000
    1.0000    3.1000    8.2000     3.0000
    9.0000    4.0000    5.9000     4.0000
    6.0000    4.5000    5.0000     5.0000
    4.0000    5.3000    3.6000     6.0000
    8.0000    5.9000    3.3000     7.0000
    8.0000    6.4000    3.0000     8.0000
    6.0000    7.1000    1.8000     9.0000
    3.0000    9.0000    1.1000    10.0000
```

The first column seems to be random, and in fact it was created using the **randi** function. In the second column, the numbers are in the range from 2 to 9 and rise from one row to the next. In the third column, the numbers go down from 9.1 to 1.1. The final column stores the integers 1 to 10, which rise regularly in steps of 1. So, questions might be: how well do these columns correlate with each other, and is there a good way to visualize this? The correlation coefficient matrix shows all of the correlations.

```
>> corrcoef(mat)
ans=
     1.0000     0.1833    -0.3284     0.2528
     0.1833     1.0000    -0.9699     0.9872
    -0.3284    -0.9699     1.0000    -0.9835
     0.2528     0.9872    -0.9835     1.0000
```

For example, the last row shows how well the fourth column correlates with each of the columns. As we might expect, there is not much of a correlation between the first and fourth columns, as evidenced by the correlation coefficient of .02528. We can visualize the correlations between each of the first three columns and the last column using a **for** loop to create a subplot, as seen in Fig. 5.2.

```
for i=1:3
    subplot(1,3,i)
    plot(mat(:,i), mat(:,4), '*')
end
sgtitle('Correlations')
```

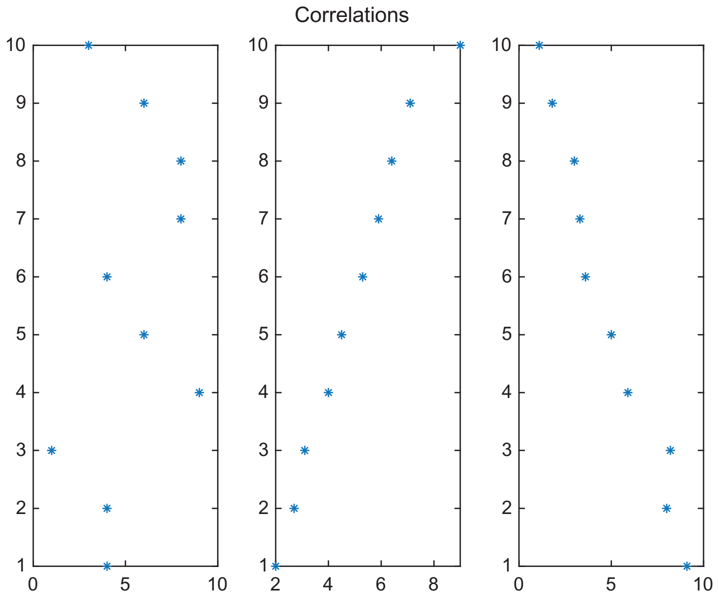

FIGURE 5.2

Correlations.

The first plot, on the left, shows the first column plotted against the fourth, and there does not seem to be any kind of a trend. The second, middle, plot shows the second column plotted against the fourth, and it almost looks like a straight line rising, which corresponds to the positive correlation coefficient 0.9872. The plot on the right plots the third column against the fourth. These points go down, but not quite in as straight a line as the previous, which is explained by the negative correlation coefficient of −0.9835.

■ Explore Other Interesting Features

Explore what happens when you use a matrix rather than a vector to specify the range in a **for** loop. For example,

```
for i=mat
    disp(i)
end
```

Take a guess before you investigate!

Try the **pause** function in loops.

Investigate the **vectorize** function.

The **tic** and **toc** functions are in the **timefun** help topic. Type **help timefun** to investigate some of the other timing functions. ■

SUMMARY

COMMON PITFALLS

- Forgetting to initialize a running sum or count variable to 0
- Forgetting to initialize a running product variable to 1
- In cases where loops are necessary, not realizing that if an action is required for every row in a matrix, the outer loop must be over the rows (and if an action is required for every column, the outer loop must be over the columns)
- Not realizing that it is possible that the action of a **while** loop will never be executed
- Not error-checking input into a program
- Not vectorizing code whenever possible. If it is not necessary to use loops in MATLAB, don't!
- Forgetting that **subplot** numbers the plots rowwise rather than columnwise.
- Not realizing that the **subplot** function just creates a matrix within the Figure Window. Each part of this matrix must then be filled with a plot, using any type of plot function.

PROGRAMMING STYLE GUIDELINES

- Use loops for repetition only when necessary
  - **for** statements as counted loops.
  - **while** statements as conditional loops.
- Do not use *i* or *j* for iterator variable names if the use of the built-in constants **i** and **j** is desired.
- Indent the action of loops.
- If the loop variable is just being used to specify how many times the action of the loop is to be executed, use the colon operator 1:n, where *n* is the number of times the action is to be executed.
- Preallocate vectors and matrices whenever possible (when the size is known ahead of time).
- When data are read in a loop, only store them in an array if it will be necessary to access the individual data values again.
- Vectorize whenever possible.

MATLAB Reserved Words
for
end
while

MATLAB Functions and Commands

subplot
sgtitle
factorial
checkcode
tic / toc
profile

Exercises

1. Write a **for** loop that will print the column of real numbers from 1.5 to 2.7 in steps of 0.2.
2. In the Command Window, write a **for** loop that will iterate through the integers from 32 to 255. For each, show the corresponding character from the character encoding. Play with this! Try printing characters beyond the standard ASCII, in small groups. For example, print the characters that correspond to integers from 300 to 340.
3. Prompt the user for an integer *n* and print "MATLAB rocks!" n times.
4. When would it matter if a **for** loop contained `for i = 1:3` versus `for i = [3 5 6]`, and when would it not matter?
5. Write a function *sumsteps2* that calculates and returns the sum of 1 to *n* in steps of 2, where *n* is an argument passed to the function. For example, if 11 is passed, it will return 1+3+5+7+9+11. Do this using a **for** loop.
6. Write a function *prodby2* that will receive a value of a positive integer *n* and will calculate and return the product of the odd integers from 1 to *n* (or from 1 to *n-1* if *n* is even). Use a **for** loop.
7. Write a script that will:
    - generate a random integer in the inclusive range from 2 to 5.
    - loop that many times to
        - prompt the user for a number.
        - print the sum of the numbers entered so far with one decimal place.
8. Write a script that will load data from a file into a matrix. Create the data file first, and make sure that there is the same number of values on every line in the file so that it can be loaded into a matrix. Using a **for** loop, it will then create a subplot for every row in the matrix, and will plot the numbers from each row element in the Figure Window. Create an overall title using **sgtitle**.
9. Write code that will prompt the user for five numbers, and store them in a vector. Make sure that you preallocate the vector!
10. With a matrix, when would:
    - your outer loop be over the rows?
    - your outer loop be over the columns?
    - it not matter which is the outer and which is the inner loop?

11. Write a function *myones* that will receive two input arguments *n* and *m* and will return an *nxm* matrix of all ones. Do NOT use any built-in functions (so, yes, the code will be inefficient).
12. Write a script that will print the following multiplication table:

```
1
2    4
3    6    9
4    8    12    16
```

13. Write a function that will receive a matrix as an input argument, and will calculate and return the overall average of all numbers in the matrix. Use loops, not built-in functions, to calculate the average.
14. Trace this to determine the output, and then enter it to verify your answer.

```
fprintf('%d: ', i)
for j=i:-1:1
    fprintf('*')
end
fprintf('\n')
end
```

15. Write an algorithm for an ATM program. Think about where there would be selection statements, menus, loops (counted vs. conditional), and so forth, but do not write MATLAB code, just an algorithm (pseudo-code).
16. Trace this to figure out what the result will be, and then type it into MATLAB to verify the results.

Ch5Ex16.m

```
count=0;
number=8;
while number > 3
    fprintf('number is %d\n', number)
    number=number-2;
    count=count+1;
end
fprintf('count is %d\n', count)
```

17. Write a script that will generate random integers in the range from 0 to 50, and print them, until one is finally generated that is greater than 25. The script should print how many attempts it took.
18. The inverse of the mathematical constant *e* can be approximated as follows:

$$\frac{1}{e} \approx \left(1-\frac{1}{n}\right)^{n}$$

Write a script that will loop through values of *n* until the difference between the approximation and the actual value is less than 0.0001. The script should then print out the built-in value of e^{-1} and the approximation to four decimal places, and also print the value of *n* required for such accuracy.

19. Write a script will prompt the user for a keyword in MATLAB, error-checking until a keyword is entered.
20. A blizzard is a massive snowstorm. Definitions vary, but for our purposes we will assume that a blizzard is characterized by both winds of 30 mph or higher and blowing snow that leads to visibility of 0.5 miles or less, sustained for at least four hours. Data from a storm one day have been stored in a file *stormtrack.dat*. There are 24 lines in the file, one for each hour of the day. Each line in the file has the wind speed and visibility at a location. Create a sample data file. Read this data from the file and determine whether blizzard conditions were met during this day or not.
21. For the following code, explain under what circumstance(s) the action of the while loop would be skipped:

```
num=input('Enter a number: ');
while num >= 0
    fprintf('You entered a %.1f!\n', num)
    num=input('Enter a number: ');
end
disp('That is all.')
```

22. Explain why the following code would result in an infinite loop and give an example of how this could be fixed.

```
value=3;

while value < 6
    fprintf('value is %d\n', value)
end
```

23. Write a script called *prtemps* that will prompt the user for a maximum Celsius value in the range from −16 to 20; error-check to make sure it is in that range. Then, print a table showing degrees Fahrenheit and degrees Celsius until this maximum is reached. The first value that exceeds the maximum should not be printed. The table should start at 0 degrees Fahrenheit, and increment by 5 degrees Fahrenheit until the max (in Celsius) is reached. Both temperatures should be printed with a field width of 6 and one decimal place. The formula is $C = 5/9\ (F-32)$.
24. Vectorize the following codes. Write one statement that would accomplish the same end result. Assume that *v* is a vector variable that has been initialized.

```
for i=1:length(v)
    newv(i)=sqrt(v(i));
end
newv % Just for display
```

25. The following code was written by somebody who does not know how to use MATLAB efficiently. Rewrite this as a single statement that will accomplish exactly the same thing for a matrix variable *mat* (e.g., vectorize this code):

```
[r c]=size(mat);
for i=1:r
    for j=1:c
        mat(i,j)=mat(i,j)*2;
    end
end
```

26. Vectorize the following code. Write one statement that would accomplish the same end result. Assume that *mata* is a matrix variable that has been initialized.

```
[r c]=size(mata);
for j=1:c
   runsum=0;
   for i=1:r
      runsum=runsum+mata(i,j);
   end
   resvec(j)=runsum;
end
resvec % Just for display
```

27. Unvectorize the following code! Write code, including a nested for loop, that will accomplish the same end result. You may assume that the variable mat has been initialized to be a matrix of numbers.

```
result=mat+2
```

28. Give some examples of when you would need to use a counted loop in MATLAB, and when you would not.
29. For each of the following, decide whether you would use a **for** loop, a **while** loop, a nested loop (and if so what kind, e.g., a **for** loop inside of another **for** loop, a **while** loop inside of a **for** loop, etc.), or no loop at all.
    - sum the integers 1 through 50:
    - add 3 to all numbers in a vector:
    - prompt the user for a string, and keep doing this until the string that the user enters is a keyword in MATLAB:
    - find the minimum in every column of a matrix:
    - prompt the user for 5 numbers and find their sum:
    - prompt the user for 10 numbers, find the average and also find how many of the numbers were greater than the average:
    - generate a random integer n in the range from 10 to 20. Prompt the user for n positive numbers, error-checking to make sure you get n positive numbers (and just echo print each one):
    - prompt the user for positive numbers until the user enters a negative number. Calculate and print the average of the positive numbers, or an error message if none are entered:
30. Write a script that will prompt the user for a number in the inclusive range from 1 to 10 and error-check until the user enters a number in the correct range. Each time the user enters an invalid number, it prints whether it is too low or too high. It then prints the valid number.

31. The Wind Chill Factor (WCF) measures how cold it feels with a given air temperature T (in degrees Fahrenheit) and wind speed V (in miles per hour). One formula for WCF is

    $$\mathrm{WCF} = 35.7 + 0.6\,\mathrm{T} - 35.7\left(\mathrm{V}^{0.16}\right) + 0.43\,\mathrm{T}\left(\mathrm{V}^{0.16}\right)$$

    Write a function to receive the temperature and wind speed as input arguments, and return the WCF. Using loops, print a table showing wind chill factors for temperatures ranging from −20 to 55 in steps of 5, and wind speeds ranging from 0 to 55 in steps of 5. Call the function to calculate each wind chill factor.
32. Instead of printing the WCFs in the previous problem, create a matrix of WCFs and write them to a file.
33. Write a script to add two 30-digit numbers and print the result. This is not as easy as it might sound at first, because integer types may not be able to store a value this large. One way to handle large integers is to store them in vectors, where each element in the vector stores a digit of the integer. Your script should initialize two 30-digit integers, storing each in a vector, and then add these integers, also storing the result in a vector. Create the original numbers using the **randi** function. Hint: add two numbers on paper first, and pay attention to what you do!
34. Write a "Guess My Number Game" program. The program generates a random integer in a specified range, and the user (the player) has to guess the number. The program allows the use to play as many times as they would like; at the conclusion of each game, the program asks whether the player wants to play again.

    The basic algorithm is:

    1. The program starts by printing instructions on the screen.
    2. For every game:
        - the program generates a new random integer in the range from MIN to MAX. Treat MIN and MAX like constants; start by initializing them to 1 and 100
        - loop to prompt the player for a guess until the player correctly guesses the integer
            - for each guess, the program prints whether the player's guess was too low, too high, or correct
        - at the conclusion (when the integer has been guessed):
            - print the total number of guesses for that game
            - print a message regarding how well the player did in that game (e.g., the player took way too long to guess the number, the player was awesome, etc.). To do this, you will have to decide on ranges for your messages and give a rationale for your decision in a comment in the program.
    3. After all games have been played, print a summary showing the average number of guesses.

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35. How many possible permutations are there for character vectors? For example, a character vector that stores 'A' and 'B' could be 'AB' or 'BA'. What about 3 characters, or 4?
36. Create a character vector variable as follows:

    ```
    >> word='AALMTB';
    ```

    Use the **randperm** function to randomly scramble the characters, and store the result in a variable 'newword', for example:

    ```
    newword=
        'TALMBA'
    ```

    Now put this in a loop! 20 times, randomly scramble the characters and display the results. Did you get 'MATLAB'?

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CHAPTER 6

MATLAB Programs

KEY TERMS

functions that return more than one value
functions that do not return any values
side effects
call-by-value
modular programs
main program
main function
local function
subfunction
menu-driven
variable scope
base workspace
local variable
global variable
persistent variable
declaring variables
bug
debugging
syntax errors
runtime errors
logical errors
tracing
breakpoints
breakpoint alley
function stubs
code cells

CONTENTS

Chapter 3 introduced scripts, live scripts, and user-defined functions. In that chapter, we saw how to write scripts, which are sequences of statements that are stored in MATLAB® code files and then executed. We also saw how to write user-defined functions, also stored in MATLAB code files (either in their own or in scripts) that calculate and return a single value. In this chapter, we will expand on these concepts and introduce other kinds of user-defined functions. We will show how MATLAB programs consist of combinations of scripts and user-defined functions. The mechanisms for interactions of variables in code files and the Command Window will be explored. Techniques for finding and fixing mistakes in programs will be reviewed. Finally, the use of tasks in live scripts and using code cells in scripts will be introduced.

6.1 MORE TYPES OF USER-DEFINED FUNCTIONS

We have already seen how to write a user-defined function that calculates and returns one value. This is just one type of function. It is also possible to have ***functions that return more than one value***, and ***functions that do not return any values***. We will categorize functions as follows:

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00006-8

- Functions that calculate and return one value
- Functions that calculate and return more than one value
- Functions that just accomplish a task, such as printing, without returning any values

Thus, although many functions calculate and return values, some do not. Instead, some functions just accomplish a task. There are differences between these three types of functions, including the format of the function headers and also the way in which the functions are called. Regardless of what kind of function it is, all functions must be defined, and all function definitions consist of the ***header*** and the ***body***. Also, the function must be called for it to be utilized. Although functions can be stored in script code files, for now we will concentrate on functions that are stored in their own code files with an extension of .m.

In general, any function in MATLAB consists of the following:

- The function header (the first line); this has:
  - the reserved word **function**
  - if the function ***returns*** values, the name(s) of the output argument(s), followed by the assignment operator (=)
  - the name of the function (important: this should be the same as the name of the file in which this function is stored to avoid confusion)
  - the input arguments in parentheses, if there are any (separated by commas if there is more than one).
- A comment that describes what the function does (this is printed if **help** is used).
- The body of the function, which includes all statements, including putting values in all output arguments if there are any.
- **end** at the end of the function.

6.1.1 Functions That Return More Than One Value

Functions that return one value have one output argument, as we saw previously. Functions that return more than one value must, instead, have more than one output argument in the function header in square brackets. That means that in the body of the function, values must be put in all output arguments listed in the function header. The general form of a function definition for a function that calculates and returns more than one value looks like this:

```
functionname.m
```

```
function [output arguments]=functionname(input arguments)
% Comment describing the function
% Format of function call

Statements here; these must include putting values in all of the
output arguments listed in the header
end
```

In the vector of output arguments, the output argument names are by convention separated by commas.

Choosing New, then Function brings up a template in the Editor that can then be filled in. If this is not desired, it may be easier to start with New Script.

For example, here is a function that calculates two values, both the area and the circumference of a circle; this is stored in a file called *areacirc.m*:

```
areacirc.m
```

```
function [area, circum]=areacirc(rad)
% areacirc returns the area and
% the circumference of a circle
% Format: areacirc(radius)

area=pi * rad .* rad;
circum=2 * pi * rad;
end
```

Because this function is calculating two values, there are two output arguments in the function header (*area* and *circum*), which are placed in square brackets [ ]. Therefore, somewhere in the body of the function, values have to be stored in both.

Because the function is returning two values, it is important to capture and store these values in separate variables when the function is called. In this case, the first value returned, the area of the circle, is stored in a variable *a* and the second value returned is stored in a variable *c*:

Note

that in capturing the values the order matters. In this example, the function first returns the area and then the circumference of the circle. The order in which values are assigned to the output arguments within the function, however, does not matter.

```
>> [a, c]=areacirc(4)
a =
    50.2655
c =
    25.1327
```

If this is not done, only the first value returned is retained, in this case, the area:

```
>> disp(areacirc(4))
   50.2655
```

QUICK QUESTION!

What would happen if a vector of radii was passed to the function?

Answer: As the .* operator is used in the function to multiply *rad* by itself, a vector can be passed to the input argument *rad*. Therefore, the results will also be vectors, so the variables on the left side of the assignment operator would become vectors of areas and circumferences.

```
>> [a, c]=areacirc(1:4)
a =
   3.1416    12.5664    28.2743    50.2655
c =
   6.2832    12.5664    18.8496    25.1327
```

QUICK QUESTION!

What if you want only the second value that is returned?

Answer: Function outputs can be ignored using the tilde:

```
>> [~, c]=areacirc(1:4)
c =
    6.2832    12.5664    18.8496    25.1327
```

The **help** function shows the comment listed under the function header:

```
>> help areacirc
  This function calculates the area and
  the circumference of a circle
  Format: areacirc(radius)
```

The *areacirc* function could be called from the Command Window, as has been shown, or from a script. Here is a script that will prompt the user for the radius of just one circle, call the *areacirc* function to calculate and return the area and circumference of the circle, and print the results:

calcareacirc.m

```
% This script prompts the user for the radius of a circle,
%  calls a function to calculate and return both the area
%  and the circumference, and prints the results
% It ignores units and error-checking for simplicity

radius=input('Please enter the radius of the circle: ');
[area, circ]=areacirc(radius);
fprintf('For a circle with a radius of %.1f,\n', radius)
fprintf('the area is %.1f and the circumference is %.1f\n',...
    area, circ)
```

```
>> calcareacirc
Please enter the radius of the circle: 5.2
For a circle with a radius of 5.2,
the area is 84.9 and the circumference is 32.7
```

PRACTICE 6.1

Write a function *perimarea* that calculates and returns the perimeter and area of a rectangle. Pass the length and width of the rectangle as input arguments. For example, this function might be called from the following script:

calcareaperim.m

```
% Prompt the user for the length and width of a rectangle,
%  call a function to calculate and return the perimeter
%  and area, and print the result
% For simplicity it ignores units and error-checking

length=input('Please enter the length of the rectangle: ');
width=input('Please enter the width of the rectangle: ');
[perim, area]=perimarea(length, width);
fprintf('For a rectangle with a length of %.1f and a', length)
fprintf(' width of %.1f,\nthe perimeter is %.1f,', width, perim)
fprintf(' and the area is %.1f\n', area)
```

As another example, consider a function that calculates and returns three output arguments. The function receives one input argument representing a total number of seconds and returns the number of hours, minutes, and remaining seconds that it represents. For example, 7515 total seconds is 2 hours, 5 minutes, and 15 seconds because $7515 = 3600 * 2 + 60 * 5 + 15$.

The algorithm is as follows.

- Divide the total seconds by 3600, which is the number of seconds in an hour. For example, 7515/3600 is 2.0875. The integer part is the number of hours (e.g., 2).
- The remainder of the total seconds divided by 3600 is the remaining number of seconds; it is useful to store this in a local variable.
- The number of minutes is the remaining number of seconds divided by 60 (again, the integer part).
- The number of seconds is the remainder of the previous division.

breaktime.m

```
function [hours, minutes, secs]=breaktime(totseconds)
% breaktime breaks a total number of seconds into
% hours, minutes, and remaining seconds
% Format: breaktime(totalSeconds)

hours=floor(totseconds/3600);
remsecs=rem(totseconds, 3600);
minutes=floor(remsecs/60);
secs=rem(remsecs,60);
end
```

An example of calling this function is:

```
>> [h, m, s] = breaktime(7515)
h =
     2
m =
     5
s =
    15
```

As before, it is important to store all values that the function returns by using three separate variables on the left of the assignment.

6.1.2 Functions That Accomplish a Task Without Returning Values

Many functions do not calculate values but rather accomplish a task, such as printing formatted output. Because these functions do not return any values, there are no output arguments in the function header.

The general form of a function definition for a function that does not return any values looks like this:

Note

what is missing in the function header: there are no output arguments and no assignment operator.

```
functionname.m
```

```
function functionname(input arguments)
% Comment describing the function

Statements here
end
```

For example, the following function just prints the two arguments, numbers, passed to it in a sentence format:

```
printem.m
```

```
function printem(a,b)
% printem prints two numbers in a sentence format
% Format: printem(num1, num2)

fprintf('The first number is %.1f and the second is %.1f\n',a,b)
end
```

As this function performs no calculations, there are no output arguments in the function header and no assignment operator (=). An example of a call to the *printem* function is:

```
>> printem(3.3, 2)
The first number is 3.3 and the second is 2.0
```

Note that, because the function does not return a value, it cannot be called from an assignment statement. Any attempt to do this would result in an error, such as the following:

```
>> x=printem(3, 5)  % Error!!
Error using printem
Too many output arguments.
```

We can therefore think of the call to a function that does not return values as a statement by itself, in that the function call cannot be imbedded in another statement such as an assignment statement or a statement that prints.

The tasks that are accomplished by functions that do not return any values (e.g., output from an **fprintf** statement or a **plot**) are sometimes referred to as ***side effects***. Some standards for commenting functions include putting the side effects in the block comment.

PRACTICE 6.2

Write a function that receives a vector as an input argument and prints the individual elements from the vector in a sentence format.

```
>> printvecelems([5.9 33 11])
Element 1 is 5.9
Element 2 is 33.0
Element 3 is 11.0
```

6.1.3 Functions That Return Values Versus Printing

A function that calculates and ***returns*** values (through the output arguments) does not normally also print them; that is left to the calling script or function. It is good programming practice to separate these tasks.

If a function just prints a value, rather than returning it, the value cannot be used later in other calculations. For example, here is a function that just prints the circumference of a circle:

calccircum1.m

```
function calccircum1(radius)
% calccircum1 displays the circumference of a circle
%   but does not return the value
% Format: calccircum1(radius)

disp(2*pi*radius)
end
```

Calling this function prints the circumference, but there is no way to store the value so that it can be used in subsequent calculations:

```
>> calccircum1(3.3)
   20.7345
```

Because no value is returned by the function, attempting to store the value in a variable would be an error:

```
>> c=calccircum1(3.3)
Error using calccircum1
Too many output arguments.
```

By contrast, the following function calculates and returns the circumference so that it can be stored and used in other calculations. For example, if the circle is the base of a cylinder, and we wish to calculate the surface area of the cylinder, we would need to multiply the result from the *calccircum2* function by the height of the cylinder.

calccircum2.m

```
function circle_circum=calccircum2(radius)
% calccircum2 calculates and returns the
%   circumference of a circle
% Format: calccircum2(radius)

circle_circum=2*pi*radius;
end
```

```
>> circumference=calccircum2(3.3)
circumference=
   20.7345

>> height=4;
>> surf_area=circumference*height
surf_area=
    82.9380
```

One possible exception to this rule of not printing when returning is to have a function return a value if possible but throw an error if not.

6.1.4 Passing Arguments to Functions

In all function examples presented thus far, at least one argument was passed in the function call to be the value(s) of the corresponding input argument(s) in the function header. The ***call-by-value*** method is the term for this method of passing the values of the arguments to the input arguments in the functions.

In some cases, however, it is not necessary to pass any arguments to the function. Consider, for example, a function that simply prints a random real number with two decimal places:

```
printrand.m
```

```
function printrand()
% printrand prints one random number
% Format: printrand or printrand()

fprintf('The random # is %.2f\n',rand)
end
```

Here is an example of calling this function:

```
>> printrand()
The random # is 0.94
```

As nothing is passed to the function, there are no arguments in the parentheses in the function call and none in the function header, either. The parentheses are not even needed in either the function or the function call. The following works as well:

```
printrandnp.m
```

```
function printrandnp
% printrandnp prints one random number
% Format: printrandnp or printrandnp()

fprintf('The random # is %.2f\n',rand)
end
```

```
>> printrandnp
The random # is 0.52
```

In fact, the function can be called with or without empty parentheses, whether or not there are empty parentheses in the function header.

This was an example of a function that did not receive any input arguments, nor did it return any output arguments; it simply accomplished a task.

The following is another example of a function that does not receive any input arguments, but, in this case, it does return a value. The function prompts the user for a string (meaning, actually, a character vector) and returns the value entered.

```
stringprompt.m
```

```
function outstr=stringprompt
% stringprompt prompts for a string and returns it
% Format stringprompt or stringprompt()

disp('When prompted, enter a string of any length.')
outstr=input('Enter the string here: ', 's');
end
```

```
>> mystring=stringprompt
When prompted, enter a string of any length.
Enter the string here: Hi there

mystring=
    'Hi there'
```

PRACTICE 6.3

Write a function that will prompt the user for a string of at least one character, loop to error-check to make sure that the string has at least one character, and return it as a character vector.

QUICK QUESTION!

It is important that the number of arguments passed in the call to a function must be the same as the number of input arguments in the function header, even if that number is zero. Also, if a function returns more than one value, it is important to "capture" all values by having an equivalent number of variables in a vector on the left side of an assignment statement. Although it is not an error if there are not enough variables, some of the values returned will be lost. The following question is posed to highlight this.

Given the following function header (note that this is just the function header, not the entire function definition):

```
function [outa, outb]=qq1(x, y, z)
```

Which of the following proposed calls to this function would be valid?

```
a) [var1, var2]=qq1(a, b, c);

b) answer=qq1(3, y, q);

c) [a, b]=myfun(x, y, z);

d) [outa, outb]=qq1(x, z);
```

Answer: The first proposed function call, (a), is valid. There are three arguments that are passed to the three input arguments in the function header, the name of the function is *qq1*, and there are two variables in the assignment statement to store the two values returned from the function. Function call (b) is valid, although only the first value returned from the function would be stored in *answer*; the second value would be lost. Function call (c) is invalid because the name of the function is given incorrectly. Function call (d) is invalid because only two arguments are passed to the function, but there are three input arguments in the function header.

6.2 MATLAB PROGRAM ORGANIZATION

Typically, a MATLAB program consists of a script that calls functions to do the actual work.

6.2.1 Modular Programs

A ***modular program*** is a program in which the solution is broken down into modules, and each is implemented as a function. The script that calls these functions is typically called the ***main program***.

To demonstrate the concept, we will use the very simple example of calculating the area of a circle. In Section 6.3, a much longer example will be given. For this example, there are three steps in the algorithm to calculate the area of a circle:

- Get the input (the radius)
- Calculate the area
- Display the results

In a modular program, there would be one main script (or, possibly a function instead) that calls three separate functions to accomplish these tasks:

- A function to prompt the user and read in the radius
- A function to calculate and return the area of the circle
- A function to display the results

Assuming that each is stored in a separate code file, there would be four separate code files altogether for this program; one script file and three function code files, as follows:

calcandprintarea.m

```
% This is the main script to calculate the
%   area of a circle
% It calls 3 functions to accomplish this
radius=readradius;
area=calcarea(radius);
printarea(radius,area)
```

readradius.m

```
function radius=readradius
% readradius prompts the user and reads the radius
% Ignores error-checking for now for simplicity
% Format: readradius or readradius()

disp('When prompted, please enter the radius in inches.')
radius=input('Enter the radius: ');
end
```

calcarea.m

```
function area=calcarea(rad)
% calcarea returns the area of a circle
% Format: calcarea(radius)

area=pi*rad .* rad;
end
```

```
printarea.m
```

```
function printarea(rad,area)
% printarea prints the radius and area
% Format: printarea(radius, area)

fprintf('For a circle with a radius of %.2f inches,\n',rad)
fprintf('the area is %.2f inches squared.\n',area)
end
```

When the program is executed, the following steps will take place:

- the script *calcandprintarea* begins executing
- *calcandprintarea* calls the *readradius* function
    - *readradius* executes and returns the radius
- *calcandprintarea* resumes executing and calls the *calcarea* function, passing the radius to it
    - *calcarea* executes and returns the area
- *calcandprintarea* resumes executing and calls the *printarea* function, passing both the radius and the area to it
    - *printarea* executes and prints
- the script finishes executing

Running the program would be accomplished by typing the name of the script; this would call the other functions:

```
>> calcandprintarea
When prompted, please enter the radius in inches.
Enter the radius: 5.3
For a circle with a radius of 5.30 inches,
the area is 88.25 inches squared.
```

Note how the function calls and the function headers match up. For example:

readradius function:

```
function call: radius=readradius;
function header: function radius=readradius
```

In the *readradius* function call, no arguments are passed so there are no input arguments in the function header. The function returns one output argument so that is stored in one variable.

calcarea function:

```
function call: area=calcarea(radius);
function header: function area=calcarea(rad)
```

In the *calcarea* function call, one argument is passed in parentheses so there is one input argument in the function header. The function returns one output argument so that is stored in one variable.

printarea function:

```
function call: printarea(radius,area)
function header: function printarea(rad,area)
```

In the *printarea* function call, there are two arguments passed, so there are two input arguments in the function header. The function does not return anything, so the call to the function is a statement by itself; it is not in an assignment or output statement.

PRACTICE 6.4

Modify the *readradius* function to error-check the user's input to make sure that the radius is valid. The function should ensure that the radius is a positive number by looping to print an error message until the user enters a valid radius.

6.2.2 Local Functions

Thus far, every function has been stored in a separate code file. However, it is possible to have more than one function in a given file. For example, if one function calls another, the first (calling) function would be the ***main function*** and the function that is called is a ***local function***, or sometimes a ***subfunction***. These functions would both be stored in the same code file, first the main function and then the local function. The name of the code file would be the same as the name of the main function, to avoid confusion.

To demonstrate this, a program that is similar to the previous one, but calculates and prints the area of a rectangle, is shown here. The script first calls a function that reads the length and width of the rectangle, and then calls a function to print the results. This function calls a local function to calculate the area.

rectarea.m

```
% This program calculates & prints the area of a rectangle

% Call a fn to prompt the user & read the length and width
[length, width]=readlenwid;
% Call a fn to calculate and print the area
printrectarea(length, width)
```

readlenwid.m

```
function [l,w]=readlenwid
% readlenwid reads & returns the length and width
% Format: readlenwid or readlenwid()

l = input('Please enter the length: ');
w = input('Please enter the width: ');
end
```

printrectarea.m

```
function printrectarea(len, wid)
% printrectarea prints the rectangle area
% Format: printrectarea(length, width)

% Call a local function to calculate the area
area = calcrectarea(len,wid);
fprintf('For a rectangle with a length of %.2f\n',len)
fprintf('and a width of %.2f, the area is %.2f\n', ...
   wid, area);

end

function area=calcrectarea(len, wid)
% calcrectarea returns the rectangle area
% Format: calcrectarea(length, width)
area = len * wid;
end
```

An example of running this program follows:

```
>> rectarea
Please enter the length: 6
Please enter the width: 3
For a rectangle with a length of 6.00
and a width of 3.00, the area is 18.00
```

Note how the function calls and function headers match up. For example:

readlenwid function:

```
function call: [length, width]=readlenwid;
function header: function [l,w]=readlenwid
```

In the *readlenwid* function call, no arguments are passed so there are no input arguments in the function header. The function returns two output arguments so there is a vector with two variables on the left side of the assignment statement in which the function is called.

printrectarea function:

```
function call: printrectarea(length, width)
function header: function printrectarea(len, wid)
```

In the *printrectarea* function call, there are two arguments passed, so there are two input arguments in the function header. The function does not return anything, so the call to the function is a statement by itself; it is not in an assignment or output statement.

calcrectarea local function:

```
function call: area=calcrectarea(len,wid);
function header: function area=calcrectarea(len, wid)
```

In the *calcrectarea* function call, two arguments are passed in parentheses so there are two input arguments in the function header. The function returns one output argument so that is stored in one variable.

The **help** command can be used with the script *rectarea*, the function *readlenwid*, and with the main function, *printrectarea*. To view the first comment in the local function, as it is contained within the *printrectarea.m* file, the operator > is used to specify both the main and local functions:

```
>> help rectarea
  This program calculates & prints the area of a rectangle

>> help printrectarea
  printrectarea prints the rectangle area
  Format: printrectarea(length, width)

>> help printrectarea>calcrectarea
  calcrectarea returns the rectangle area
  Format: calcrectarea(length, width)
```

So, local functions can be in script code files, and also in function code files.

PRACTICE 6.5

For a right triangle with sides *a*, *b*, and *c*, where *c* is the hypotenuse and θ is the angle between sides a and c, the lengths of sides *a* and *b* are given by:

```
a  =c*cos(θ)
b  =c*sin(θ)
```

Write a script *righttri* that calls a function to prompt the user and read in values for the hypotenuse and the angle (in radians), and then calls a function to calculate and return the lengths of sides *a* and *b*, and a function to print out all values in a sentence format. For simplicity, ignore units. Here is an example of running the script; the output format should be exactly as shown here:

```
>> righttri
Enter the hypotenuse: 5
Enter the angle: .7854
For a right triangle with hypotenuse 5.0
 and an angle 0.79 between side a & the hypotenuse,
 side a is 3.54 and side b is 3.54
```

For extra practice, do this using two different program organizations:

- One script that calls three separate functions, each stored in separate code files
- One script that calls two functions; the function that calculates the lengths of the sides will be a local function to the function that prints

6.3 APPLICATION: MENU-DRIVEN MODULAR PROGRAM

Many longer, more involved programs that interact with the user are ***menu-driven***, which means that the program prints a menu of choices and then continues to loop to print the menu of choices until the user chooses to end the program. A modular menu-driven program would typically have a function that presents the menu and gets the user's choice, as well as functions to implement the action for each choice. These functions may have local functions. Also, the functions would error-check all user input.

As an example of such a menu-driven program, we will write a program to explore the constant *e*.

The constant *e*, called the natural exponential base, is used extensively in mathematics and engineering. There are many diverse applications of this constant. The value of the constant *e* is approximately 2.7183... Raising *e* to the power of x, or e^x, is so common that this is called the exponential function. In MATLAB, as we have seen, there is a function for this, **exp**.

One way to determine the value of *e* is by finding a limit.

$$e = \lim_{n \to \infty} \left(1 + \frac{1}{n}\right)^n$$

As the value of *n* increases toward infinity, the result of this expression approaches the value of *e*.

An approximation for the exponential function can be found using what is called a Maclaurin series:

$$e^x \approx 1 + \frac{x^1}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$

We will write a program to investigate the value of *e* and the exponential function. It will be menu-driven. The menu options will be:

- Print an explanation of *e*.
- Prompt the user for a value of *n* and then find an approximate value for *e* using the expression $(1+1/n)^n$.
- Prompt the user for a value for *x*. Print the value of **exp(x)** using the built-in function. Find an approximate value for e^x using the Maclaurin series just given.
- Exit the program.

The algorithm for the script main program follows:

- Call a function *eoption* to display the menu and return the user's choice.
- Loop until the user chooses to exit the program. If the user has not chosen to exit, the action of the loop is to:

- Depending on the user's choice, do one of the following:
    - Call a function *explaine* to print an explanation of *e*.
    - Call a function *limite* that will prompt the user for *n* and calculate an approximate value for *e*
    - Prompt the user for *x* and call a function *expfn* that will print both an approximate value for e^x and the value of the built-in **exp(x)**. Note that because any value for *x* is acceptable, the program does not need to error-check this value.
- Call the function *eoption* to display the menu and return the user's choice again.

The algorithm for the *eoption* function follows:

- Display the four choices.
- Error-check by looping to display the menu until the user chooses one of the four options.
- Return the integer value corresponding to the choice.

The algorithm for the *explaine* function is:

- Print an explanation of *e*, the **exp** function, and how to find approximate values.

The algorithm for the *limite* function is:

- Call a local function *askforn* to prompt the user for an integer *n*.
- Calculate and print the approximate value of *e* using *n*.

The algorithm for the local function *askforn* is:

- Prompt the user for a positive integer for *n*.
- Loop to print an error message and reprompt until the user enters a positive integer.
- Return the positive integer *n*.

The algorithm for the *expfn* function is:

- Receive the value of *x* as an input argument.
- Print the value of **exp(x)**.
- Assign an arbitrary value for the number of terms *n* (an alternative method would be to prompt the user for this).
- Call a local function *appex* to find an approximate value of **exp(x)** using a series with *n* terms.
- Print this approximate value.

The algorithm for the local function *appex* is:

- Receive *x* and *n* as input arguments.
- Initialize a variable for the running sum of the terms in the series (to 1 for the first term) and for a running product that will be the factorials in the denominators.

- Loop to add the *n* terms to the running sum.
- Return the resulting sum.

The entire program consists of the following script file and four function code files:

eapplication.m

```
% This script explores e and the exponential function

% Call a function to display a menu and get a choice
choice=eoption;

% Choice 4 is to exit the program
while choice ~= 4
   switch choice
       case 1
           % Explain e
           explaine;
       case 2
           % Approximate e using a limit
           limite;
       case 3
           % Approximate exp(x) and compare to exp
           x=input('Please enter a value for x: ');
           expfn(x);
   end
   % Display menu again and get user's choice
   choice=eoption;
end
```

eoption.m

```
function choice=eoption
% eoption prints a menu of options and error-checks
%  until the user chooses one of the options
% Format: eoption or eoption()

printchoices
choice=input('');
while ~any(choice==1:4)
    disp('Error - please choose one of the options.')
    printchoices
    choice=input('');
end
end

function printchoices
fprintf('Please choose an option:\n\n');
fprintf('1) Explanation\n')
fprintf('2) Limit\n')
fprintf('3) Exponential function\n')
fprintf('4) Exit program\n\n')
end
```

explaine.m

```
function explaine
% explaine explains a little bit about e
% Format: explaine or explaine()

fprintf('The constant e is called the natural')
fprintf(' exponential base.\n')
fprintf('It is used extensively in mathematics and')
fprintf(' engineering.\n')
fprintf('The value of the constant e is ~ 2.7183\n')
fprintf('Raising e to the power of x is so common that')
fprintf(' this is called the exponential function.\n')
fprintf('An approximation for e is found using a limit.\n')
fprintf('An approximation for the exponential function')
fprintf(' can be found using a series.\n')
end
```

limite.m

```
function limite
% limite returns an approximate of e using a limit
% Format: limite or limite()

% Call a local function to prompt user for n
n = askforn;
fprintf('An approximation of e with n=%d is %.2f\n', ...
    n, (1+1/n) ^ n)
end

function outn=askforn
% askforn prompts the user for n
% Format askforn or askforn()
% It error-checks to make sure n is a positive integer

inputnum=input('Enter a positive integer for n: ');
num2=int32(inputnum);
while num2 ~= inputnum || num2 < 0
   inputnum=input('Invalid! Enter a positive integer:');
   num2=int32(inputnum);
end
outn=inputnum;
end
```

```
expfn.m
```

```
function expfn(x)
% expfn compares the built-in function exp(x)
%  and a series approximation and prints
% Format expfn(x)

fprintf('Value of built-in exp(x) is %.2f\n',exp(x))

% n is arbitrary number of terms
n = 10;
fprintf('Approximate exp(x) is %.2f\n', appex(x,n))
end

function outval=appex(x,n)
% appex approximates e to the x power using terms up to
%  x to the nth power
% Format appex(x,n)

% Initialize the running sum in the output argument
% outval to 1 (for the first term)
outval=1;

for i=1:n
   outval=outval+(x^i)/factorial(i);
end
end
```

Running the script will bring up the menu of options.

```
>> eapplication
Please choose an option:

1) Explanation
2) Limit
3) Exponential function
4) Exit program
```

Then, what happens will depend on which option(s) the user chooses. Every time the user chooses, the appropriate function will be called and then this menu will appear again. This will continue until the user chooses 4 for ‘Exit Program’. Examples will be given of running the script, with different sequences of choices.

In the following example, the user

- Chose 1 for ‘Explanation’.
- Chose 4 for ‘Exit Program’.

```
>> eapplication
Please choose an option:
```

```
1) Explanation
2) Limit
3) Exponential function
4) Exit program

1
The constant e is called the natural exponential base.
It is used extensively in mathematics and engineering.
The value of the constant e is ~ 2.7183
Raising e to the power of x is so common that this is called the
exponential function.
An approximation for e is found using a limit.
An approximation for the exponential function can be found using a
series.
Please choose an option:

1) Explanation
2) Limit
3) Exponential function
4) Exit program

4
```

In the following example, the user

- Chose 2 for 'Limit'.
  - When prompted for *n*, entered two invalid values before finally entering a valid positive integer.
- Chose 4 for 'Exit Program'.

```
>> eapplication
Please choose an option:

1) Explanation
2) Limit
3) Exponential function
4) Exit program

2
Enter a positive integer for n:-4
Invalid! Enter a positive integer: 5.5
Invalid! Enter a positive integer: 10
An approximation of e with n=10 is 2.59
Please choose an option:

1) Explanation
2) Limit
3) Exponential function
4) Exit program

4
```

To see the difference in the approximate value for *e* as *n* increases, the user kept choosing 2 for 'Limit', and entering larger and larger values each time in the following example (the menu is not shown for simplicity):

```
>> eapplication
Enter a positive integer for n: 4
An approximation of e with n=4 is 2.44
Enter a positive integer for n: 10
An approximation of e with n=10 is 2.59
Enter a positive integer for n: 30
An approximation of e with n=30 is 2.67
Enter a positive integer for n: 100
An approximation of e with n=100 is 2.70
```

In the following example, the user

- Chose 3 for 'Exponential function'.
    - When prompted, entered 4.6 for x.
- Chose 3 for 'Exponential function' again.
    - When prompted, entered -2.3 for x.
- Chose 4 for 'Exit Program'.

Again, for simplicity, the menu options and choices are not shown.

```
>> eapplication
Please enter a value for x: 4.6
Value of built-in exp(x) is 99.48
Approximate exp(x) is 98.71
Please enter a value for x:-2.3
Value of built-in exp(x) is 0.10
Approximate exp(x) is 0.10
```

6.4 VARIABLE SCOPE

The ***scope*** of any variable is the workspace in which it is valid. The workspace created in the Command Window is called the ***base workspace***.

As we have seen before, if a variable is defined in any function it is a ***local variable*** to that function, which means that it is only known and used within that function. Local variables only exist while the function is executing; they cease to exist when the function stops executing. For example, in the following function that calculates the sum of the elements in a vector, there is a local loop variable *i*.

mysum.m

```
function runsum=mysum(vec)
% mysum returns the sum of a vector
% Format: mysum(vector)

runsum=0;
for i=1:length(vec)
    runsum=runsum+vec(i);
end
end
```

Running this function does not add any variables to the base workspace, as demonstrated in the following:

```
>> clear
>> who
>> disp(mysum([5 9 1]))
    15
>> who
>>
```

In addition, variables that are defined in the Command Window cannot be used in a function (unless passed as arguments to the function).

However, scripts (as opposed to functions) *do* interact with the variables that are defined in the Command Window. For example, the previous function is changed to be a script *mysumscript*.

```
mysumscript.m
```

```
% This script sums a vector
vec=1:5;
runsum=0;
for i=1:length(vec)
    runsum=runsum+vec(i);
end
disp(runsum)
```

The variables defined in the script do become part of the base workspace:

```
>> clear
>> who
>> mysumscript
      15
>> who
Your variables are:
i       runsum  vec
```

Because variables created in scripts and in the Command Window both use the base workspace, many programmers begin scripts with a **clearvars** command to eliminate variables that may have already been created elsewhere (either in the Command Window or in another script).

Instead of a program consisting of a script that calls other functions to do the work, in some cases programmers will write a main function to call the other functions. Therefore, the program consists of all functions rather than one script and the rest functions. The reason for this is again because both scripts and the Command Window use the base workspace. By using only functions in a program, no variables are added to the base workspace.

It is possible, in MATLAB as well in other languages, to have ***global variables*** that can be shared by functions without passing them. Although there are some cases in which using **global** variables is efficient, it is generally regarded as poor programming style and therefore will not be explained further here.

6.4.1 Persistent Variables

Normally, when a function stops executing, the local variables from that function are cleared. That means that every time a function is called, memory is allocated and used while the function is executing but released when it ends. With variables that are declared as ***persistent variables***, however, the value is not cleared so the next time the function is called, the variable still exists and retains its former value.

The following program demonstrates this. The script calls a function *func1*, which initializes a variable *counter* to 0, increments it, and then prints the value. Every time this function is called, the variable is created, initialized to 0, changed to 1, and then cleared when the function exits. The script then calls a function *func2*, which first declares a **persistent** variable *counter*. If the variable has not yet been initialized, which will be the case the first time the function is called, it is initialized to 0. Then, like the first function, the variable is incremented and the value is printed. With the second function, however, the variable remains with its value when the function exits, so the next time the function is called the variable is incremented again.

persistex.m

```
% This script demonstrates persistent variables

% The first function has a variable "counter"
fprintf('This is what happens with a "normal" variable:\n')
func1
func1

% The second function has a persistent variable "counter"
fprintf('\nThis is what happens with a persistent variable:\n')
func2
func2
```

func1.m

```
function func1
% func1 increments a normal variable "counter"
% Format func1 or func1()

counter=0;
counter=counter+1;
fprintf('The value of counter is %d\n',counter)
end
```

func2.m

```
function func2
% func2 increments a persistent variable "counter"
% Format func2 or func2()

persistent counter % Declare the variable

if isempty(counter)
    counter=0;
end
counter=counter+1;
fprintf('The value of counter is %d\n',counter)
end
```

The line

```
persistent counter
```

***declares the variable** counter*, which allocates space for it but does not initialize it. The **if** statement then initializes it (the first time the function is called). In many languages, variables always have to be declared before they can be used; in MATLAB, this is true only for **persistent** variables.

The functions can be called from the script or from the Command Window, as shown. For example, the functions are called first from the script. With the **persistent** variable, the value of *counter* is incremented. Then, *func1* is called from the Command Window and *func2* is also called from the Command Window. As the value of the **persistent** variable had the value 2, this time it is incremented to 3.

```
>> persistex
This is what happens with a "normal" variable:
The value of counter is 1
The value of counter is 1

This is what happens with a persistent variable:
The value of counter is 1
The value of counter is 2

>> func1
The value of counter is 1

>> func2
The value of counter is 3
```

As can be seen from this, every time the function *func1* is called, whether from *persistex* or from the Command Window, the value of 1 is printed. However, with *func2*, the variable *counter* is incremented every time it is called. It is first called in this example from *persistex* twice, so *counter* is 1 and then 2. Then, when called from the Command Window, it is incremented to 3 (so it is counting how many times the function is called).

The way to restart a **persistent** variable is to use the **clear** function. The command

```
>> clear functions
```

will restart all **persistent** variables (see **doc clear** for more options). It is also possible to clear an individual function rather than all of them, for example,

```
>> clear func2
```

PRACTICE 6.6

The following function *posnum* prompts the user to enter a positive number and loops to error-check. It returns the positive number entered by the user. It calls a local function in the loop to print an error message. The local function has a **persistent** variable to count the number of times an error has occurred. Here is an example of calling the function:

```
>> enteredvalue=posnum
Enter a positive number:-5
Error # 1 ... Follow instructions!
Does-5.00 look like a positive number to you?
Enter a positive number:-33
Error # 2 ... Follow instructions!
Does-33.00 look like a positive number to you?
Enter a positive number: 6
enteredvalue=
     6
```

Fill in the local function below to accomplish this.

```
posnum.m
```

```
function num=posnum
% Prompt user and error-check until the
% user enters a positive number
% Format posnum or posnum()

num=input('Enter a positive number: ');
while num < 0
    errorsubfn(num)
    num=input('Enter a positive number: ');
end
end

function errorsubfn(num)
% Fill this in

end
```

Of course, the numbering of the error messages will continue if the function is executed again without clearing it first.

6.5 DEBUGGING TECHNIQUES

Any error in a computer program is called a ***bug***. This term is thought to date back to the 1940s, when a problem with an early computer was found to have been caused by a moth in the computer's circuitry! The process of finding errors in a program, and correcting them, is still called ***debugging***.

As we have seen, the **checkcode** function can be used to help find mistakes or potential problems in script and function files.

6.5.1 Types of Errors

There are several different kinds of errors that can occur in a program, which fall into the categories of ***syntax errors***, ***runtime errors***, and ***logical errors***.

Syntax errors are mistakes in using the language. Examples of syntax errors are missing a comma or a quotation mark, or misspelling a word. MATLAB itself will flag syntax errors and give an error message. For example, the following character vector is missing the end quote:

```
>> mystr='how are you;
mystr='how are you;
      ↑
Error: Character vector is not terminated properly.
```

If this type of error is typed in a script or function using the Editor, the Editor will flag it.

Another common mistake is to spell a variable name incorrectly; MATLAB will also catch this error. MATLAB will typically be able to correct this for you, as in the following:

```
>> value=5;
>> newvalue=valu+3;
Unrecognized function or variable 'valu'.

Did you mean:
>> newvalue=value+3;
```

Runtime, or execution-time, errors are found when a script or function is executing. With most languages, an example of a runtime error would be attempting to divide by zero. However, in MATLAB, this will return the constant Inf. Another example would be attempting to refer to an element in an array that does not exist.

```
runtimeEx.m
```

```
% This script shows an execution-time error

vec=3:5;

for i=1:4
    disp(vec(i))
end
```

The previous script initializes a vector with three elements but then attempts to refer to a fourth. Running it prints the three elements in the vector, and then an error message is generated when it attempts to refer to the fourth element.

Note that MATLAB explains the error, and it gives the line number in the script in which the error occurred.

```
>> runtimeEx
     3
     4
     5
Index exceeds the number of array elements (3).
Error in runtimeEx (line 6)
     disp(vec(i))
```

Logical errors are more difficult to locate because they do not result in any error message. A logical error is a mistake in reasoning by the programmer, but it is not a mistake in the programming language. An example of a logical error would be dividing by 2.54 instead of multiplying to convert inches to centimeters. The results printed or returned would be incorrect, but this might not be obvious.

All programs should be robust and should wherever possible anticipate potential errors, and guard against them. For example, whenever there is input into a program, the program should error-check and make sure that the input is in the correct range of values. Also, before dividing, any denominator should be checked to make sure that it is not zero. In Chapter 10, we will see that it is possible to validate function arguments, meaning making sure that they are the correct dimensions, types, and so forth.

Despite the best precautions, there are bound to be errors in programs.

6.5.2 Tracing

Many times, when a program has loops and/or selection statements and is not running properly, it is useful in the debugging process to know exactly which statements have been executed. For example, the following is a function that attempts to display "In middle of range" if the argument passed to it is in the range from 3 to 6, and "Out of range" otherwise.

testifelse.m

```
function testifelse(x)
% testifelse will test the debugger
% Format: testifelse(Number)

if 3 < x < 6
    disp('In middle of range')
else
    disp('Out of range')
end
end
```

However, it seems to print "In middle of range" for all values of *x*:

```
>> testifelse(4)
In middle of range

>> testifelse(7)
In middle of range

>> testifelse(-2)
In middle of range
```

One way of following the flow of the function, or ***tracing*** it, is to use the **echo** function. The **echo** function, which is a toggle, will display every statement as it is executed as well as results from the code. For scripts, just **echo** can be typed, but for functions, the name of the function must be specified. For example, the general form is

```
echo functionname on/off
```

For the *testifelse* function, it can be called as:

```
>> echo testifelse on
>> testifelse(-2)
function testifelse(x)
% testifelse will test the debugger
% Format: testifelse(Number)

if 3 < x < 6
    disp('In middle of range')
In middle of range
end
end
```

We can see from this result that the action of the **if** clause was executed.

6.5.3 Editor/Debugger

MATLAB has many useful functions for debugging, and debugging can also be done through its Editor, which is more properly called the Editor/Debugger.

Typing **doc debug** at the prompt in the Command Window will show some of the debugging functions. Also, in the Help Documentation, typing "debugging" in the Search Documentation will display basic information about the debugging processes.

It can be seen in the previous example that the action of the **if** clause was executed and it printed "In middle of range", but just from that it cannot be determined why this happened. There are several ways to set ***breakpoints*** in a file (script or function) so that the variables or expressions can be examined. These can be done from the Editor/Debugger or commands can be typed from the Command Window. For example, the following **dbstop** command will set a breakpoint in the sixth line of this function (which is the action of the **if** clause), which allows the values of variables and/or expressions to be examined at that point in the execution. The function **dbcont** can be used to continue the execution, and **dbquit** can be used to quit the debug mode.

Note

that the prompt becomes K>> in debug mode.

```
>> dbstop testifelse 6
>> testifelse(-2)
6       disp('In middle of range')
K>> x
x =
    -2

K>> 3 < x
ans =
     0

K>> 3 < x < 6
ans =
     1

K>> dbcont
    disp('In middle of range')
In middle of range
end
end
>>
```

By typing the expressions 3 < x and then 3 < x < 6, we can determine that the expression 3 < x will return either 0 or 1. Both 0 and 1 are less than 6, so the expression will always be **true**, regardless of the value of *x*! Once in the debug mode, instead of using **dbcont** to continue the execution, **dbstep** can be used to step through the rest of the code one line at a time. Also, in debug mode, hovering over a variable in the Editor will show the value of the variable.

Breakpoints can also be set and cleared through the Editor. When a file is open in the Editor, in between the line numbers on the left and the lines of code is a thin gray strip which is the ***breakpoint alley***. In this, there are underscore marks next to the executable lines of code (as opposed to comments, for example). Clicking the mouse in the alley next to a line will create a breakpoint at that line (and then clicking on the red dot that indicates a breakpoint will clear it). This can be seen in Fig. 6.1.

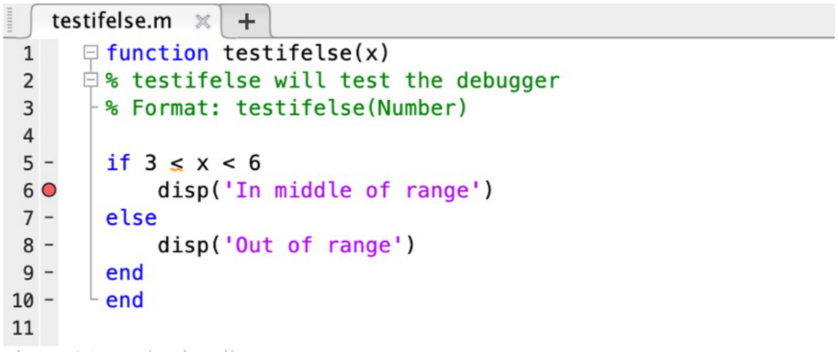
PRACTICE 6.7

The following script is bad code in several ways. Use **checkcode** first to check it for potential problems, and then use the techniques described in this section to set breakpoints and check values of variables.

debugthis.m

```
for i = 1:5
    i = 3;
    disp(i)
end

for j=2:4
    vec(j)=j
end
```



```
function testifelse(x)
% testifelse will test the debugger
% Format: testifelse(Number)

if 3 < x < 6
    disp('In middle of range')
else
    disp('Out of range')
end
end
```

FIGURE 6.1
Breakpoint alley.

6.5.4 Function Stubs

Another common debugging technique that is used when there is a script main program that calls many functions is to use ***function stubs***. A function stub is a place holder, used so that the script will work even though that particular function has not been written yet. For example, a programmer might start with a script main program which consists of calls to three functions that accomplish all of the tasks.

mainscript.m

```
% This program gets values for x and y, and
%   calculates and prints z

[x, y]=getvals;
z = calcz(x,y);
printall(x,y,z)
```

The three functions have not yet been written, however, so function stubs are put in place so that the script can be executed and tested. The function stubs consist of the proper function headers, followed by a simulation of what the function will eventually do. For example, the first two functions put arbitrary values in for the output arguments, and the last function prints.

getvals.m

```
function [x, y] = getvals
x = 33;
y = 11;
end
```

calcz.m

```
function z = calcz(x,y)
z = x+y;
end
```

printall.m

```
function printall(x,y,z)
disp(x)
disp(y)
disp(z)
end
```

Then, the functions can be written and debugged one at a time. It is much easier to write a working program using this method than to attempt to write everything at once. Then, when errors occur, it is not always easy to determine where the problem is!

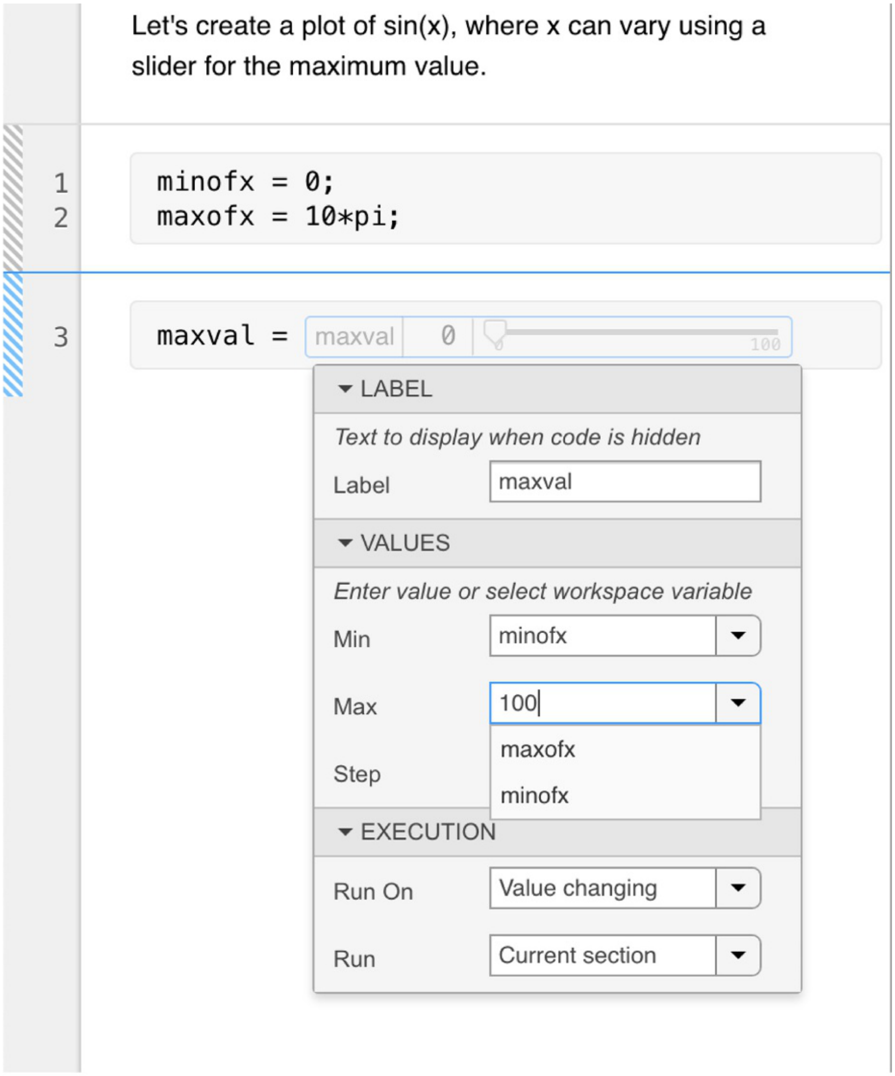
6.6 TASKS IN LIVE SCRIPTS, CODE CELLS, AND PUBLISHING CODE

6.6.1 Tasks in Live Scripts

In Chapter 3, we saw how to create simple live scripts using the Live Editor, which can contain text, equations, images, code, and the code results. It is also possible to embed controls in live scripts, such as sliders, drop down menus, check boxes, edit fields, and push buttons. There are also tasks that can be used to auto-generate code. There are quite a few tasks for preprocessing data sets, and also a plotting task. Depending on which toolboxes you have, there may be tasks associated with those toolboxes, also.

As an example, we will create a live script that plots **sin(x)**, using a slider for the maximum value of *x*. The following steps were taken, once in the Live Editor.

- Click on Text and write a sentence description of the script.
- Click on Section Break.
- Write code for the minimum and maximum possible values of x, and run that section.
- Click on Section Break.
- Start an assignment statement "maxval=" and then click on Control, and then Numeric Slider. This brings up a box that allows you to choose a label for the slider (the default is the variable name), and values for the minimum, maximum, and steps for the slider. There are defaults listed for each of those, and workspace variables can also be chosen. This is seen in Fig. 6.2. What was chosen here were the variables *minofx* and *maxofx*, and 0.1 for the step.



Let's create a plot of sin(x), where x can vary using a slider for the maximum value.

```
minofx = 0;
maxofx = 10*pi;
```

```
maxval = 
```

▾ LABEL

Text to display when code is hidden

Label: maxval

▾ VALUES

Enter value or select workspace variable

Min: minofx

Max: 100

Step

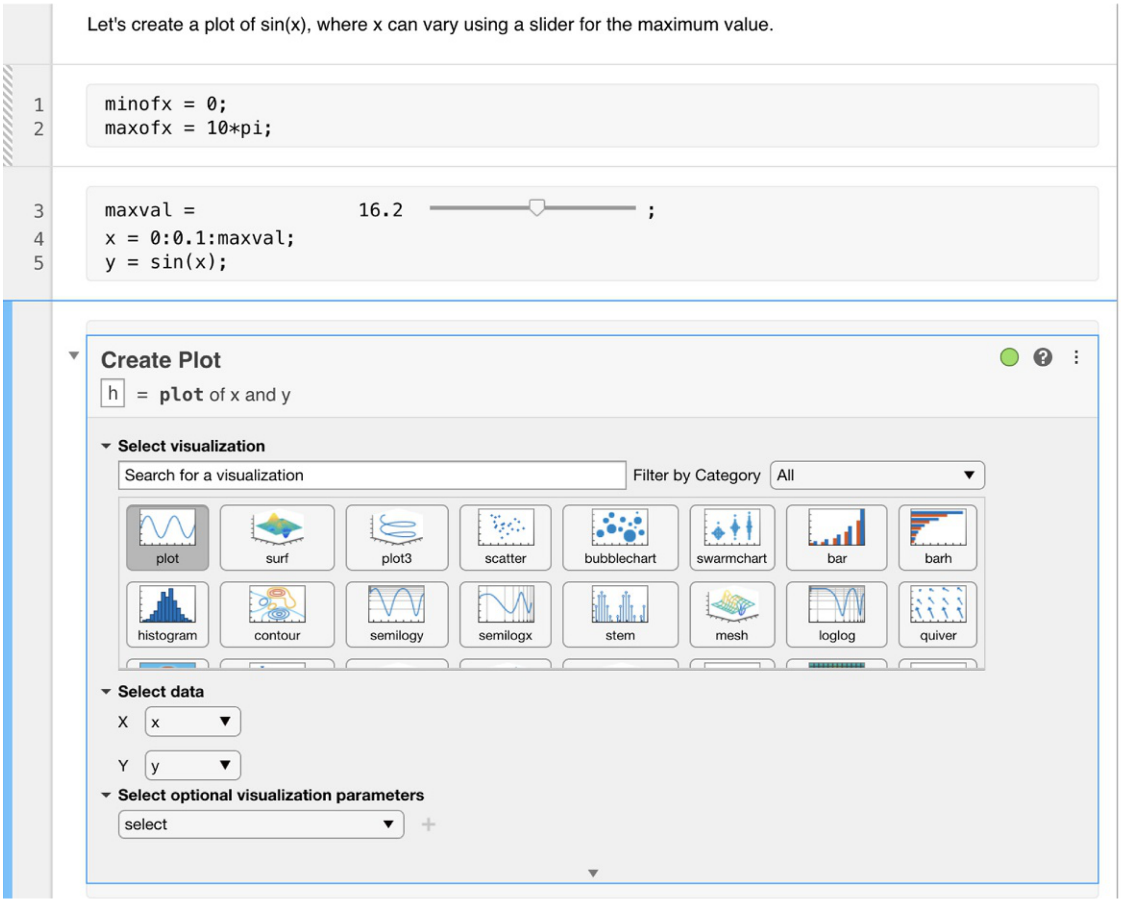
▾ EXECUTION

Run On: Value changing

Run: Current section

FIGURE 6.2
Choosing slider values.

- Add assignments for x and y variables to that section and run it.
- Click on Section Break.
- Click on Task, and then Create Plot. This brings up a task that allows you to choose the type of plot, and variables for x and y. This is seen in Fig. 6.3.



Let's create a plot of sin(x), where x can vary using a slider for the maximum value.

```
minofx = 0;
maxofx = 10*pi;
```

```
maxval =          16.2 ;
x = 0:0.1:maxval;
y = sin(x);
```

Create Plot

h = **plot** of x and y

Select visualization

Search for a visualization

Filter by Category: All

Select data

X: x

Y: y

Select optional visualization parameters

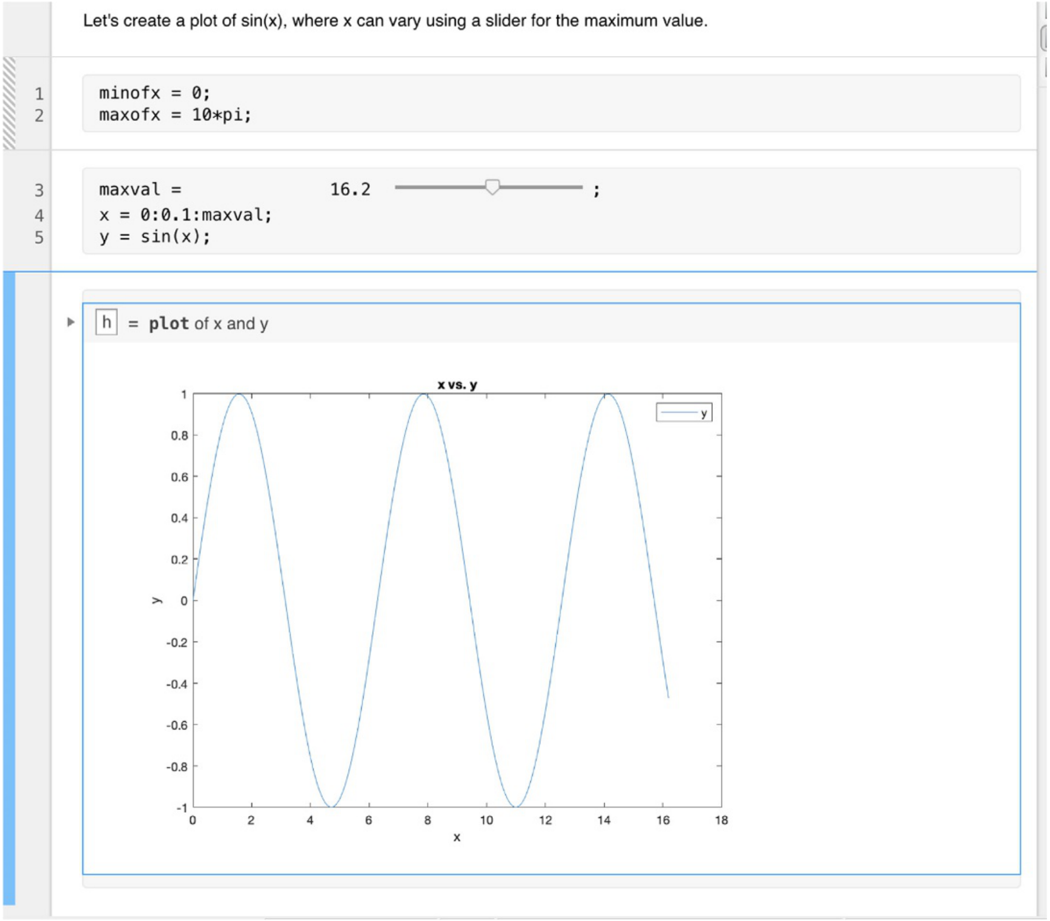
select

FIGURE 6.3
Create plot task.

- Choose **plot**, and the x and y variable. Run this section and then collapse the task by clicking on the down arrow to the left of it. This brings up the plot as seen in Fig. 6.4 (which was put inline).

6.6.2 Code Cells and Publishing

With simple code file scripts, one can break the code into sections, called ***code cells***. With code cells, you can run one cell at a time and you can also publish the code in an HTML format with plots embedded and with formatted equations.



Let's create a plot of sin(x), where x can vary using a slider for the maximum value.

```
minofx = 0;
maxofx = 10*pi;
```

```
maxval =            16.2  ;
x = 0:0.1:maxval;
y = sin(x);
```

h = plot of x and y

FIGURE 6.4

Result from plot task.

To break code into cells, create comment lines that begin with two % symbols; these become the cell titles. For example, a script from Chapter 3 that plots **sin** and **cos** has been modified to have two cells: one that creates vectors for sin(x) and cos(x) and plots them, and a second that adds a legend, title, and axis labels to the plot.

sinncosCells.m

```
% This script plots sin(x) and cos(x) in the same Figure
% Window for values of x ranging from 0 to 2pi

%% Create vectors and plot
clf
x = 0: 2*pi/40: 2*pi;
y = sin(x);
plot(x,y)
hold on
y = cos(x);
plot(x,y)
axis padded

%% Add legends, axis labels, and title
legend('sin', 'cos')
xlabel('x')
ylabel('sin(x) or cos(x)')
title('sin and cos on one graph')
```

When viewing this script in the Editor, the individual cells can be chosen by clicking the mouse anywhere within the cell. This will highlight the cell with a background color. Then, from the Editor tab, you can choose “Run Section” to run just that one code cell and remain within that cell, or you can choose “Run and Advance” to run that code cell and then advance to the next.

By choosing the “Publish” tab and then “Publish”, the code is published by default in HTML document. For the *sinncosCells* script, this creates a document in which there is a table of contents (consisting of the two cell titles), the first code block which plots, followed by the actual plot, and then the second code block that annotates the Figure Window, followed by the modified plot.

Data Science and Machine Learning Supplement

Splitting Data Sets Into Training and Test Sets

As we have seen in Chapter 5, labeled data sets for classification models are frequently randomized, and then broken into training and test sets. A basic algorithm for this might include:

- Get and clean data
- Randomize and split data
- Train and test model

What follows is a script that calls functions to accomplish each of these tasks. The data will be represented by a matrix named *dataset*.

```
dataset = getandclean;
[traindata, testdata] = splitdata(dataset);
trainandtest(traindata, testdata);
```

Function stubs have been written for the *getandclean* and *trainandtest* functions:

```
function outdata = getandclean
outdata = randi([1, 100], 10, 4);
end

function trainandtest(traind, testd)
disp(traind)
disp('Test')
disp(testd)
end
```

The *splitdata* function will first randomize the rows in the original dataset matrix, and then split the data into training and testing sets, using an 80/20 split.

```
function [traind, testd]=splitdata(dataset)
[r c] = size(dataset);
dataset = dataset(randperm(r), :);
numtrain = floor(.8*r);
traind = dataset(1:numtrain, :);
testd = dataset(numtrain+1:end, :);
end
```

Clustering and Hyperparameter Tuning

Figure 6.5 shows a scatterplot of some data points. It can clearly be seen by the naked eye that there are two distinct clusters of points. It is certainly not always this straight-forward, but ***clustering*** is a technique that is used in both supervised and unsupervised algorithms.

Mathematically, one technique for deciding in which cluster a point falls is by calculating the distance between points. There are several different ways to calculate the distance.

The ***Euclidean distance*** between two points (x1, y1) and (x2, y2) is given by:

$$E = \sqrt{(x1 - x2)^2 + (x2 - y2)^2}$$

The Manhattan distance is

$$\mathrm{M = abs(x1 - x2) + abs(y1 - y2)}$$

The Manhattan distance between points is used in some ML algorithms because it is faster and easier to calculate than the Euclidean distance.

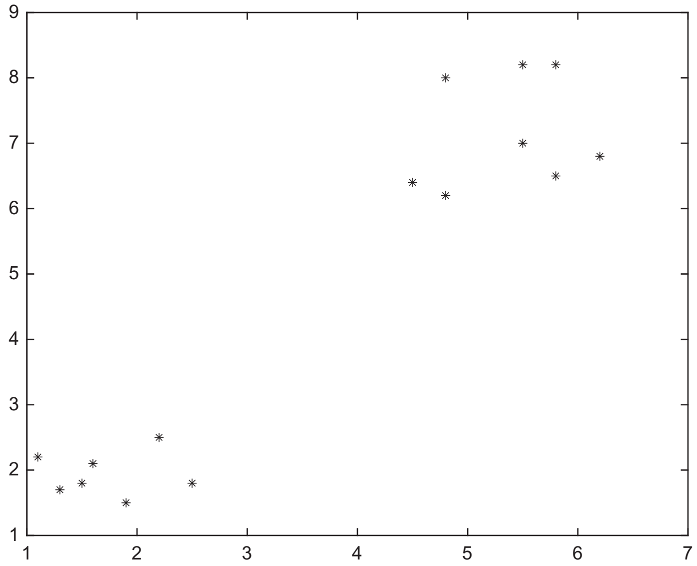


FIGURE 6.5

Scatter plot.

When working with ML models, parameters such as which distance metric to use are called ***hyperparameters***. Hyperparameters can be modified. Therefore, for example, it would be possible to test the model using Euclidean distance, get the assessment results, and then run it again using Manhattan distance, and compare the results before deciding which distance metric to use. This is called ***hyperparameter tuning***.

■ Explore Other Interesting Features

From the Command Window, type **help debug** to find out more about the debugging, and **help dbstop** in particular to find out more options for stopping code. Breakpoints can be set at specified locations in a file, only when certain condition(s) apply, and when errors occur.

Investigate the **dbstatus** function.

Explore the use of the functions **mlock** and **munlock** to block functions from being cleared using **clear**.

As of R2017a, it is possible to interactively edit figures in the Live Editor. Create Live script with a plot. Click on the plot, zoom in, and click on the "Update Code" button to modify the x and y limits.

It is also possible to create code cells in functions. Investigate this. ■

SUMMARY

COMMON PITFALLS

- Not matching up arguments in a function call with the input arguments in a function header.
- Not having enough variables in an assignment statement to store all of the values returned by a function through the output arguments.
- Attempting to call a function that does not return a value from an assignment statement, or from an output statement.
- Not using the same name for the function and the file in which it is stored.
- Not thoroughly testing functions for all possible inputs and outputs.
- Forgetting that **persistent** variables are updated every time the function in which they are declared is called – whether from a script or from the Command Window.

PROGRAMMING STYLE GUIDELINES

- If a function is calculating one or more values, return these value(s) from the function by assigning them to output variable(s).
- Give the function and the file in which it is stored the same name.
- Function headers and function calls must correspond. The number of arguments passed to a function must be the same as the number of input arguments in the function header. If the function returns values, the number of variables in the left side of an assignment statement should match the number of output arguments returned by the function.
- If arguments are passed to a function in the function call, do not replace these values by using **input** in the function itself.
- Functions that calculate and return value(s) will not normally also print them.
- Functions should not normally be longer than one page in length.
- Do not declare variables in the Command Window and then use them in a script, or vice versa.
- Pass all values to be used in functions to input arguments in the functions.
- When writing large programs with many functions, start with the main program script and use function stubs, filling in one function at a time while debugging.

MATLAB Reserved Words

global
persistent

MATLAB Functions and Commands

echo
dbstop
dbcont
dbquit
dbstep

MATLAB Operator

> path for local function
%% code cell title

Exercises

1. Write a function that will receive as an input argument a number of kilometers (K). The function will convert the kilometers to miles and to U.S. nautical miles, and return both results. The conversions are: 1 K = 0.621 miles and 1 US nautical mile = 1.852 K.
2. Write a function that receives an input argument x and returns y and z, which should be calculated as follows:

   $$y = 2x^2$$
   $$z = 3x - 4y$$

3. Write a function *ret2* that will return two random integers, the first in the range from 0 to 10 (inclusive) and the second in the range from 50 to 100 (inclusive).
4. Write a function *splitem* that will receive one vector of numbers as an input argument, and will return two vectors: one with the positive (>=0) numbers from the original vector, and the second, the negative numbers from the original vector. Use vectorized code (no loops) in your function.
5. Given the following function header:

   ```
   function doit(a, b)
   ```

   Which of the following function calls would be valid – and why?

   ```
   fprintf('The result is %.1f\n', doit(4,11))
   ```

   ```
   doit(5, 2, 11.11)
   ```

   ```
   x=11;
   y=3.3;
   doit(x,y)
   ```

6. Write a function that receives an input argument and returns its length and first element.

7. Write a function *promptletnum* that will prompt the user for one letter and an integer in the range from 1 to 5 (inclusive), error-checking until the user enters valid values, and then return them. The function will convert upper case letters to lower case.
8. Write a function "ps" that will receive one input argument, and will print the dimensions of the input argument in a sentence format.
9. Write a function that will receive an integer *n* and a character as input arguments, and will print the character *n* times.
10. Write a function that receives a matrix as an input argument, and prints a random column from the matrix.
11. Write a function that receives a count as an input argument and prints the value of the count in a sentence that would read "It happened 1 time." if the value of the counter is 1, or "It happened xx times." if the value of counter (xx) is greater than 1.
12. Write a function that receives an *x* vector, a minimum value, and a maximum value, and plots **sin(x)** from the specified minimum to the specified maximum.
13. Write a function that prompts the user for a value of an integer *n*, and returns the value of *n*. No input arguments are passed to this function. Error-check to make sure that an integer is entered.
14. Write a script that will:
    - Call a function to prompt the user for an angle in degrees
    - Call a function to calculate and return the angle in radians. (Note: π radians = 180°)
    - Call a function to print the result

    Write all of the functions, also. Put the script and all functions in separate code files.
15. Modify the program in Exercise 14 so that the function to calculate the angle is a local function to the function that prints.
16. Some Machine Learning algorithms are trained on data sets that have known outcomes. If *Yobs* is a vector of observed data values, and *Ypred* is a vector of predicted data values, the error vector is *Yobs* – *Ypred*, and the Mean Squared Error is defined as the mean of the squares of the errors, or:

    $$\text{MSE} = \text{mean}((\text{Yobs} - \text{Ypred}) \wedge 2)$$

    A script:
    - calls a function to get *Yobs* and *Ypred*
    - calls a function to calculate and return the error vector and the MSE
    - calls a function to print the MSE

    The script and a stub for the first function are given here. Write the other two functions, in separate code files.

    ```
    [yobs, ypred]=getvecs;
    [errorvec, mse]=findmse(yobs, ypred);
    printmse(mse)
    ```

```
function [yobs, ypred]=getvecs
yobs=3:7;
ypred=[2.8 4 5.1 5.9 7.3];
end
```

17. The lump sum S to be paid when interest on a loan is compounded annually is given by $S = P(1+i)^n$ where *P* is the principal invested, i is the interest rate, and *n* is the number of years. Write a program that will plot the amount S as it increases through the years from 1 to *n*. The main script will call a function to prompt the user for the number of years (and error-check to make sure that the user enters a positive integer). The script will then call a function that will plot S for years 1 through n. It will use 0.05 for the interest rate and $10,000 for P.
18. The distance between any two points (x_1,y_1) and (x_2,y_2) is given by:

$$\text{distance} = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

The area of a triangle is:

$$\text{area} = \sqrt{s*(s-a)^*(s-b)^*(s-c)}$$

where a, b, and c are the lengths of the sides of the triangle, and s is equal to half the sum of the lengths of the three sides of the triangle. Write a script that will prompt the user to enter the coordinates of three points that determine a triangle (e.g., the x and y coordinates of each point). The script will then calculate and print the area of the triangle. It will call one function to calculate the area of the triangle. This function will call a local function that calculates the length of the side formed by any two points (the distance between them).

19. Write a program to write a temperature conversion chart to a file. The main script will:
   - call a function that explains what the program will do
   - call a function to prompt the user for the minimum and maximum temperatures in degrees Fahrenheit, and return both values. This function checks to make sure that the minimum is less than the maximum, and calls a local function to swap the values if not.
   - call a function to write temperatures to a file: the temperature in degrees F from the minimum to the maximum in one column and the corresponding temperature in degrees Celsius in another column. The conversion is $C = (F - 32) * 5/9$.
20. Modify the function *func2* from Section 6.4.1 that has a **persistent** variable *counter.* Instead of having the function print the value of *counter*, the value should be returned.

21. Assume a matrix variable *mat*, as in the following example:

```
mat=

    4     2     4     3     2
    1     3     1     0     5
    2     4     4     0     2
```

The following **for** loop

```
[r, c] = size(mat);
for i = 1:r
    sumprint(mat(i,:))
end
```

prints this result:

```
The sum is now 15
The sum is now 25
The sum is now 37
```

Write the function *sumprint*.

22. Assume that you have the following function:

```
function outarg = mystfun(inarg)
persistent loc
loc=[loc inarg];
outarg=loc;
end
```

Explain why an **if** statement with **isempty** is not necessary.

23. The percentage change (for example, of a salary) is defined as the (new – old)/old * 100. Write a script that will
    - prompt the user for the user's previous salary and new salary
    - call a function to calculate and return the percentage change
    - print the resulting percentage increase if it was an increase, or a sympathy message if not

    Also, write the function that calculates and returns the percentage change. Note: to print one percent sign (%), put two in a row (%%) in the format specifier.

24. Write a menu-driven program to convert a time in seconds to other units (minutes, hours, and so on). The main script will loop to continue until the user chooses to exit. Each time in the loop, the script will generate a random time in seconds, call a function to present a menu of options, and print the converted time. The conversions must be made by individual functions (e.g., one to convert from seconds to minutes). All user-entries must be error-checked.

25. Write a menu-driven program to investigate the constant π. Model it after the program that explores the constant *e*. Pi (π) is the ratio of a circle's circumference to its diameter. Many mathematicians have found ways to approximate π. For example, Machin's formula is:

$$\left(\frac{\pi}{4}\right) = 4 \arctan\left(\frac{1}{5}\right) - \arctan\left(\frac{1}{239}\right)$$

Leibniz found that π can be approximated by:

$$\pi = \frac{4}{1} - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \frac{4}{9} - \frac{4}{11} + \ldots$$

This is called a *sum of a series*. There are six terms shown in this series. The first term is 4, the second term is –4/3, the third term is 4/5, and so forth. For example, the menu-driven program might have the following options:

- Print the result from Machin's formula.
- Print the approximation using Leibniz' formula, allowing the user to specify how many terms to use.
- Print the approximation using Leibniz' formula, looping until a "good" approximation is found.
- Exit the program.

26. Write a program to calculate the position of a projectile at a given time t. For an initial velocity v_0 and angle of departure θ_0, the position is given by x and y coordinates as follows (note: the gravity constant g is 9.81 m/s^2):

$$x = v_0 \cos(\theta_0) t$$

$$y = v_0 \sin(\theta_0) t - \frac{1}{2} g t^2$$

The program should initialize the variables for the initial velocity, time, and angle of departure. It should then call a function to find the x and y coordinates, and then another function to print the results.

27. Write the program for Problem 26 as a Live Script. Plot the results.
28. Create a live script. In the script, create x and y vectors and use the Plot Data task to create a scatter plot.

Data Science and Machine Learning

29. Machine Learning algorithms predict outcomes. In some cases, the outcome is basically yes/no which is expressed as positive/negative; for example, is the email spam (positive) or not (negative)? The algorithm may or may not correctly make this prediction. There are four numbers that are used when training a ML algorithm on a data set: true positives, true negatives, false positives, and false negatives. For a Machine Learning Algorithm, the Precision is:

$$\text{Precision} = \text{true positives}/(\text{true positives} + \text{false positives})$$

Write a program that will

- call a function to prompt the user for the number of true positives and false positives

- call a function to calculate and return the precision
- call a function to print the results

Write the script and all functions.

30. To find the equation of the straight line y = mx + b that best fits some data points using a least squares regression, the equations for *m* and *b* are:

$$\mathrm{m} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}$$

$$\mathrm{b} = \overline{y} - m\overline{x}$$

where *n* is the number of points in the data vectors x and y, and $\overline{y}$ and $\overline{x}$ represent the means of the vectors y and x. Write a function *mylinfit* that implements this; it receives the two data vectors *x* and *y*, and returns the values of *m* and *b*. Assume that the two vectors are the same length, and use the built-in **mean** function to find the mean of a vector.

This might be called from a script that calls one function to read the data vectors from a file, calls the *mylinfit* function to get the best straight line fit, and then calls a third function to plot the points and the line. The script has been written, and function stubs have been written, as follows:

```
[x, y]=getpoints;
[m, b]=mylinfit(x,y);
ploteverything(x,y,m,b)
```

```
function [x, y]=getpoints
x=1:5;
y=2:6;
end
```

```
function ploteverything(x,y,m,b)
plot(x(1)*y(1), m*b, 'k*')
end
```

31. Write a function that will receive the x and y coordinates of two points, and will return the Euclidean distance between them and also the Manhattan distance.

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CHAPTER 7

Text Manipulation

KEY TERMS

character vectors
string arrays
control characters
white space characters
string scalars
substring
leading blanks
trailing blanks
delimiter
token

CONTENTS

Text can be represented in the MATLAB® software using ***character vectors***, or using ***string arrays***, which were introduced in R2016b.

MATLAB has many built-in functions that are written specifically to manipulate strings and character vectors. Many functions that were created to manipulate character vectors also work on the new **string** type. Additionally, when **string** was introduced, many new string-manipulating functions were introduced. In some cases, strings contain numbers, and it is useful to convert from strings to numbers and vice versa; MATLAB has functions to do this as well.

There are many applications for text data, even in fields that are predominantly numerical. For example, when data files consist of combinations of numbers and characters, it is often necessary to read each line from the file as a string, break the string into pieces, and convert the parts that contain numbers to number variables that can be used in computations. In this chapter, the string manipulation techniques necessary for this will be introduced, and applications in file input/output will be demonstrated in Chapter 9.

7.1 CHARACTERS, CHARACTER VECTORS, AND STRING ARRAYS

Individual characters are stored in single quotation marks, are displayed using single quotes, and are the type **char**. Characters include letters of the alphabet, digits, punctuation marks, white space, and control characters. *Control*

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00007-X

characters are characters that cannot be printed, but accomplish a task (e.g., a backspace or tab). ***White space characters*** include the space, tab, newline (which moves the cursor down to the next line), and carriage return (which moves the cursor to the beginning of the current line).

```
>> letter='x'
letter=
      'x'
>> class(letter)
ans=
    'char'
>> size(letter)
ans=
      1      1
```

The function **newline** returns a newline character:

```
>> var=newline
var=
    '
     '
```

Groups of characters, such as words, can be stored in character vectors or in ***string scalars***. Prior to R2016b, the word "*string*" was used when referring to character vectors. However, as a result of the new **string** type, in MATLAB there is now a distinction between character vectors and strings.

A character vector consists of any number of characters (including, possibly, none), is contained in and displayed using single quotes, and has the type **char**. These are all examples of character vectors:

```
''
' '
'x'
'cat'
'Hello there'
'123'
```

Character vectors are vectors in which every element is a single character, which means that many of the vector operations and functions that we have already seen work with these character vectors.

```
>> myword='Hello';
>> class(myword)
ans=
    'char'
>> size(myword)
ans=
    1      5
>> length(myword)
ans=
    5
>> myword'    % Note transpose
```

```
ans=
  5×1 char array
    'H'
    'e'
    'l'
    'l'
    'o'
>> myword(1)
ans=
    'H'
```

A ***string scalar*** can also be used to store a group of characters such as words. String scalars (which means a single string) can be created using the **string** function or using double quotes. String scalars are displayed using double quotes.

```
>> mystr= "Awesome"
mystr=
    "Awesome"
>> mystr=string('Awesome')
mystr=
    "Awesome"
>> class(mystr)
ans=
    'string'
>> size(mystr)
ans=
    1     1
```

Note

that since a string is a scalar, the dimensions are 1 x 1.

Since this is a string scalar, the **length** of the string is 1. To find the number of characters in a string scalar, the **strlength** function is used:

```
>> strlength(mystr)
ans=
    7
```

Because this is a scalar, the first element is the string itself. Using parentheses to index will show this. However, using curly braces to index will return the character vector that is contained in the string scalar; this can be used to extract individual characters.

```
>> mystr(1)
ans=
    "Awesome"
>> mystr{1}
ans=
    'Awesome'
>> mystr{1}(2)
ans=
    'w'
```

Groups of strings can be stored in string arrays or character matrices (or, as we will see in Chapter 8, cell arrays).

String arrays are the preferred method for storing groups of strings. As with other arrays, string arrays can be created using square brackets. The following creates a row vector of strings.

```
>> majors=["English", "History", "Engineering"]
majors=
  1×3 string array
     "English"     "History"     "Engineering"
>> class(majors)
ans=
    'string'
>> majors(1)
ans=
    "English"
>> majors{1}
ans=
    'English'
```

The **char** function can be used to create an array of character vectors, for example,

```
>> majmat=char('English', 'History', 'Engineering')
majmat=
  3×11 char array
    'English    '
    'History    '
    'Engineering'
```

This is a matrix of characters, which appears as a column vector of strings. It is really a matrix in which every element is a single character. Because every row in a matrix must have the same number of columns, this means that shorter words are padded with extra blank spaces so that they all have the same length. This is one reason that this is not a preferred method for storing groups of strings.

There are several terms that can be used for either strings or character vectors. A ***substring*** is a subset or part of a string. For example, “there” is a substring within the string “Hello there”. ***Leading blanks*** are blank spaces at the beginning of a string, for example, “ hello”, and ***trailing blanks*** are blank spaces at the end of a string.

7.2 OPERATIONS ON TEXT

MATLAB has many built-in functions that work with strings and character vectors. Most of these functions, including those that were present in earlier versions and the new functions introduced with the **string** type, can operate on either strings or character vectors. A few work with either strings or character vectors, but not both. Some of the text manipulation functions that perform the most common operations will be described here.

7.2.1 Operations on Character Vectors

Character vectors are created using single quotes, as we have seen. The **input** function is another method of creating a character vector:

```
>> phrase= input('Enter something: ', 's')
Enter something: hello there
phrase=
    'hello there'
```

Another function that creates only character vectors is the **blanks** function, which creates a character vector consisting of *n* blank characters.

```
>> b=blanks(4)
b=
    '    '
```

Displaying the transpose of the result from the **blanks** function can also be used to move the cursor down. In the Command Window, it would look like this:

```
>> disp(blanks(4)')




>>
```

Another example is to insert blank spaces into a character vector:

```
>> ['Space' blanks(10) 'Cowboy']
ans=
    'Space          Cowboy'
```

PRACTICE 7.1

Prompt the user for a character vector. Print the length of the character vector and also its first and last characters. Make sure that this works regardless of what the user enters.

7.2.2 Operations on Strings

String scalars and string arrays can be created using double quotes, as we have seen. The **string** function is another method of creating a string from a character vector, as we have seen.

Without any arguments, the **string** function creates a string scalar that contains no characters. However, since it is a scalar, it is not technically empty. The **strlength** function should be used to determine whether a string contains any characters, not the **isempty** function.

```
>> es=string
es=
    ""
>> isempty(es)
ans=
    0
```

```
>> strlength(es) == 0
ans=
    1
```

The **plus** function or operator can join, or concatenate, two strings together:

```
>> "hello"+" goodbye"
ans=
    "hello goodbye"
```

The **plus** operator cannot be used to concatenate two character vectors. However, it can concatenate a string and a character vector, resulting in a string.

PRACTICE 7.2

Prompt the user for a character vector. Use the **string** function to convert it to a string. Print the length of the string and also its first and last characters. Concatenate "!!" to the end of your string using the plus operator.

7.2.3 Operations on Strings or Character Vectors

Most text functions can have either strings or character vectors as input arguments. Unless specified otherwise, for text manipulating functions, if the argument is a character vector, the result will be a character vector, and if the argument is a string, the result will be a string.

Note that in some explanations the word "string" will be used generically to mean either a MATLAB **string**, or a character vector.

7.2.3.1 Creating and Concatenating

We have already seen several methods of creating and concatenating both strings and character vectors, including the **plus** function putting them in square brackets. The **append** (introduced in R2019a) and **strcat** functions can be used to concatenate text horizontally, meaning the result is one longer piece of text. One difference is that **strcat** will remove trailing blanks (but not leading blanks) for character vectors, whereas it will not remove either from strings. The **append** function will not remove blanks.

```
>> strcat('Hello', ' there')
ans=
    'Hello there'
>> strcat('Hello ', 'there')
ans=
    'Hellothere'
>> strcat('Hello', ' ', 'there')
ans=
    'Hellothere'
>> strcat("Hello", " ", "there")
ans=
    "Hello there"
```

```
>> append('Hello   ', 'there')
ans=
    'Hello    there'
```

The **sprintf** function can be used to create customized strings or character vectors. The **sprintf** function works exactly like the **fprintf** function, *but instead of printing it creates a string (or character vector)*. Here are several examples in which the output is not suppressed so the value of the resulting variable is shown:

```
>> sent1=sprintf('The value of pi is %.2f', pi)
sent1=
    'The value of pi is 3.14'

>> sent2=sprintf("Some numbers: %5d, %2d", 33, 6)
sent2=
    "Some numbers:    33, 6"
```

All of the formatting options that can be used in the **fprintf** function can also be used in the **sprintf** function.

Note

Notice that in the first example the format specifier used a character vector, so the result was a character vector, whereas the second example used a string for the format specifier so that the result was a string.

One very useful application of the **sprintf** function is to create customized text, including formatting and/or numbers that are not known ahead of time (e.g., entered by the user or calculated). This customized text can then be passed to other functions, for example for plot titles or axis labels. For example, assume that a file "expnoanddata.dat" stores an experiment number, followed by the experiment data. In this case, the experiment number is "123", and then the rest of the file consists of the actual data.

```
123  4.4  5.6  2.5  7.2  4.6  5.3
```

The following script would load these data and plot them with a title that includes the experiment number.

plotexpno.m

```
% This script loads a file that stores an experiment number
% followed by the actual data. It plots the data and puts
% the experiment # in the plot title

load expnoanddata.dat
experNo=expnoanddata(1);
data=expnoanddata(2:end);
plot(data,'ko')
xlabel('Sample #')
ylabel('Weight')
title(sprintf('Data from experiment %d', experNo))
axis padded
```

The script loads all numbers from the file into a row vector. It then separates the vector; it stores the first element, which is the experiment number, in a variable *experNo*, and the rest of the vector in a variable *data* (the rest being from the

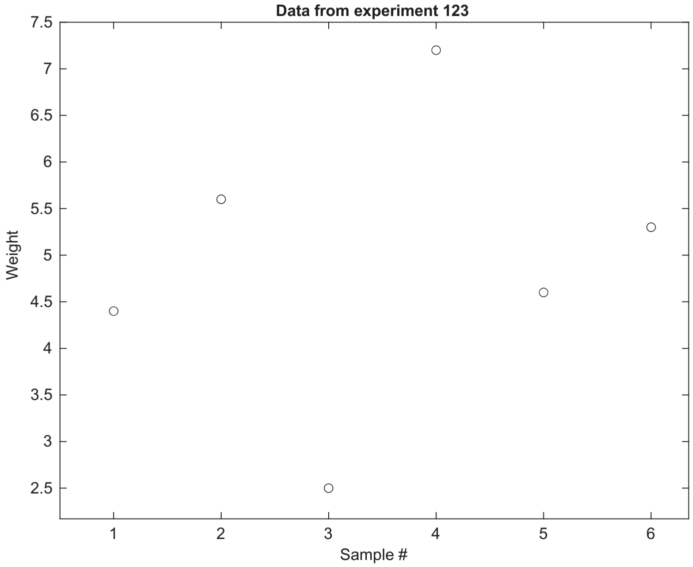

FIGURE 7.1

Customized title in plot using **sprintf.**

second element to the end). It then plots the data, using **sprintf** to create the title, which includes the experiment number as seen in Fig. 7.1.

PRACTICE 7.3

In a loop, create and print strings with file names "file1.dat", "file2.dat", and so on for file numbers 1 through 5.

QUICK QUESTION!

How could we use the **sprintf** function to customize prompts for the **input** function?

Answer: For example, if it is desired to have the contents of a string variable printed in a prompt, **sprintf** can be used:

```
>> username=input('Please enter your name:','s');
Please enter your name: Bart
>> prompt=sprintf('%s, Enter your id #: ',...
username);
>> id_no=input(prompt)
Bart, Enter your id #: 177
id_no=
   177
```

Another way of accomplishing this (in a script or function) would be:

```
fprintf('%s, Enter your id #: ',username);
id_no=input('');
```

Note that the calls to the **sprintf** and **fprintf** functions are identical except that the **fprintf** prints (so there is no need for a prompt in the **input** function), whereas the **sprintf** creates a string that can then be displayed by the **input** function. In this case, using **sprintf** seems cleaner than using **fprintf** and then having an empty string for the prompt in **input**.

As another example, the following program prompts the user for endpoints (x_1, y_1) and (x_2, y_2) of a line segment, and calculates the midpoint of the line segment, which is the point (x_m, y_m). The coordinates of the midpoint are found by:

$$x_m = \frac{1}{2}(x_1 + x_2) \qquad y_m = \frac{1}{2}(y_1 + y_2)$$

The script *midpoint* calls a function *entercoords* to separately prompt the user for the x and y coordinates of the two endpoints, calls a function *findmid* twice to calculate separately the x and y coordinates of the midpoint, and then prints this midpoint. When the program is executed, the output looks like this:

```
>> midpoint
Enter the x coord of the first endpoint: 2
Enter the y coord of the first endpoint: 4
Enter the x coord of the second endpoint: 3
Enter the y coord of the second endpoint: 8
The midpoint is (2.5, 6.0)
```

In this example, the word 'first' or 'second' is passed to the *entercoords* function so that it can use whichever word is passed in the prompt. The prompt is customized using **sprintf**.

midpoint.m

```
% This program finds the midpoint of a line segment

[x1, y1]=entercoords('first');
[x2, y2]=entercoords('second');

midx=findmid(x1,x2);
midy=findmid(y1,y2);

fprintf('The midpoint is (%.1f, %.1f )\n',midx,midy)
```

entercoords.m

```
function [xpt, ypt]=entercoords(word)
% entercoords reads in & returns the coordinates of
%   the specified endpoint of a line segment
% Format: entercoords(word) where word is 'first'
%       or 'second'

prompt=sprintf('Enter the x coord of the %s endpoint: ', ...
      word);
xpt=input(prompt);

prompt=sprintf('Enter the y coord of the %s endpoint: ', ...
      word);
ypt=input(prompt);
end
```

findmid.m

```
function mid=findmid(pt1,pt2)
% findmid calculates a coordinate (x or y) of the
%  midpoint of a line segment
% Format: findmid(coord1, coord2)

mid=0.5*(pt1+pt2);
end
```

7.2.3.2 Removing Characters

MATLAB has functions that will remove trailing and/or leading blanks from strings and character vectors and also will delete specified characters and substrings.

The **deblank** function will remove trailing blank spaces from the end of text (but it does not remove leading blanks).

```
>> deblank("   Hello ")
ans=
    "   Hello"
```

The **strtrim** function will remove both leading and trailing blanks from text, but not blanks in the middle. In the following example, the three blanks in the beginning and four blanks in the end are removed, but not the two blanks in the middle.

```
>> strtrim("   Hello  there    ")
ans=
    "Hello  there"
>> strlength(ans)
ans=
    12
```

The **strip** function can be used to remove leading and/or trailing characters, either whitespace or other specified characters. One simple method of calling it follows:

```
>> teststr= "xxHelloxxxthere!x";
>> strip(teststr, "x")
ans=
    "Helloxxxthere!"
```

The **erase** function removes all occurrences of a substring within a string (or character vector).

```
>> erase(teststr, "x")
ans=
    "Hellothere!"
```

7.2.3.3 Changing Case

MATLAB has two functions that convert text to all uppercase letters, or lowercase, called **upper** and **lower**.

```
>> mystring= "AbCDEfgh";
>> lower(mystring)
ans=
    "abcdefgh"
>> upper('Char vec')
ans=
    'CHAR VEC'
```

PRACTICE 7.4

Assume that these expressions are typed sequentially in the Command Window. Think about it, write down what you think the results will be, and then verify your answers by actually typing them.

```
lnstr='1234567890';
mystr=' abc   xy';
newstr=strtrim(mystr)
length(newstr)
upper(newstr(1:3))
numstr=sprintf("Number is %4.1f", 3.3)
erase(numstr," ") % Note 2 spaces
```

7.2.3.4 Comparing text

There are several functions that compare strings or character vectors and return **logical true** if they are equivalent, or **logical false** if not. The function **strcmp** compares text, character by character. It returns **logical true** if the strings (or character vectors) are completely identical (which infers that they must also be of the same length), or **logical false** if they are not the same length or any corresponding characters are not identical. Note that for character vectors, these functions are used to determine whether two character vectors are equal to each other or not, not the equality operator ==. Here are some examples of these comparisons:

```
>> word1='cat';
>> word2='car';
>> word3='cathedral';
>> word4='CAR';
>> strcmp(word1,word3)
ans=
    0
>> strcmp(word1,word1)
ans=
    1
>> strcmp(word2,word4)
ans=
    0
```

The function **strncmp** compares only the first *n* characters in strings and ignores the rest. The first two arguments are the strings to compare and the third argument is the number of characters to compare (the value of *n*).

```
>> strncmp(word1,word3,3)
ans=
    1
```

The function **strcmpi** compares the strings but ignores the case of the characters.

```
>> strcmpi(word2,word4)
ans=
    1
```

There is also a function **strncmpi,** which compares *n* characters, ignoring the case.

For character vectors, the equality operator will compare character by character, or it will throw an error message if the vectors are not the same length.

```
>> 'hello' == 'hello'
ans=
  1×5 logical array
   1   1   1   1   1
>> 'hello' == 'help'
Arrays have incompatible sizes for this operation.
Related documentation
```

For strings, however, the equality operator will return simply 1 for true if the two strings are exactly the same, or 0 for false if not.

```
>> "hello" == "hello"
ans=
   1
>> "hello" == "help"
ans=
   0
```

7.2.3.5 Finding, Replacing, and Separating Text

There are functions that find and replace strings, or parts of strings, within other strings and functions that separate strings into substrings.

The function **strfind** receives two strings as input arguments. The general form is **strfind(string, substring)**; it finds all occurrences of the substring within the string, and returns the subscripts of the beginning of the occurrences. The substring can consist of one character, or any number of characters. If there is more than one occurrence of the substring within the string, **strfind** returns a vector with all indices. Note that what is returned is the index of the beginning of the substring.

```
>> strfind('abcde', 'd')
ans=
    4
>> strfind("abcde", "bc")
ans=
    2
>> strfind('abcdeabcdedd', 'd')
ans=
     4      9     11     12
```

Note that the arguments can be character vectors or strings. If there are no occurrences, the empty vector is returned.

```
>> strfind('abcdeabcde','ef')
ans=
    []
```

The function **strrep** finds all occurrences of a substring within a string and replaces them with a new substring. The order of the arguments matters. The format is

```
strrep(string, oldsubstring, newsubstring)
```

The following replaces all occurrences of the substring 'e' with the substring 'x':

```
>> strrep('abcdeabcde','e','x')
ans=
    'abcdxabcdx'
```

All strings can be any length, and the lengths of the old and new substrings do not have to be the same. If the old substring is not found, nothing is changed in the original string.

The function **count** counts the number of occurrences of a substring within a string (or character vector).

```
>> count('xxhelloxxxhix','x')
ans=
    6
>> count("hello everyone", " ")
ans=
      1
>> count("hello everyone", "el")
ans=
      1
```

Note: the empty string (or character vector) is considered a substring within every string (or character vector). In fact, there is an empty string at the beginning of every string, at the end of every string, and in between every two characters within the string! Therefore, counting the number of empty strings in a string with n characters results in n + 1.

```
>> count("hello", "")
ans=
    6
>> count('abc', '')
ans=
    4
```

In addition to the string functions that find and replace, there is a function that separates a string into two substrings. The **strtok** function breaks a string or character vector into two pieces; it can be called several ways. The function receives one string as an input argument. It looks for the first ***delimiter***, which is a character or set of characters that act as a separator within the string.

By default, the delimiter is any white space character. The function returns a ***token*** that is the beginning of the string, up to (but not including) the first delimiter. It also returns the rest of the string, which includes the delimiter. Assigning the returned values to a vector of two variables will capture both of these. The format is

```
[token, rest]=strtok(string)
```

where *token* and *rest* are variable names. For example,

```
>> sentence1= "Hello there";
>> [word, rest]=strtok(sentence1)
word=
    "Hello"
rest=
    " there"
>> strlength(word)
ans=
    5
>> strlength(rest)
ans=
    6
```

Note
that the rest of the string includes the blank space delimiter.

Alternate delimiters can be defined. The format

```
[token, rest]=strtok(string, delimeters)
```

returns a token that is the beginning of the string, up to the first character contained within the delimiters string, and also the rest of the string. In the following example, the delimiter is the character ‘l’.

```
>> [word, rest]=strtok(sentence1,'l')
word=
    "He"
rest=
    "llo there"
```

Leading delimiter characters are ignored, whether it is the default white space or a specified delimiter. For example, the leading blanks are ignored here:

```
>> [firstpart, lastpart]=strtok(' materials science')
firstpart=
    'materials'
lastpart=
    ' science'
```

QUICK QUESTION!

What do you think **strtok** returns if the delimiter is not in the string?

Answer: The first result returned will be the entire input argument. The second result depends on whether the input argument is a string or character vector. If it is a string, the second result will be a string scalar that contains no characters, whereas if it is a character vector, the result will be an empty character vector.

```
>> [first, rest]=strtok("ABCDE")
first=
    "ABCDE"
rest=
    ""
>> [first, rest]=strtok('ABCDE')
first=
    'ABCDE'
rest=
  0×0 empty char array
```

PRACTICE 7.5

Think about what would be returned by the following sequence of expressions and statements, and then type them into MATLAB to verify your results.

```
dept="Electrical";
strfind(dept,'e')

strfind(lower(dept),'e')

phone_no='703-987-1234';
[area_code, rest]=strtok(phone_no,'-')

rest=rest(2:end)

strcmpi('Hi','HI')
```

QUICK QUESTION!

The function **date** returns the current date as a character vector (e.g., '10-Dec-2021'). How could we write a function to return the day, month, and year as separate output arguments?

Answer: We could use **strrep** to replace the '-' characters with blanks and then use **strtok** with the blank as the default delimiter to break up the character vector (twice) or, more simply, we could just use **strtok** and specify the '-' character as the delimiter.

As we need to separate the character vector into three parts, we need to use the **strtok** function twice. The first time the character vector is separated into '10' and '-Dec-2021' using **strtok**. Then, the second character vector is separated into 'Dec' and '-2021' using **strtok**. (As leading delimiters are ignored the second '-' is found as the delimiter in '-Dec-2021'.) Finally, we need to remove the '-' from the character vector '-2021'; this can be done by just indexing from the second character to the end of the character vector.

separatedate.m

```
function [todayday, todaymo, todayyr]=separatedate
% separatedate separates the current date into day,
% month, and year
% Format: separatedate or separatedate()

[todayday, rest]=strtok(date,'-');
[todaymo, todayyr]=strtok(rest,'-');
todayyr=todayyr(2:end);
end
```

An example of calling this function follows:

```
>> [d, m, y]=separatedate
d=
   '10'
m=
   'Dec'
y=
   '2021'
```

Note that no input arguments are passed to the *separatedate* function; instead, the **date** function returns the current date as a character vector. Also, note that all three output arguments are character vectors

7.2.4 Operations on String Arrays

So far, we have focused mostly on individual "strings," stored in either string scalars or character vectors. In this section, we will see that there are operations and functions that can be applied to all string scalars that are stored in string arrays.

A string array can be preallocated using the **strings** function, for example,

```
>> sa=strings(2,4)
sa=
   2×4 string array
     ""     ""     ""     ""
     ""     ""     ""     ""
```

Strings could then be stored in the individual elements by indexing into the array.

The lengths of all strings in a string array can be found using the **strlength** function.

```
>> majors=["English", "History", "Engineering"];
>> strlength(majors)
ans=
     7     7     11
```

In fact, many string functions can have a string array as an input argument, and will return the function of each element in the array. For example, we could convert all to upper case:

```
>> upmaj=upper(majors)
upmaj=
      "ENGLISH"   "HISTORY"   "ENGINEERING"
```

The plus operator can be used to concatenate the same string to all strings, or a subset of strings determined by indexing, in a string array.

```
>> "BA in "+majors(1:2)
ans=
    "BA in English"    "BA in History"
```

Two string arrays can also be concatenated, as long as they have the same length (note: this means the same number of elements in the string arrays, not the lengths of individual strings within them).

```
>> degrees=["BA" "BA" "BS"];
>> (degrees+" in "+majors)'    % Note transpose
ans=
  3×1 string array
     "BA in English"
     "BA in History"
     "BS in Engineering"
```

A function that joins strings together (but not character vectors) is **strjoin**, which will concatenate strings in a string array together (putting spaces in between them); **strsplit** does the reverse:

```
>> majlist=strjoin(majors)
majlist=
    "English History Engineering"
>> strsplit(majlist)
ans=
  1×3 string array
    "English"    "History"    "Engineering"
```

The function **join** will concatenate strings in corresponding elements of columns in a string array, for example:

```
>> newsa=[degrees; majors]'  % Note transpose
newsa=
   3×2 string array
     "BA"    "English"
     "BA"    "History"
     "BS"    "Engineering"
```

```
>> join(newsa)
ans=
   3×1 string array
     "BA English"
     "BA History"
     "BS Engineering"
```

7.3 THE “IS” FUNCTIONS FOR TEXT

There are several “is” functions for strings and character vectors, which return **logical true** or **false**. The function **isletter** returns **logical true** for every character in a character vector if the character is a letter of the alphabet or **false** if not. The function **isspace** returns **logical true** for every character in a character vector that is a white space character.

```
>> isletter('EK125')
ans=
    1      1      0      0      0

>> isspace('a b')
ans=
    0      1      0
```

The **ischar** function will return **logical true** if the vector argument is a character vector, or **logical false** if not.

```
>> vec='EK125';
>> ischar(vec)
ans=
    1
>> vec=3:5;
>> ischar(vec)
ans=
    0
>> ischar("EK125")
ans=
    0
```

The **isstring** function will return **logical true** if the vector argument is a string, or **logical false** if not.

```
>> isstring("EK125")
ans=
      1
>> isstring('hello')
ans=
    0
```

The **isStringScalar** will return **logical true** if the vector argument is a string scalar (a string array with only one element), or **logical false** if not.

```
>> isStringScalar("hello")
ans=
    1
```

```
>> isStringScalar(["hello" "hi"])
ans=
    0
```

The **isstrprop** function determines whether the characters in a string are in a category specified by a second argument. For example, the following tests to see whether the characters are alphanumeric; all are except for the dot '.'.

```
>> isstrprop('AB123.4','alphanum')
ans=
    1      1      1      1      1      0      1
```

There are several other true/false functions that do not start with "is". The **contains** function will return **logical true** if a specified substring is within a string (or character vector), or **logical false** if not.

```
>> contains("hello", "ll")
ans=
    1
>> contains("hello", "x")
ans=
    0
>> majors=["English", "History", "Engineering"];
>> contains(majors, "Eng")
ans=
  1×3 logical array
   1   0   1
```

The **endsWith** and **startsWith** functions will return **logical true** if a string ends with (or starts with, respectively) a specified string, or **logical false** if not.

```
>> endsWith("filename.dat", ".dat")
ans=
    1
>> startsWith('abcde', 'b')
ans=
    0
```

Recall that every string starts with and ends with the empty string.

```
>> endsWith("abc", "")
ans=
    1
```

7.4 CONVERTING BETWEEN TEXT AND NUMBER TYPES

MATLAB has several functions that convert numbers to strings or character vectors and vice versa.

Note
that these are different from the functions such as **char** and **double** that convert characters to ASCII equivalents and vice versa.

To convert numbers to character vectors, MATLAB has the functions **int2str** for integers and **num2str** for real numbers (which also works with integers). The function **int2str** would convert, for example the integer 38 to the character vector '38'.

```
>> num = 38;
>> cv1 = int2str(num)
cv1 =
    '38'
>> length(num)
ans =
    1
>> length(cv1)
ans =
    2
>> vec = 2:5;
>> result = int2str(vec)
result =
    '2    3    4    5'
```

The variable *num* is a scalar that stores one number, whereas *cv1* is a character vector that stores two characters, '3' and '8'.

The **num2str** function, which converts real numbers, can be called in several ways. If only one real number is passed to the **num2str** function, it will create a character vector that has four decimal places, which is the default in MATLAB for displaying real numbers. The precision can also be specified (which is the number of digits), and format specifiers can also be passed, as shown in the following:

```
>> cv2 = num2str(3.456789)
cv2 =
   '3.4568'
>> length(cv2)
ans =
   6
>> cv3 = num2str(3.456789, 3)
cv3 =
   '3.46'
>> cv4 = num2str(3.456789, '%6.2f')
cv4 =
   '3.46'
```

Note

that in the last example, MATLAB removed the leading blanks from the character vector (from the field width of 6).

The functions **str2double** and **str2num** do the reverse; they take a character vector in which number(s) are stored and converts them to the type **double**:

```
>> num = str2double('123.456')
num =
  123.4560
```

If there is a string in which there are numbers separated by blanks, the **str2num** function will convert this to a vector of numbers (of the default type **double**). For example,

```
>> mycv = '66 2 111';
>> numvec = str2num(mycv)
numvec =
    66   2   111
>> size(numvec)
ans =
    1       3
```

The **str2double** function is a better function to use in general than **str2num**, but it can only be used when a scalar is passed; it would not work, for example, for the variable *mycv* above. If the argument that is passed to **str2num** is a string or character vector that contains a math expression, the result of that expression will be evaluated.

```
>> str2num('5+2')
ans=
    7
```

The **str2double** and **str2num** functions perform the same operations on strings. To convert numbers to strings, the function **string** can be used.

```
>> num=38;
>> st1=string(num)
st1=
   "38"
>> vec=2:5;
>> starr=string(vec)
starr=
  1×4 string array
    "2"    "3"    "4"    "5"
```

PRACTICE 7.6

Think about what would be returned by the following sequence of expressions and statements, and then type them into MATLAB to verify your results.

```
vec='yes or no';
isspace(vec)

all(isletter(vec)~=isspace(vec))

ischar(vec)

nums=[33 1.5];
num2str(nums)

nv=num2str(nums)

sum(nums)

string([11 33])
```

Data Science and Machine Learning Supplement

Annotating Plots

In Chapter 5, we saw how to use the **subplot** function to visualize correlations between columns in a matrix.

```
>> mat
mat=
    4.0000    2.0000    9.1000    1.0000
    4.0000    2.7000    8.0000    2.0000
    1.0000    3.1000    8.2000    3.0000
    9.0000      4.0000      5.9000      4.0000
    6.0000      4.5000      5.0000      5.0000
    4.0000      5.3000      3.6000      6.0000
    8.0000      5.9000      3.3000      7.0000
    8.0000      6.4000      3.0000      8.0000
    6.0000      7.1000      1.8000      9.0000
    3.0000      9.0000      1.1000     10.0000
```

However, the plots did not have any indicators (labels, title) of which columns were being compared. Therefore, with text manipulation, we can now improve on that, as seen in Fig. 7.2.

```
for i=1:3
   subplot(1,3,i)
   plot(mat(:,i), mat(:,4), '*')
   xlabel(sprintf('Column %d', i))
   ylabel('Column 4')
   title(sprintf('Column %d vs. Column 4', i))
end
sgtitle('Visualizing Correlations')
```

Natural Language Processing

Natural language processing involves analyzing text (for example, written works) and speech (for example, audio files) for patterns in the data. One type of classification problem is ***Sentiment Analysis***. For example, blog posts might be examined to determine whether the author had a positive, negative, or neutral reaction to an event. To do this, the text in the blogs would be searched for

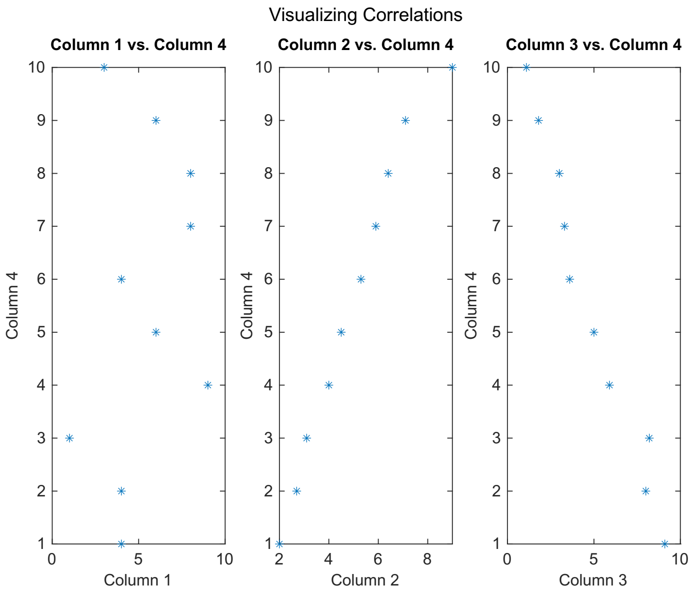

FIGURE 7.2
Visualizing correlations.

words that are known to be positive or negative in nature. MATLAB has Text Analytics Toolbox™ that has many useful functions for accomplishing these tasks. Although ML with text data is used in a lot of applications, it will not be covered in depth in this book.

Explore Other Interesting Features

In many of the search and replace functions, search patterns can be specified which use ***regular expressions***. Use **help** to find out about these patterns.

Explore the **replace** and **replaceBetween** functions, which find and replace.

Explore the **split** and **splitlines** functions, which split text.

Explore the **extractAfter**, **extractBefore**, and **extractBetween** functions, which extract substrings.

Explore the **insertAfter** and **insertBefore** functions, which insert text.

Explore the **strjust** function, which justifies a string or character vector.

Explore the **mat2str** function, to convert from a matrix to a character vector.

Explore the use of patterns, introduced in 2020b, for searching text.

Explore the use of the **matches** function, introduced in 2019b.

■

SUMMARY

COMMON PITFALLS

- Putting arguments to **strfind** in incorrect order.
- Trying to use == to compare character vectors for equality, instead of the **strcmp** function (or its variations)
- Confusing **sprintf** and **fprintf**. The syntax is the same, but **sprintf** creates a string whereas **fprintf** prints.
- Trying to create a vector of strings with varying lengths (one way is to use **char** which will pad with extra blanks automatically; a better way is to use a string array).
- Forgetting that when using **strtok**, the second argument returned (the “rest”) contains the delimiter.
- When breaking a string into pieces, forgetting to convert the numbers in the strings to actual numbers that can then be used in calculations.

PROGRAMMING STYLE GUIDELINES

- Make sure the correct string comparison function is used, for example **strcmpi** if ignoring case is desired.

MATLAB Functions and Commands			
string	strip	count	isstring
newline	erase	strtok	isStringScalar
strlength	upper	date	isstrprop
blanks	lower	strings	contains
plus	strcmp	strjoin	endsWith
append	strncmp	strsplit	startsWith
strcat	strcmpi	join	int2str
sprintf	strncmpi	isletter	num2str
deblank	strfind	isspace	str2double
strtrim	strrep	ischar	str2num

Exercises

1. Write a function *getstr* that prompts the user for a character vector, error-checking until the user enters something (the error would occur if the user just hits the Enter key without characters other than white space characters first).
2. Write a script that will, in a loop, prompt the user for four course numbers. Each will be a character vector of length 5 of the form 'CS101'. Convert them to strings and store in a string array.
3. Write a function that will generate two random integers, each in the inclusive range from 10 to 30. It will then return a character vector consisting of the two integers joined together, e.g., if the random integers are 11 and 29, the character vector that is returned will be '1129'.
4. Modify the function from Exercise 3 to return a string instead.
5. Write a script that will create x and y vectors. Then, it will ask the user for a color ('red', 'blue', or 'green') and for a plot style (circle or star). It will then create a character vector *pstr* that contains the color and plot style, so that the call to the **plot** function would be: **plot(x,y,pstr)**. For example, if the user enters 'blue' and '*', the variable *pstr* would contain 'b*'.
6. Consider the following string array:

```
>> dogs=["golden retriever" "german shepherd" "border collie"];
```

   Using *dogs* and text manipulation techniques, write expressions that will create the given variables.

7. Given the variable num:

```
>> num=33;
```

   Write an assignment statement to create the variable *sent* as shown here, using **sprintf**.

8. Assume that you have the following function and that it has not yet been called.

strfunc.m

```
function strfunc(instr)
persistent mystr
if isempty(mystr)
    mystr='';
end
mystr=strcat(instr,mystr);
fprintf('The string is %s\n',mystr)
end
```

What would be the result of the following sequential expressions?

```
strfunc('hi')
strfunc("hello")
```

Note that the argument can be either a character vector or string.

9. Write a function "faveprompt" that prompts the user for his or her favorite 'something' where 'something' is a string that is passed to the function. For example, it might prompt the user for a favorite food, or favorite color. The function will error-check until the user enters a string (of any length except 0), and returns that string.
10. Create a string array that contains pet types, e.g.,

    ```
    pets=["cat" "dog" "gerbil"];
    ```

    Show the difference in the following methods of indexing into the first two strings:

    ```
    pets(1:2)
    pets{1:2}
    [p1 p2]=pets{1:2}
    ```

11. Show the difference between assigning an empty vector to an element in a string array, by using parentheses and by using curly braces to index into the element.
12. Given the following variables:

    ```
    >> mystring="No Halloween Parties!!";
    >> yourchvec='Be Safe!!';
    ```

    Explain why length(yourchvec) is 9 but length(mystring) is 1. Also, show how you could index into mystring to get the 'H' using just one expression, without using any functions, and **explain your answer**.
13. Explain why you would use **strlength** for a string instead of **length**. Give examples.
14. Explain in words what the following function accomplishes (not step-by-step, but what the end result is).

    dostr.m

    ```
    function out=dostr(inp)
    persistent str
    [w, r]=strtok(inp);
    str=strcat(str,w);
    out=str;
    end
    ```

15. Write a function "createUniqueName" that will create a series of unique names. When the function is called, a string or character vector is passed as an input argument. The function adds an integer to the end of the input, and returns the resulting text. Every time the function is called, the integer that it adds is incremented. Here are some examples of calling the function:

```
>> createUniqueName("myvar")
ans=
    "myvar1"
>> createUniqueName('filename')
ans=
    'filename2'
```

16. Write a function that will prompt the user separately for a filename and extension and will create and return a string with the form 'filename.ext'.
17. Write a function that will receive one input argument, which is an integer *n*. The function will prompt the user for a number in the range from 1 to *n* (the actual value of *n* should be printed in the prompt) and return the user's input. The function should error-check to make sure that the user's input is in the correct range.
18. Write a script that will generate a random integer, ask the user for a field width, and print the random integer with the specified field width. The script will use **sprintf** to create a string such as "The # is %4d\n" (if, for example, the user entered 4 for the field width) which is then passed to the **fprintf** function. To print (or create a string using **sprintf**) either the % or \ character, there must be two of them in a row.
19. If the strings (or character vectors) passed to **strfind** are the same length, what are the only two possible results that could be returned?
20. Vectorize this for a character vector *mystrn*:

```
while mystrn(end)== ' '   % Note one space in quotes
      mystrn=mystrn(1:end-1);
end
```

21. Vectorize this for a character vector sentence:

```
loc=findstr(sentence, ' ');
where=loc(1);
first=sentence(1:where-1);

last=sentence(where:end);
```

22. Vectorize this:

```
vec=[];
for i=1:8
   vec=[ vec ' '];  % one blank space
end
vec % just for display
```

23. Write a function *nchars* that will create a character vector of n characters, without using any loops or selection statements.

```
>> nchars('*', 6)
ans=
    '*****'
```

24. Write a function *rid_multiple_blanks* that will receive a string or character vector as an input argument. The text input contains a sentence that has multiple blank spaces in between some of the words. The function will return the text (as a character vector or a string, depending on what type the input argument was) with only one blank in between words. For example,

```
>> mystr='Hello  and how  are  you?';
>> rid_multiple_blanks(mystr)
ans=
'Hello and how are you? '
```

25. Two variables store character vectors that consist of a letter of the alphabet, a blank space, and a number (in the form 'R 14.3'). Write a script that would initialize two such variables. Then, use functions to extract the numbers from the character vectors and add them together.
26. Load files named *file1.dat*, *file2.dat*, and so on in a loop. To test this, create just 2 files with these names in your Current Folder first.
27. Create the following three variables:

```
>> var1=123;
>> var2='123';
>> var3="123";
```

Then, add 1 to each of the variables. Explain the differences.

28. Use **help isstrprop** to find out what properties can be tested; try some of them on a string variable.
29. Write a script that will first initialize a character vector variable that will store x and y coordinates of a point in the form 'x 3.1 y 6.4'. Then, use text manipulating functions to extract the coordinates and plot them.
30. Write a function *plotstuff* that will receive an x vector and a positive integer n. It will plot, in one Figure Window, sin(1*x), sin(2*x), etc. up to sin(n*x) in a row using black *'s. Put sin(1x), sin(2x), etc. in the individual plot titles.
31. Investigate the use of the **date** function. Replace the dashes in the result with spaces.
32. Investigate the use of the **datestr** function, for example with **datestr(now)**. Extract the date and time separately.

Data Science and Machine Learning

33. Create x and y vectors (with the same length), as in:

```
x=1:10;
y=[2, 2.7, 3.8, 4, 4.5, 5.3, 6.3, 6.4, 7.1, 9];
```

Plot the vectors with their correlation coefficient in the title.

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CHAPTER 8

Data Structures

KEY TERMS

data structures
cell array
structures
fields
database
record
categorical arrays
tables
sorting
cells
content indexing
cell indexing
comma-separated list
dot operator
dynamic field names
vector of structures
nested structure
categorical arrays
ordinal categorical arrays
descending order
ascending order
selection sort

CONTENTS

Data structures are variables that store more than one value. For it to make sense to store more than one value in a variable, the values should somehow be logically related. There are many different kinds of data structures. We have already been working with one kind, arrays (e.g., vectors and matrices). An array is a data structure in which all of the values are logically related in that they are of the same type and represent, in some sense, “the same thing”. So far, that has been true for the vectors and matrices that we have used. We use vectors and matrices when we want to be able to loop through them (or, essentially, have this done for us using vectorized code).

A ***cell array*** is a kind of data structure that stores values of different types. Cell arrays can be vectors or matrices; the different values are referred to as the elements of the array. One very common use of a cell array in previous versions of the MATLAB® software was to store strings of different lengths, although as of R2016b string arrays are now used for strings of different lengths.

Structures are data structures that group together values that are logically related but are not the same thing and not necessarily the same type. The different values are stored in separate ***fields*** of the structure.

One use of structures is to set up a ***database*** of information. For example, a professor might want to store for every student in a class: the student’s name,

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00008-1

university identifier number, grades on all assignments and quizzes, and so forth. In many programming languages and database programs, the terminology is that within a database file there would be one ***record*** of information for each student; each separate piece of information (name, quiz 1 score, and so on) would be called a ***field*** of the record. In MATLAB , these records are called structures, or **structs**.

Both cell arrays and structures can be used to store values that are different types in a single variable. The main difference between them is that cell arrays are indexed and can therefore be used with loops or vectorized code. Structures, however, are not indexed; the values are referenced using the names of the fields, which are more mnemonic than indexing.

Other, more advanced, data structures are also covered in this chapter. These include ***categorical arrays*** and ***tables***. Categorical arrays are a type of array that allows one to store a finite, countable number of different possible values. A ***table*** is a data structure that stores information in a table format with rows and columns, each of which can be mnemonically labeled. An advantage of a table is that information can be extracted using either numeric indexing or by using row and variable names.

Finally, ***sorting*** the various types of data structures will be covered, both programmatically and using built-in sort functions.

8.1 CELL ARRAYS

A ***cell array*** in MATLAB is an array, but, unlike the vectors and matrices we have used so far, elements in cell arrays are ***cells*** that can store different types of values.

8.1.1 Creating Cell Arrays

There are several ways to create cell arrays. For example, we will create a cell array in which one element will store an integer, one element will store a character, one element will store a vector, and one element will store a string. Just like with the arrays we have seen so far, this could be a *1 × 4* row vector, a *4 × 1* column vector, or a *2 × 2* matrix. Some of the syntax for creating vectors and matrices is the same as before in that values within rows are separated by spaces or commas, and rows are separated by semicolons. However, for cell arrays, curly braces are used rather than square brackets. For example, the following creates a row vector cell array with four different types of values:

```
>> cellrowvec={23, 'a', 1:2:9, "hello"}
cellrowvec=
  1×4 cell array
    {[23]}    {'a'}    {1×5 double}    {["hello"]}
```

This method creates a 2 × 2 cell array matrix:

```
>> cellmat={23, 'a'; 1:2:9, "hello"}
cellmat=
  2×2 cell array
   {[       23]}     {'a'        }
   {1×5 double}     {["hello"]}
```

The type of cell arrays is **cell**.

```
>> class(cellmat)
ans=
    'cell'
```

Another method of creating a cell array is simply to assign values to specific array elements and build it up element by element. However, as explained before, extending an array element by element is a very inefficient and time-consuming method.

It is much more efficient, if the size is known ahead of time, to preallocate the array. For cell arrays, this is done with the **cell** function. For example, to preallocate a variable *mycellmat* to be a 2 × 2 cell array, the **cell** function would be called as follows:

Note

that this is a function call, so the arguments to the function are in parentheses; a matrix is created in which all of the elements are empty vectors. Then, each element can be replaced by the desired value.

```
>> mycellmat=cell(2,2)
mycellmat=
  2×2 cell array
   {0×0 double}    {0×0 double}
   {0×0 double}    {0×0 double}
```

How to refer to each element to accomplish this will be explained next.

8.1.2 Referring to and Displaying Cell Array Elements and Attributes

Just like with the other vectors we have seen so far, we can refer to individual elements of cell arrays. However, with cell arrays, there are two different ways to do this. The elements in cell arrays are cells. These cells can contain different types of values. With cell arrays, you can refer to the cells, or to the contents of the cells.

Using curly braces for the subscripts will reference the contents of a cell; this is called ***content indexing***. For example, this refers to the contents of the second element of the cell array *cellrowvec*; *ans* will have the type **char**:

```
>> cellrowvec{2}
ans=
    'a'
```

Values can be assigned to cell array elements. For example, after preallocating the variable *mycellmat* in the previous section, the elements can be initialized:

```
>> mycellmat{1,1}=23
mycellmat=
    2×2 cell array
      {[       23]}      {0×0 double}
      {0×0 double}      {0×0 double}
```

Using parentheses for the subscripts references the cells; this is called ***cell indexing***. For example, this refers to the second cell in the cell array *cellrowvec*; *onec* will be a *1*×*1* **cell** array:

```
>> onec=cellrowvec(2)
onec=
   1×1 cell array
     {'a'}
>> class(onec)
ans=
    'cell'
```

When an element of a cell array is itself a data structure, only the type of the element is displayed when the cells are shown. For example, in the previous cell arrays, the vector is shown just as "*1* × *5* double" (this is a high-level view of the cell array). This is what will be displayed with cell indexing; content indexing would display its contents:

```
>> cellmat(2,1)
     1×1 cell array
       {1×5 double}

>> cellmat{2,1}
ans=
      1      3      5      7      9
```

Note

that the index into the cell array is given in curly braces; parentheses are then used to refer to an element of the vector.

Because this results in a vector, parentheses can be used to refer to its elements. For example, the fourth element of the vector is:

```
>> cellmat{2,1}(4)
ans=
      7
```

One can also refer to subsets of cell arrays, such as in the following:

```
>> cellrowvec{2:3}
ans=
    'a'
ans=
      1      3      5      7      9
```

Note, however, that MATLAB stored *cellrowvec*{2} in the default variable *ans*, and then replaced that with the value of *cellrowvec*{3}. Using content indexing returns them as a ***comma-separated list***. However, they could be stored in two separate variables by having a vector of variables on the left side of an assignment:

```
>> [c1, c2]=cellrowvec{2:3}
c1=
    'a'
c2=
     1      3      5      7      9
```

Using cell indexing, the two cells would be put in a new cell array (in this case, in *ans*):

```
>> cellrowvec(2:3)
ans=
  1×2 cell array
     {'a'       }   {1×5 double}
```

There are several methods for displaying cell arrays. The **celldisp** function displays the contents of all elements of the cell array. The function **cellplot** puts a graphical display of the cell array into a Figure Window; however, it is a high-level view and basically just displays the same information as typing the name of the variable (so, for instance, it would not show the contents of the vector in the previous example). In other words, it shows the cells, not their contents.

Note
that the cell indexing using parentheses and the content indexing using curly braces is analogous to the methods for indexing into string arrays. With a string array, using parentheses refers to an individual string scalar, whereas using curly braces refers to the character vector that is stored within the string.

Many of the functions and operations on arrays that we have already seen also work with cell arrays, such as dimensioning.

8.1.3 Storing Character Vectors in Cell Arrays

One useful application of a cell array is to store character vectors of different lengths. Because cell arrays can store different types of values, character vectors of different lengths can be stored in the elements. Prior to R2016b, this was the preferred method for storing strings of different lengths. Now, however, string arrays are preferred.

```
>> cvnames={'Sue', 'Cathy', 'Xavier'}
cvnames=
  1×3 cell array
     {'Sue'}    {'Cathy'}    {'Xavier'}
```

It is possible to convert from a cell array of character vectors to a string array, and vice versa. MATLAB has several functions that facilitate this. The **string** function can convert from a cell array to a string array. The **cellstr** function will convert from a string array to a cell array of character vectors.

The function **strjoin** will concatenate, or join, all strings from a cell array into one character vector separated by one space each by default (but other delimiters can be specified). The function **strsplit** will essentially do the opposite; it splits a string into elements in a cell array with either a specified delimiter or a blank space by default.

The function **iscellstr** will return **logical true** if a cell array is a cell array of all character vectors, or **logical false** if not.

```
>> iscellstr(cvnames)
ans=
    1

>> iscellstr(cellrowvec)
ans=
    0
```

We will see several examples that utilize cell arrays containing character vectors of varying lengths in later chapters, including advanced file input functions and customizing plots.

PRACTICE 8.1

Write an expression that would display a random element from a cell array (without assuming that the number of elements in the cell array is known). Create two different cell arrays and try the expression on them to make sure that it is correct.

For more practice, write a function that will receive one cell array as an input argument and will display a random element from it.

8.2 STRUCTURES

Structures are data structures that group together values that are logically related in what are called ***fields*** of the structure. An advantage of structures is that the fields are named, which helps to make it clear what values are stored in the structure. However, structure variables are not arrays. They do not have elements that are indexed, so it is not possible to loop through the values in a structure or to use vectorized code.

8.2.1 Creating and Modifying Structure Variables

Creating structure variables can be accomplished by simply storing values in fields using assignment statements or by using the **struct** function.

In our first example, assume that the local Computer Super Mart wants to store information on the software packages that it sells. For each one, they will store the following:

- item number
- cost to the store
- price to the customer
- character code indicating the type of software

An individual structure variable for a given software package might look like this:

package

item_no	cost	price	code
123	19.99	39.95	g

The name of the structure variable is *package*; it has four fields: *item_no*, *cost*, *price*, and *code*.

One way to initialize a structure variable is to use the **struct** function. The names of the fields are passed as character vectors (or strings as of R2018b); each one is followed by the value for that field. So, pairs of field names and values are passed to **struct**. These are called ***name-value pairs***.

Note that some programmers use names that begin with an uppercase letter for structure variables (e.g., *Package*) to make them easily distinguishable.

```
>> package=struct('item_no',123,'cost',19.99,...
     'price',39.95,'code','g')

package=
    item_no: 123
       cost: 19.9900
      price: 39.9500
       code: 'g'
```

As of R2021a, there is a new ***name = value*** syntax, which is much easier to read.

```
>> allpack=struct(item_no=123, cost=19.99,...
      price=39.95, code='g');
```

This name = value syntax can be used for any function that previously accepted name-value pairs, not just **struct**.

```
>> class(package)
ans=
   'struct'
```

Note that in the Workspace Window, the variable *package* is listed as a *1 x 1* struct; the type of the variable is **struct**.

MATLAB, as it is written to work with arrays, assumes the array format. Just like a single number is treated as a *1* × *1* double, a single structure is treated as a *1* × *1* struct. Later in this chapter we will see how to work more generally with vectors of structs.

The ***dot operator*** is used to refer to fields within the structure. The name of the structure variable is followed by a dot, or period, and then the name of the field within that structure.

```
>> package.code
ans=
   'g'
```

Adding a field to a structure later is inefficient but can be done by using an assignment statement, as in

```
>> allpack.weight=22
allpack=
  struct with fields:

    item_no: 123
       cost: 19.9900
      price: 39.9500
       code: 'g'
     weight: 22
```

An entire structure variable can be assigned to another. This would make sense, for example, if the two structures had some values in common. Here, for example, the values from one structure are copied into another and then two fields are selectively changed, referring to them using the dot operator.

```
>> newpack=package;
>> newpack.item_no=111;
>> newpack.price=34.95
newpack=
    item_no: 111
       cost: 19.9900
      price: 34.9500
       code: 'g'
```

To print from a structure, the **disp** function will display either the entire structure or an individual field.

```
>> disp(package)
    item_no: 123
       cost: 19.9900
      price: 39.9500
       code: 'g'

>> disp(package.cost)
   19.9900
```

However, using **fprintf** only individual fields can be printed; the entire structure cannot be printed without referring to all fields individually.

```
>> fprintf('%d %c\n', package.item_no, package.code)
123 g
```

The function **rmfield** removes a field from a structure. It returns a new structure with the field removed, but does not modify the original structure (unless the returned structure is assigned to that variable). To change the value of *newpack*, the structure that results from calling **rmfield** must be assigned to *newpack*.

```
>> newpack=rmfield(newpack, 'code')
newpack=
     item_no: 111
        cost: 19.9000
       price: 34.9500
```

PRACTICE 8.2

A silicon wafer manufacturer stores, for every part in its inventory, a part number, quantity in the factory, and the cost for each.

onepart

part_no	quantity	costper
123	4	33.95

Create this structure variable using **struct**. Print the cost in the form $xx.xx.

8.2.2 Passing Structures to Functions

An entire structure can be passed to a function or individual fields can be passed. For example, here are two different versions of a function that calculates the profit on a software package. The profit is defined as the price minus the cost.

In the first version, the entire structure variable is passed to the function, so the function must use the dot operator to refer to the *price* and *cost* fields of the input argument.

calcprof.m

```
function profit=calcprof(packstruct)
% calcprofit calculates the profit for a
% software package
% Format: calcprof(structure w/ price & cost fields)

profit=packstruct.price - packstruct.cost;
end
```

```
>> calcprof(package)
ans=
 19.9600
```

In the second version, just the *price* and *cost* fields are passed to the function using the dot operator in the function call. These are passed to two scalar input arguments in the function header, so there is no reference to a structure variable in the function itself, and the dot operator is not needed in the function.

calcprof2.m

```
function profit=calcprof2(oneprice, onecost)
% Calculates the profit for a software package
% Format: calcprof2(price, cost)

profit=oneprice - onecost;
end
```

```
>> calcprof2(package.price, package.cost)
ans=
   19.9600
```

It is important, as always with functions, to make sure that the arguments in the function call correspond one-to-one with the input arguments in the function header. In the case of *calcprof*, a structure variable is passed to an input argument, which is a structure. For the second function *calcprof2*, two individual numbers (which could be fields from a structure) which are **double** values, are passed to two **double** input arguments.

8.2.3 Related Structure Functions

There are several functions that can be used with structures in MATLAB. The function **isstruct** will return **logical** 1 for **true** if the variable argument is a structure variable or 0 if not. The **isfield** function returns **logical true** if a fieldname (as a character vector or string) is a field in the structure argument or **logical false** if not.

```
>> isstruct(package)
ans=
    1

>> isfield(package,'cost')
ans=
    1
```

The **fieldnames** function will return the names of the fields that are contained in a structure variable.

```
>> pack_fields=fieldnames(package)
pack_fields=
  4×1 cell array
     {'item_no'}
     {'cost'    }
     {'price'   }
     {'code'    }
```

As the names of the fields are of varying lengths, the **fieldnames** function returns a cell array with the names of the fields as character vectors.

QUICK QUESTION!

How can we ask the user for a field in a structure and either print its value or an error if it is not actually a field?

Answer: To do this, we need to use a ***dynamic field name*** to refer to a field in the structure. A static field name is

```
struct.fieldname'
```

whereas a dynamic field name uses a character vector

```
struct.('fieldname')
```

which means that the fieldname could be read in from the user. The **isfield** function can be used to determine whether or not it is a field of the structure. Then, by using a dynamic field name, we can make the code general. The following is the code for the variable *package*:

```
   inputfield=input('Which field would you like to see: ','s');
if isfield(package, inputfield)
    fldtouse=package.(inputfield);
    fprintf('The value of the %s field is: ', ...
           inputfield)
    disp(fldtouse)
else
    fprintf('Error: %s is not a valid field\n', inputfield)
end
```

This code would produce this output (assuming the *package* variable was initialized as shown previously):

```
Which field would you like to see: cost
The value of the cost field is: 19.9900
```

Curly braces are used to refer to the elements, as *pack_fields* is a cell array. For example, we can refer to the length of one of the field names:

```
>> length(pack_fields{2})
ans=
    4
```

8.2.4 Vectors of Structures

In many applications, including database applications, information would normally be stored in a ***vector of structures***, rather than in individual structure variables. For example, if the computer super mart is storing information on all of the software packages that it sells, it would likely be in a vector of structures such as the following:

packages

	item_no	cost	price	code
1	123	19.99	39.95	g
2	456	5.99	49.99	l
3	587	11.11	33.33	w

In this example, *packages* is a vector that has three elements. It is depicted as a column vector, although it may be a row vector. Each element is a structure consisting of four fields: *item_no*, *cost*, *price*, and *code*. It may look like a matrix, which has rows and columns, but it is, instead, a vector of structures.

This vector of structures can be created several ways. One method is to create a structure variable, as shown earlier, to store information on one software package. This can then be expanded to be a vector of structures by assigning to packages(2) and packages(3).

Alternatively, the first structure could be treated as a vector to begin with by assigning to packages(1), then packages(2), then packages(3).

Both of these methods, however, involve extending the vector. As we have already seen, preallocating any vector in MATLAB is more efficient than extending it. There are several methods of preallocating the vector. By starting with the last element, MATLAB would create a vector with that many elements. Then, the elements from 1 through end-1 could be initialized. For example, for a vector of structures that has three elements, start with the third element.

```
>> packages(3)=struct(item_no=587,cost=11.11,...
         price=33.33, code='w');
>> packages(1)=struct(item_no=123,cost=19.99,...
         price=39.95, code='g');
>> packages(2)=struct(item_no=456, cost=5.99,...
         price=49.99,code='l');
```

Also, the vector of structures can be preallocated without assigning any values.

```
>> packages(3)= ...
   struct('item_no',[],'cost',[],'price',[],'code',[])
packages=
1x3 struct array with fields:
    item_no
    cost
    price
    code
```

Then, the values in the individual structures could be replaced in any order.

Typing the name of the variable will display only the size of the structure vector and the names of the fields:

```
>> packages
packages=
1x3 struct array with fields:
    item_no
    cost
    price
    code
```

The variable *packages* is now a vector of structures, so each element in the vector is a structure. To display one element in the vector (one structure), an index into the vector would be specified. For example, to refer to the second element:

```
>> packages(2)
ans=
   item_no: 456
      cost: 5.9900
     price: 49.9900
      code: 'l'
```

To refer to a field, it is necessary to refer to the particular structure, and then the field within it. This means using an index into the vector to refer to the structure, and then the dot operator to refer to a field. For example:

```
>> packages(1).code
ans=
   'g'
```

Thus, there are essentially three levels to this data structure. The variable *packages* is the highest level, which is a vector of structures. Each of its elements is an individual structure. The fields within these individual structures are the lowest level.

To refer to a particular field for all structures, in most programming languages it would be necessary to loop through all elements in the vector and use the dot operator to refer to the field for each element. However, this is not the case in MATLAB.

For example, to print all of the costs, the **fprintf** would do this automatically in MATLAB:

```
>> fprintf('%f\n',packages.cost)
19.990000
5.990000
11.110000
```

Using the dot operator in this manner to refer to all values of a field would result in the values being stored successively in the default variable *ans* as this method results in a comma-separated list:

```
>> packages.cost
ans=
   19.9900

ans=
   5.9900

ans=
   11.1100
```

However, the values can all be stored in a vector by using square brackets.

```
>> pc=[packages.cost]
pc=
  19.9900    5.9900    11.1100
```

Using this method, MATLAB allows the use of functions on all of the same fields within a vector of structures. For example, to sum all three cost fields, the vector of cost fields is passed to the **sum** function:

```
>> sum([packages.cost])
ans=
   37.0900
```

For vectors of structures, the entire vector (e.g., *packages*) could be passed to a function, or just one element (e.g., *packages(1)*) which would be a structure, or a field within one of the structures (e.g., *packages(2).price*).

PRACTICE 8.3

A silicon wafer manufacturer stores, for every part in their inventory, a part number, how many are in the factory, and the cost for each. First, create a vector of structs called *parts* so that when displayed it has the following values:

```
>> parts
parts=
1x3 struct array with fields:
    partno
    quantity
    costper

>> parts(1)
ans=
    partno: 123
  quantity: 4
   costper: 33

>> parts(2)
ans=
    partno: 142
  quantity: 1
   costper: 150
```

```
>> parts(3)
ans=
      partno: 106
    quantity: 20
     costper: 7.5000
```

Next, write general code that will, for any values and any number of structures in the variable *parts*, print the part number and the total cost (quantity of the parts multiplied by the cost of each) in a column format.

For example, if the variable *parts* stores the previous values, the result would be:

```
123 132.00
142 150.00
106 150.00
```

The previous example involved a vector of structs. In the next example, a somewhat more complicated data structure will be introduced: a vector of structs in which some fields are vectors themselves. The example is a database of information that a professor might store for a course. This will be implemented as a vector of structures. The vector will store all of the course information.

Every element in the vector will be a structure, representing all information about one particular student. For every student, the professor wants to store (for now, this would be expanded later):

- name (a character vector)
- university identifier (ID) number
- quiz scores (a vector of four quiz scores)

The vector variable, called *student*, might look like the following:

		student				
	name	id_no	quiz			
			1	2	3	4
1	C, Joe	999	10.0	9.5	0.0	10.0
2	Hernandez, Pete	784	10.0	10.0	9.0	10.0
3	Brownnose, Violet	332	7.5	6.0	8.5	7.5

Each element in the vector is a struct with three fields (*name, id_no, quiz*). The *quiz* field is a vector of quiz grades. The *name* field is a character vector.

This data structure could be defined as follows.

```
>> student(3)=struct('name','Brownnose, Violet',...
   'id_no',332,'quiz', [7.5 6 8.5 7.5]);
>> student(1)=struct('name','C, Joe',...
   'id_no',999,'quiz', [10 9.5 0 10]);
>> student(2)=struct('name','Hernandez, Pete',...
   'id_no',784,'quiz', [10 10 9 10]);
```

Once the data structure has been initialized, in MATLAB we could refer to different parts of it. The variable *student* is the entire array; MATLAB just shows the names of the fields.

```
>> student
student=
1x3 struct array with fields:
    name
    id_no
    quiz
```

To see the actual values, one would have to refer to individual structures and/or fields.

```
>> student(1)
ans=
     name: 'C, Joe'
    id_no: 999
     quiz: [10 9.5000 0 10]

>> student(1).quiz
ans=
   10.0000         9.5000    0   10.0000

>> student(1).quiz(2)
ans=
   9.5000

>> student(3).name(1)
ans=
    'B'
```

With a more complicated data structure like this, it is important to be able to understand different parts of the variable. The following are examples of expressions that refer to different parts of this data structure:

- `student` is the entire data structure, which is a vector of structs
- `student(1)` is an element from the vector, which is an individual struct
- `student(1).quiz` is the *quiz* field from the structure, which is a vector of **double** values
- `student(1).quiz(2)` is an individual **double** quiz grade
- `student(3).name(1)` is the first letter of the third student's name (a **char**)

One example of using this data structure would be to calculate and print the quiz average for each student. The following function accomplishes this. The *student* structure, as defined before, is passed to this function. The algorithm for the function is:

- Print column headings
- Loop through the individual students; for each:
  - Calculate the average of the quiz grades
  - Print the student's name and quiz average

With the programming method, a second (nested) loop would be required to find the running sum of the quiz grades. However, we can use the **mean** function to find the aveage grades for each student. The function is defined as follows:

```
printAves.m
```

```
function printAves(student)
% This function prints the average quiz grade
% for each student in the vector of structs
% Format: printAves(student array)

fprintf('%-20s %-10s\n', 'Name', 'Average')
for i=1:length(student)
    ave=mean([student(i).quiz]);
    fprintf('%-20s %.1f\n', student(i).name, ave);
end
```

Here is an example of calling the function:

```
>> printAves(student)
Name                 Average
C, Joe               7.4
Hernandez, Pete      9.8
Brownnose, Violet    7.4
```

8.2.5 Nested Structures

A ***nested structure*** is a structure in which at least one member is itself a structure. For example, a structure for a line segment might consist of fields representing the two points at the ends of the line segment. Each of these points would be represented as a structure consisting of the x and y coordinates.

lineseg			
endpoint1		endpoint2	
x	y	x	y
2	4	1	6

This shows a structure variable called *lineseg* that has two fields for the endpoints of the line segment, *endpoint1* and *endpoint2*. Each of these is a structure consisting of two fields for the x and y coordinates of the individual points, *x* and *y*.

One method of defining this is to nest calls to the **struct** function:

```
>> lineseg=struct('endpoint1',struct(x=2, y=4), ...
                  'endpoint2',struct(x=1, y=6))
```

This method is the most efficient.

Another method would be to create structure variables first for the points, and then use these for the fields in the **struct** function (instead of using another **struct** function).

```
>> pointone=struct(x=5, y=11);
>> pointtwo=struct(x=7, y=9);
>> lineseg=struct(endpoint1=pointone,...
                  endpoint2=pointtwo);
```

Once the nested structure has been created, we can refer to different parts of the variable *lineseg*. Just typing the name of the variable shows only that it is a structure consisting of two fields, *endpoint1* and *endpoint2*, each of which is a structure.

```
>> lineseg
lineseg=
    endpoint1: [1x1 struct]
    endpoint2: [1x1 struct]
```

Typing the name of one of the nested structures will display the field names and values within that structure:

```
>> lineseg.endpoint1
ans=
   x: 2
   y: 4
```

Using the dot operator twice will refer to an individual coordinate, such as in the following example:

```
>> lineseg.endpoint1.x
ans=
    2
```

QUICK QUESTION!

How could we write a function *strpoint* that returns a string "(x,y)" containing the x and y coordinates? For example, it might be called separately to create strings for the two endpoints and then printed as shown here:

```
>> fprintf('The line segment consists of %s and %s\n',...
   strpoint(lineseg.endpoint1), ...
   strpoint(lineseg.endpoint2))
The line segment consists of (2, 4) and (1, 6)
```

Answer: As an *endpoint* structure is passed to an input argument in the function, the dot operator is used within the function to refer to the x and y coordinates. The **sprintf** function is used to create the string that is returned.

strpoint.m

```
function ptstr=strpoint(ptstruct)
% strpoint receives a struct containing x
and y
% coordinates and returns a string '(x,y)'
% Format: strpoint(structure with x and y
fields)

ptstr=sprintf("(%d, %d) ", ptstruct.x,...
ptstruct.y);
end
```

8.2.6 Vectors of Nested Structures

Combining vectors and nested structures, it is possible to have a vector of structures in which some fields are structures themselves. Here is an example in which a company manufactures cylinders from different materials for industrial use. Information on them is stored in a data structure in a program. The variable *cyls* is a vector of structures, each of which has fields *code*, *dimensions*, and *weight*. The *dimensions* field is a structure itself consisting of fields *rad* and *height* for the radius and height of each cylinder.

	cyls			
	code	dimensions		weight
		rad	height	
1	x	3	6	7
2	a	4	2	5
3	c	3	6	9

The following is an example of initializing the data structure by preallocating:

```
>> cyls(3)=struct(code='c', dimensions=...
     struct(rad=3, height=6), weight=9);
>> cyls(1)=struct(code='x', dimensions=...
     struct(rad=3, height=6), weight=7);
>> cyls(2)=struct(code='a', dimensions=...
     struct(rad=4, height=2), weight=5);
```

There are several layers in this variable. For example:

- `cyls` is the entire data structure, which is a vector of structs
- `cyls(1)` is an individual element from the vector, which is a struct
- `cyls(2).code` is the *code* field from the struct *cyls(2)*; it is a **char**
- `cyls(3).dimensions` is the *dimensions* field from the struct *cyls(3)*; it is a struct itself
- `cyls(1).dimensions.rad` is the *rad* field from the struct *cyls(1).dimensions*; it is a **double** number

For these cylinders, one desired calculation may be the volume of each cylinder, which is defined as $\pi * r^2 * h$, where r is the radius and h is the height. The following function *printcylvols* prints the volume of each cylinder, along with its code for identification purposes. It calls a local function to calculate each volume.

printcylvols.m

```
function printcylvols(cyls)
% printcylvols prints the volumes of each cylinder
% in a specialized structure
% Format: printcylvols(cylinder structure)

% It calls a local function to calculate each volume

for i=1:length(cyls)
    vol=cylvol(cyls(i).dimensions);
    fprintf('Cylinder %c has a volume of %.1f in^3\n', ...
       cyls(i).code, vol);
end
end

function cvol=cylvol(dims)
% cylvol calculates the volume of a cylinder
% Format: cylvol(dimensions struct w/ fields 'rad', 'height')

cvol=pi*dims.rad ^ 2*dims.height;
end
```

The following is an example of calling this function.

```
>> printcylvols(cyls)
Cylinder x has a volume of 169.6 in^3
Cylinder a has a volume of 100.5 in^3
Cylinder c has a volume of 169.6 in^3
```

Note that the entire data structure, *cyls*, is passed to the function. The function loops through every element, each of which is a structure. It prints the *code* field for each, which is given by *cyls(i).code*. To calculate the volume of each cylinder, only the radius and height are needed, so rather than passing the entire structure to the local function *cylvol* (which would be *cyls(i)*), only the *dimensions* field is passed (*cyls(i).dimensions*). The function then receives the *dimensions* structure as an input argument and uses the dot operator to refer to the *rad* and *height* fields within it.

PRACTICE 8.4

Modify the function *cylvol* to calculate and return the surface area of the cylinder in addition to the volume (2 pi r^2+2 pi r h).

8.3 ADVANCED DATA STRUCTURES

MATLAB has several types of data structures in addition to the arrays, cell arrays, and structures that we have already seen. These can be found in the Documentation under Data Types.

8.3.1 Categorical Arrays

Categorical arrays are a type of array that allows one to store a finite, countable number of different possible values. Categorical arrays are defined using the **categorical** function.

For example, a group is polled on their favorite ice cream flavors; the results are stored in a categorical array:

```
>> icecreamfaves=categorical({'Vanilla', 'Chocolate', ...
'Chocolate', 'Rum Raisin', 'Vanilla', 'Strawberry', ...
'Chocolate', 'Rocky Road', 'Chocolate', 'Rocky Road', ...
'Vanilla', 'Chocolate', 'Strawberry', 'Chocolate'});
```

Another way to create this would be to store the strings in a cell array, and then convert using the **categorical** function:

```
>> cellicecreamfaves={'Vanilla', 'Chocolate', ...
'Chocolate', 'Rum Raisin', 'Vanilla', 'Strawberry', ...
'Chocolate', 'Rocky Road', 'Chocolate', 'Rocky Road', ...
'Vanilla', 'Chocolate', 'Strawberry', 'Chocolate'}
>> icecreamfaves=categorical(cellicecreamfaves);
```

There are several functions that can be used with categorical arrays. The function **categories** will return the list of possible categories as a cell column vector, sorted in alphabetical order.

```
>> cats=categories(icecreamfaves)
cats=
  5×1 cell array
     {'Chocolate' }
     {'Rocky Road'}
     {'Rum Raisin'}
     {'Strawberry'}
     {'Vanilla'   }
```

The functions **summary** and **countcats** will show the number of occurrences of each of the categories.

```
>> summary(icecreamfaves)
Chocolate  Rocky Road  Rum Raisin  Strawberry  Vanilla
        6           2           1           2        3
>>countcats(icecreamfaves)
ans=
     6     2     1     2     3
```

In the case of the favorite ice cream flavors, there is no natural order for them, so they are listed in alphabetical order. It is also possible to have ***ordinal categorical arrays***, however, in which an order is given to the categories.

For example, a person has a wearable fitness tracker that tracks the days on which a personal goal for the number of steps taken is reached; these are stored in a file. To simulate this, a variable *stepgoalsmet* stores these data for a few weeks. Another cell array stores the possible days of the week.

```
>> stepgoalsmet={'Tue', 'Thu', 'Sat', 'Sun', ...
'Tue', 'Sun', 'Thu', 'Sat', 'Wed', 'Sat', 'Sun'};
>> daynames=...
{'Mon','Tue','Wed','Thu','Fri','Sat','Sun'};
```

Then, an ordinal categorical array, *ordgoalsmet*, is created. This allows days to be compared using relational operators.

```
>> ordgoalsmet= categorical(stepgoalsmet,daynames,'Ordinal',true);
>> summary(ordgoalsmet)
     Mon      Tue      Wed      Thu      Fri      Sat      Sun
       0        2        1        2        0        3        3
>> ordgoalsmet(1) < ordgoalsmet(3)
ans=
    1
>> ordgoalsmet(4) < ordgoalsmet(3)
ans=
    0
```

8.3.2 Tables

A ***table*** is a data structure that stores information in a table format with rows and columns, each of which can be mnemonically labeled. The table is created using variables that have the same length, and might be stored in columns, for example, in a spreadsheet.

We saw in Chapter 1 that MATLAB has MAT-files, which store variables (names and contents). There are built-in MAT-files. For example, the file "census.mat" stores US census data every 10 years from 1790 to 1990. To use this, we can load the .mat file, find out what variables there are, and combine them to form a table using the **table** function:

```
>> clear
>> load census
>> whos
   Name      Size           Bytes Class
   cdate     21x1             168 double
   pop       21x1             168 double
>> censustable=table(cdate, pop);
```

There are 21 rows altogether. To display only the first eight rows, the **head** function can be used, and the **tail** function will display the last eight rows.

```
>> tail(censustable)
ans=
  8×2 table
    cdate    pop
    _____    _____
    1920     105.7
    1930     122.8
    1940     131.7
    1950     150.7
    1960       179
    1970       205
```

```
        1980      226.5
        1990      248.7
```

Notice that the names of the variables became the names of the columns (which are called variables). There are many ways to index into tables, to either create a new table that is a subset of the original, or to extract information from the table into other types of data structures. Using parentheses, we can index into this table to get a subset of the table, which would also be a table. The indexing can be done using integers (as with arrays we have seen so far) or with the variable name. For example, we can extract the first three rows to create a smaller table that will be easier to work with:

```
>> earlycens=censustable(1:3, :)
earlycens=
  3×2 table
     cdate     pop
     _____     ___
     1790      3.9
     1800      5.3
     1810      7.2
```

To extract the first column, we can use the integer index or the variable name. Both of these produce the same result:

```
>> earlycens(:,1);
>> earlycens(:,'cdate')
ans=
  3×1 table
     cdate
     _____
     1790
     1800
     1810
```

The dot operator can also be used, but this returns a column vector instead of a table:

```
>> earlycens.cdate
ans=
        1790
        1800
        1810
```

In R2020a, the function **renamevars** was introduced to rename the variables, using string arrays for the old and new names.

```
>> earlycens=renamevars(earlycens, ["cdate", "pop"], ...
                 ["Date", "Pop"])
earlycens=
  3×2 table
     Date    Pop
     ____    ___
     1790    3.9
     1800    5.3
     1810    7.2
```

Other table variable functions, which were introduced in R2018a, include:

- **addvars** to add variable(s)
- **removevars** to remove variable(s)
- **movevars** to move the location of variable(s)

The **array2table** function can be used to create a table from a matrix. For example, a matrix is created using the original two column vectors, and then this matrix is transformed into a table. Notice the variable names, which could be changed.

```
>> cenmat=[cdate pop];
>> centab=array2table(cenmat);
>> centab(1:3,:)
ans=
  3×2 table
     cenmat1     cenmat2

     _______     _______
     1790          3.9
     1800          5.3
     1810          7.2
```

As another example, the following uses the **table** function to store some simple information for a doctor's patients. In this case, we will create both row and column (variable) labels. There are just three patients, so there are three names in one cell array that will be used to refer to the rows, and the heights and weights of the patients are stored in column vectors (each of which has three values). The column vectors do not need to store the same types of values, but they must be the same length.

```
>> names={'Harry','Sally','Jose'};
>> weights=[185; 133; 210]; % Note column vectors
>> heights=[74; 65.4; 72.2];
>> patients=table(weights, heights, 'RowNames', names)
patients=
   3×2 table
                weights     heights

                 _______     _______
      Harry     185           74
      Sally     133         65.4
      Jose      210         72.2
```

This created a *3x2* table, with two variables named *weights* and *heights*. We can index into the rows using integers, as we have seen, or using the row names.

```
>> patients({'Harry' 'Jose'}, :)
ans=
             weights     heights

             _______     _______
     Harry   185           74
     Jose    210         72.2
```

Using curly braces to index, the data can be extracted, in the following example, into a **double** matrix or column vector.

```
>> mat=patients{{'Harry' 'Jose'}, :}
mat=
    185.0000    74.0000
    210.0000    72.2000
```

Notice that either numerical indices can be used, or the more mnemonic row or variable names. Tables combine the mnemonic names that structures have with the ability to index that is found in arrays.

The **summary** function can be used for tables; it shows the variables and some statistical data for each.

```
>> summary(patients)
Variables:
    weights: 3x1 double
        Values:
            min       133
            median    185
            max       210
    heights: 3x1 double
        Values:
            min       65.4
            median    72.2
            max         74
```

8.4 SORTING

Sorting is the process of putting a list in order - either ***descending*** (highest to lowest) or ***ascending*** (lowest to highest) order. For example, here is a list of *n* integers, visualized as a column vector.

1	85
2	70
3	100
4	95
5	80
6	91

What is desired is to sort this in ascending order in place by rearranging this vector, not creating another. The following is one basic algorithm.

- Look through the vector to find the smallest number and then put it in the first element in the vector. How? By exchanging it with the number currently in the first element.
- Then, scan the rest of the vector (from the second element down) looking for the next smallest (or, the smallest in the rest of the vector). When found, put it in the first element of the rest of the vector (again, by exchanging).
- Continue doing this for the rest of the vector. Once the next-to-last number has been placed in the correct location in the vector, the last number, by default, has been as well.

What is important in each pass through the vector is *where* the smallest value is so the elements to be exchanged are known (not what the actual smallest number is).

This table shows the progression. The left column shows the original vector. The second column (from the left) shows that the smallest number, the 70, is now in the first element in the vector. It was put there by exchanging with what had been in the first element, 85. This continues element-by-element, until the vector has been sorted.

85	70	70	70	70	70
70	85	80	80	80	80
100	100	100	85	85	85
95	95	95	95	91	91
80	80	85	100	100	95
91	91	91	91	95	100

This is called the ***selection sort***; it is one of many different sorting algorithms.

THE TRADITIONAL METHOD

The following function implements the selection sort to sort a vector:

mysort.m

```
function outv=mysort(vec)
% mysort sorts a vector using the selection sort
% Format: mysort(vector)

% Loop through the elements in the vector to end-1
for i=1:length(vec)-1
    indlow=i; % stores the index of the smallest
    % Find where the smallest number is
    %    in the rest of the vector
    for j=i+1:length(vec)
        if vec(j) < vec(indlow)
            indlow=j;
        end
    end
    % Exchange elements
    temp=vec(i);
    vec(i)=vec(indlow);
    vec(indlow)=temp;
end
outv=vec;
end
```

```
>> vec=[85 70 100 95 80 91];
>> vec=mysort(vec)
vec=
   70    80    85    91    95    100
```

THE EFFICIENT METHOD

MATLAB has a built-in function, **sort**, that will sort a vector in ascending order:

```
>> vec=[85 70 100 95 80 91];
>> vec=sort(vec)
vec=
   70    80    85    91    95    100
```

Descending order can also be specified. For example,

```
>> sort(vec,'descend')
ans=
    100     95     91     85     80     70
```

Note
that if we did not have the 'descend' option, **flip** could be used after sorting.

Sorting a row vector results in another row vector. Sorting a column vector results in another column vector.

The function **issorted** will return 1 for true if the argument is sorted, or 0 for false if not.

For matrices, the **sort** function will by default sort each column. To sort by rows, the dimension 2 is specified. For example,

```
>> mat
mat=
    4      6      2
    8      3      7
    9      7      1

>> sort(mat) % sorts by column
ans=
    4      3      1
    8      6      2
    9      7      7

>> sort(mat,2) % sorts by row
ans=
    2      4      6
    3      7      8
    1      7      9
```

8.4.1 Sorting Vectors of Structures

When working with a vector of structures, it is common to sort based on a particular field of the structures. For example, recall the vector of structures used to store information on different software packages that was created in Section 8.2.4.

packages

	item_no	cost	price	code
1	123	19.99	39.95	g
2	456	5.99	49.99	l
3	587	11.11	33.33	w

Here is a function that sorts this vector of structures in ascending order based on the *price* field.

mystructsort.m

```
function outv=mystructsort(structarr)
% mystructsort sorts a vector of structs on the price field
% Format: mystructsort(structure vector)

for i=1:length(structarr)-1
    indlow=i;
    for j=i+1:length(structarr)
        if structarr(j).price < structarr(indlow).price
            indlow=j;
        end
    end
    % Exchange elements
    temp=structarr(i);
    structarr(i)=structarr(indlow);
    structarr(indlow)=temp;
end
outv=structarr;
end
```

Note

that only the *price* field is compared in the sort algorithm, but the entire structure is exchanged. Consequently, each element in the vector, which is a structure of information about a particular software package, remains intact.

If we had a function *printpackages* that prints the information in a nice table format, calling the *mystructsort* function and also the function to print would demonstrate this:

```
>> printpackages(packages)

Item # Cost Price Code

   123  19.99  39.95   g
   456   5.99  49.99   l
   587  11.11  33.33   w

>> packByPrice=mystructsort(packages);
>> printpackages(packByPrice)

Item # Cost Price Code

   587  11.11  33.33   w
   123  19.99  39.95   g
   456   5.99  49.99   l
```

8.4.2 Sorting Other Types of Data Structures

For a string array, the **sort** function will sort the strings alphabetically.

```
>> wordarr=["Hello" "Howdy" "Hi" "Goodbye" "Ciao"];
>> sort(wordarr)
ans=
  1×5 string array
     "Ciao"    "Goodbye"    "Hello"    "Hi"    "Howdy"
```

For a character matrix, the **sort** function sorts column by column, using the ASCII equivalents of the characters. It can be seen from the results that the space character comes before the letters of the alphabet in the character encoding:

```
>> words=char('Hello', 'Howdy', 'Hi', 'Goodbye', 'Ciao')
words=
  5×7 char array
     'Hello  '
     'Howdy  '
     'Hi     '
     'Goodbye'
     'Ciao   '
>> sort(words)
ans=
  5×7 char array
     'Ce     '
     'Giad   '
     'Hildb  '
     'Hooloz '
     'Howoyye'
```

This is one reason that a character matrix is not a good idea! However, there is a way to sort these words, which are rows in the matrix. MATLAB has a function **sortrows** that will do this. The way it works is that it examines the row column by column starting from the left. If it can determine which letter comes first, it picks up the entire row and puts it in the first row. In this example, the first two rows are placed based on the first character, 'C' and 'G'. For the other three strings, they all begin with 'H' so the next column is examined. In this case, the rows are placed based on the second character, 'e', 'i', 'o'.

```
>> sortrows(words)
ans=
  5×7 char array
     'Ciao   '
     'Goodbye'
     'Hello  '
     'Hi     '
     'Howdy  '
```

The **sortrows** function sorts each row as a block, or group, and it will also work on numbers. In this example, the rows beginning with 3 and 4 are placed first.

Then, for the rows beginning with 5, the values in the second column (6 and 7) determine the order.

```
>> mat=[5 7 2; 4 6 7; 3 4 1; 5 6 2]
mat=
     5     7     2
     4     6     7
     3     4     1
     5     6     2
>> sortrows(mat)
ans=
     3     4     1
     4     6     7
     5     6     2
     5     7     2
```

The **sortrows** function can also be used to sort rows in a table, based on a particular column.

```
>> patients
patients=
  3×2 table
                weights    heights
                _______    _______
     Harry       185          74
     Sally       133        65.4
     Jose        210        72.2
>> sortrows(patients,'heights')
ans=
  3×2 table
                weights    heights
                _______    _______
     Sally       133        65.4
     Jose        210        72.2
     Harry       185          74
```

The function **issortedrows** can be used to determine whether the rows in a matrix or table are sorted, as they would be with **sortrows**.

To sort a cell array of character vectors, the **sort** function can be used. If the cell array is a row vector, a sorted row vector is returned and if the cell array is a column vector, a sorted column vector is returned. For example, note the transpose operator below which makes this a column vector.

```
>> engcellnames={'Chemical','Mechanical',...
    'Biomedical','Electrical', 'Industrial'};
>> sort(engcellnames')
ans=
  5×1 cell array
     {'Biomedical'}
     {'Chemical'  }
     {'Electrical'}
     {'Industrial'}
     {'Mechanical'}
```

Categorical arrays can also be sorted using the **sort** function. A non ordinal categorical array, such as *icecreamfaves*, will be sorted in alphabetical order.

```
>> sort(icecreamfaves)
ans=
Chocolate     Chocolate     Chocolate     Chocolate
Chocolate     Chocolate     Rocky Road    Rocky Road
Rum Raisin    Strawberry    Strawberry    Vanilla
Vanilla       Vanilla
```

An ordinal categorical array, however, will be sorted using the order specified. For example, the ordinal categorical array *ordgoalsmet* was created using *daynames*:

```
>> ordgoalsmet
ordgoalsmet=
     Tue      Thu      Sat      Sun      Tue      Sun
     Thu      Sat      Wed      Sat      Sun

>> daynames=...
      {'Mon','Tue','Wed','Thu','Fri','Sat','Sun'};
```

Thus, the sorting is done in the order given by *daynames*.

```
>> sort(ordgoalsmet)
ans=
     Tue      Tue      Wed      Thu      Thu      Sat
     Sat      Sat      Sun      Sun      Sun
```

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Datetime Objects

The function **datetime**, with no arguments, will create a datetime variable storing the current date and time. There are multiple formats for **datetime** values.

```
>> rightnow=datetime
rightnow=
  datetime
   23-May-2021 11:14:28
```

The class is shown next.

```
>> class(rightnow)
ans=
   'datetime'
```

Using the dot operator, the individual parts can be accessed using Year, Month, Day, Hour, Minute, Second, for example:

```
>> rightnow.Year
ans=
   2021
```

One-Hot Encoding to Transform Categorical Data

It is very common to have categorical feature columns in data tables. Some ML algorithms, however, can only use numerical data. To solve this, ***one-hot encoding*** can be used to transform categorical data into numerical data storing 1 for true or 0 for false. For example, data on universities might include the categories 'Public' or 'Private'. Here is an example of a table that has categorical values Public and Private.

```
universities=
  3×2 table
         Name          Type
    _______________   _______
    {'XYZ Univ'  }    Public
    {'TheBest'   }    Private
    {'AB College'}    Public
```

A new column IsPublic is created and added to the table using the **addvars** function. This column has 1 for true if the university is public, and 0 for false if not.

```
>> [r, c]=size(universities);
>> IsPublic=zeros(r, 1);
>> wherepublic=universities.Type== 'Public';
>> IsPublic(wherepublic)=1;
>> universities=addvars(universities, IsPublic)
universities=
  3×3 table
      Name              Type      IsPublic
    _______________   _______    ________
    {'XYZ Univ'  }    Public        1
    {'TheBest'   }    Private       0
    {'AB College'}    Public        1
```

The same can now be done for Private, and then the original Type column can be deleted.

```
>> IsPrivate=zeros(r,1);
>> whereprivate=universities.Type== 'Private';
>> IsPrivate(whereprivate)=1;
>> universities=addvars(universities, IsPrivate);
>> universities.Type=[]
universities=
  3×3 table
         Name          IsPublic    IsPrivate
    _______________   ________    _________
    {'XYZ Univ'  }       1            0
    {'TheBest'   }       0            1
    {'AB College'}       1            0
```

Confusion Matrices

Results of classifiers are typically displayed in what is known as a ***confusion matrix***. The actual data are in the rows, and the model predictions are the columns. For example, for a binary spam/not spam classifier, it might look like this:

		Model	Prediction
		Spam	Not Spam
Actual	Spam	TP	FN
Data	Not Spam	FP	TN

Therefore, for example, the True Positive results are in the upper left; the actual data classifies these as ‘spam’ and the model prediction also results in ‘spam’. The confusion matrix shows the number of emails that have been classified in each category. For example,

		Model	Prediction
		Spam	Not Spam
Actual	Spam	50	20
Data	Not Spam	10	200

Note that in Machine Learning, this is called a “matrix,” although in MATLAB it would be much better implemented as a table that has mnemonically labeled rows and columns.

Explore Other Interesting Features

The built-in functions **cell2struct**, which converts a cell array into a vector of structs, and **struct2cell**, which converts a struct to a cell array.

Find the functions that convert from cell arrays to number arrays and vice versa.

Explore the **orderfields** function.

MATLAB has an entire category of data types and built-in functions that operate on dates and times. Find this under Language Fundamentals, then Data Types.

Explore the “is” functions for categorical arrays, such as **iscategorical**, **iscategory**, and **isordinal**.

Explore the table function **struct2table**.

Explore **timetable**, which is a table in which every row is time-stamped.

Explore the functions **deal** (which assigns values to variables) and **orderfields**, which puts structure fields in alphabetical order.

Investigate the **randperm** function.

SUMMARY

COMMON PITFALLS

- Confusing the use of parentheses (cell indexing) versus curly braces (content indexing) for a cell array
- Forgetting to index into a vector using parentheses or referring to a field of a structure using the dot operator
- When sorting a vector of structures on a field, forgetting that although only the field in question is compared in the sort algorithm, entire structures must be interchanged.

PROGRAMMING STYLE GUIDELINES

- Use arrays when values are the same type and represent in some sense the same thing.
- Use cell arrays or structures when the values are logically related but not the same type nor the same thing.
- Use cell arrays, rather than structures, when it is desired to loop through the values or to vectorize the code.
- Use structures rather than cell arrays when it is desired to use names for the different values rather than indices.
- Use **sortrows** to sort strings stored in a matrix alphabetically; for cell arrays and string arrays, **sort** can be used.

MATLAB Functions and Commands

cell
celldisp
cellplot
cellstr
strjoin
strsplit
iscellstr
struct
rmfield
isstruct
isfield
fieldnames
categorical
categories
countcats
summary
table
head
tail
renamevars
addvars
removevars
movevars
array2table
sort
issorted
sortrows
issortedrows

MATLAB Operators

cell arrays { }
dot operator for structs .
parentheses for dynamic field names ( )

Exercises

1. Create the following cell array:

   ```
   >> ca={'abc', 11, 3:2:9, zeros(2)}
   ```

   Use the **reshape** function to make it a *2* × *2* matrix. Then, write an expression that would refer to just the last column of this cell array.
2. Create a *2* × *2* cell array using the **cell** function and then put values in the individual elements. Then, insert a row in the middle so that the cell array is now *3* × *2*.
3. Create three cell array variables that store people's names, verbs, and nouns. For example,

   ```
   names={'Harry', 'Xavier', 'Sue'};
   verbs={'loves', 'eats'};
   nouns={'baseballs', 'rocks', 'sushi'};
   ```

   Write a script that will initialize these cell arrays, and then print sentences using one random element from each cell array (e.g., 'Xavier eats sushi').
4. Create a cell array that contains character vectors, for example,

   ```
   pets={'cat', 'dog', 'snake'};
   ```

   Show the difference in the following methods of indexing:

   ```
   pets(1:2)
   pets{1:2}
   [p1 p2]=pets{1:2}
   ```

5. Write most of a script "mathprobq" that will pose some random math problems to the user and will print for each one whether or not they answered it correctly, in the format shown below. The script starts with a cell array that stores math expressions (using just operators +,-,*,/,^) in character vectors. Then, the script loops to pick 3 of these randomly (it is possible that some may repeat), poses these problems to the user, and reads the user's results. For each, it prints whether or not the user answered it correctly.
6. Write a function *countem* that will receive one cell array as an input argument and will return the total number of numbers in that cell array (including vectors and matrices). Assume that the input argument is a cell array, and that it stores only simple values such as scalars, vectors, matrices, character vectors, and strings (not more complicated data structures such as other cell arrays or structs).
7. Create a cell array variable that would store for a student their name, university id number, and GPA. Print this information.
8. Create a structure variable that would store for a student their name, university id number, and GPA. Print this information.
9. Here is an inefficient way of creating a structure variable to store the three parts of a person's phone number:

   ```
   >> myphone.area='803';
   ```

```
>> myphone.loc='878';
>> myphone.num='9876';
```

Re-write this more efficiently using the **struct** function:

10. What would be an advantage of using cell arrays over structures?
11. What would be an advantage of using structures over cell arrays?
12. A complex number is a number of the form a + ib, where a is called the real part, b is called the imaginary part, and i = $\sqrt{-1}$. Write a script that prompts the user separately to enter values for the real and imaginary parts, and stores them in a structure variable. It then prints the complex number in the form a + ib. The script should just print the value of a, then the character vector '+ i', and then the value of b.
13. Create a data structure to store information about the elements in the periodic table of elements. For every element, store the name, atomic number, chemical symbol, class, atomic weight, and a seven-element vector for the number of electrons in each shell. Create a structure variable to store the information, for example for lithium:

```
Lithium 3 Li alkali_metal 6.94 2 1 0 0 0 0 0
```

14. Write a function *separatethem* that will receive one input argument which is a structure containing fields named 'length' and 'width' and will return the two values separately.
15. Write a function *prtnames* that will receive a struct as an input and will print the names of the fields from the struct in the format shown below. You may assume that the input argument that is passed to the function is in fact a struct.

```
>> st=struct('month',3,'day',24);
>> prtnames(st)
Field 1 is: 'month'
Field 2 is: 'day'
```

16. A script stores information on potential subjects for an experiment in a vector of structures called *subjects*. The following shows an example of what the contents might be:

```
 >> subjects(1)
ans=

      name: 'Joey'
    sub_id: 111
    height: 6.7000
    weight: 222.2000
```

For this particular experiment, the only subjects who are eligible are those whose height or weight is lower than the average height or weight of all subjects. The script will print the names of those who are eligible. Create a vector with sample data in a script, and then write the code to accomplish this. Do not assume that the length of the vector is known; the code should be general.

17. Quiz data for a class is stored in a file. Each line in the file has the student ID number (which is an integer) followed by the quiz scores for that student.

For example, if there are four students and three quizzes for each, the file might look like this:

```
44   7     7.5   8
33   5.5   6     6.5
37   8     8     8
24   6     7     8
```

First create the data file, and then store the data in a script in a vector of structures. Each element in the vector will be a structure that has two members: the integer student ID number, and a vector of quiz scores. The structure will look like this:

	students			
		quiz		
	id_no	1	2	3
1	44	7	7.5	8
2	33	5.5	6	6.5
3	37	8	8	8
4	24	6	7	8

To accomplish this, first use the **load** function to read all information from the file into a matrix. Then, using nested loops, copy the data into a vector of structures as specified. Then, the script will calculate and print the quiz average for each student.

18. Create a nested struct to store a person's name, address, and phone numbers. The struct should have three fields for the name, address, and phone. The address fields and phone fields will be structs.
19. Design a nested structure to store information on constellations for a rocket design company. Each structure should store the constellation's name and information on the stars in the constellation. The structure for the star information should include the star's name, core temperature, distance from the sun, and whether it is a binary star or not. Create variables and sample data for your data structure.
20. Write a script that creates a vector of line segments (where each is a nested structure as shown in this chapter). Initialize the vector using any method. Print a table showing the values, such as shown in the following:

```
Line  From     To

====  =======  =======

  1   ( 3, 5)  ( 4, 7)
  2   ( 5, 6)  ( 2, 10)
      etc.
```

21. Given the following variables:

```
onedate=struct(Month=6, Day=4, Year=2021);
tempvals(2)=struct('Temps', struct(mint=33, maxt=55), ...
     Date=onedate);
tempvals(1)=struct('Temps', struct(mint=40, maxt=62),...
     Date=struct(Month=12, Day=10, Year=1999));
```

For each of the following, write an expression using **only** the variables above (or parts of the variables) that would result in the value or error shown.

```
>>
ans=
   12
>>

ans=
     4
>>
Unrecognized field name "Year".
>>
temprange=
           29
>>
ans=
    3×1 cell array
       {'Month'}
       {'Day'  }
       {'Year' }
```

22. A team of engineers is designing a bridge to span the Podunk River. As part of the design process, the local flooding data must be analyzed. The following information on each storm that has been recorded in the last 40 years is stored in a file: a code for the location of the source of the data, the amount of rainfall (in inches), and the duration of the storm (in hours), in that order. For example, the file might look like this:

```
321  2.4  1.5
111  3.3  12.1
     etc.
```

Create a data file. Write the first part of the program: design a data structure to store the storm data from the file and also the intensity of each storm. The intensity is the rainfall amount divided by the duration. Write a function to read the data from the file (use **load**), copy from the matrix into a vector of structs, and then calculate the intensities. Write another function to print all of the information in a neatly organized table. Add a function to the program to calculate the average intensity of the storms. Add a function to the program to print all of the information given on the most intense storm. Use a local function for this function which will return the index of the most intense storm.

23. Create an ordinal categorical array to store the four seasons.

24. Create a categorical array to store the favorite breakfast beverage of your close friends. Show the results from using the **countcats** and **summary** functions on your categorical array.
25. Create a **table** to store information on students; for each, their name, id number, and major.
26. Use **addvars** to add a GPA column to your table from Exercise 25.
27. Sort your table from Exercise 25 on the id numbers, in descending order.
28. Write a function *mydsort* that sorts a vector in descending order (using a loop, not the built-in sort function).
29. DNA is a double stranded helical polymer that contains basic genetic information in the form of patterns of nucleotide bases. The patterns of the base molecules A, T, C, and G encode the genetic information. Construct a cell array to store some DNA sequences as character vectors; such as

    TACGGCAT
    ACCGTAC

    and then sort these alphabetically. Next, construct a matrix to store some DNA sequences of the same length and then sort them alphabetically.
30. Create a cell array of all character vectors. Sort them alphabetically. Investigate the use of some string functions on the cell array, e.g., **lower**, **count**, and **contains**.
31. The **wordcloud** function (introduced in 2017b) can be used to create a word cloud from a categorical array or from a table. Create a categorical array and get a word cloud from it.

Data Science and Machine Learning

32. Investigate the **datetime** function and its multiple formats.

2

PART

Advanced Topics for Problem Solving with MATLAB

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CHAPTER 9

Data Transfer

KEY TERMS

file input and output
lower-level file I/O functions
file types
open the file
close the file
permission
file identifier
standard input
standard output
standard error
end of the file
Application Programming Interface (API)
RESTful
API calls
endpoint
query parameters

CONTENTS

This chapter extends the input and output concepts (I/O) that were introduced in Chapter 3. In that chapter, we saw how to read values entered by the user using the **input** function, and also the output functions **disp** and **fprintf** that display information in windows on the screen.

For ***file input and output*** (file I/O), we used the **load** and **save** functions that can read from a data file into a matrix and write from a matrix to a data file. If the data to be written or file to be read are not in a simple matrix format, ***lower-level file I/O functions*** must be used.

The MATLAB® software has functions that can read and write data from different ***file types*** such as spreadsheets. For example, it can read from and write to Excel spreadsheets that have filename extensions such as .xls or .xlsx. There is also an Import Tool, which allows one to import data from a variety of file formats.

In this chapter, we introduce some functions that work with different file types, as well as the programmatic methods using some of the lower-level file input and output functions. Additionally, MATLAB has functions that allow you to access data from websites; these functions will be introduced.

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00009-3

9.1 WRITING AND READING SPREADSHEET AND CSV FILES

MATLAB has functions that will write to and read from Excel spreadsheet files and comma separated value (.csv) files. Prior to R2019a, the functions **xlswrite**, **xlsread**, **csvread**, and **csvwrite** were used, but these functions are not recommended at this point.

For example, the **readtable** function will read in a spreadsheet or .csv file into a table. There is a built-in .csv file in MATLAB that can be used to test this; the file 'outages.csv' stores information on some power outages. It is a large file, so we definitely want to suppress the output when reading it in:

```
>> outs=readtable('outages.csv');
>> size(outs)
ans=
        1468         6
```

The first few rows and variables (columns) are shown here:

```
>> outs(1:3, 1:4)
ans=
  3×4 table
      Region           OutageTime           Loss        Customers
   _____________   ______________        _____       __________
  {'SouthWest'}    2002-02-01 12:18     458.98      1.8202e+06
  {'SouthEast'}    2003-01-23 00:49     530.14      2.1204e+05
  {'SouthEast'}    2003-02-07 21:15     289.4       1.4294e+05
```

The **preview** function can be used to look at the first eight rows of a file without having to read in the entire file first.

The **writetable** function can be used to write a table to a file, for example, to a .txt, .csv file, or spreadsheet file. For example, the following writes the table *outs* to a spreadsheet file with a .xls extension, clears the variables, and reads it back in.

```
>> writetable(outs,'tab2xls.xls')
>> clear
>> xouts=readtable('tab2xls.xls');
```

If a matrix is to be used instead of a table, the functions **writematrix** and **readmatrix** can be used.

For example, the following will create a *3 x 5* matrix of random integers, and then write it to a spreadsheet file "ranexcel.xls" that has three rows and five columns, and then read it back in.

```
>> ranmat=randi(100, 3, 5)
ranmat=
    42    34    41    44    38
     1     4    14    46    69
    78    58    22    13    38
```

```
>> writematrix(ranmat, 'ranexcel.xls')
>> clear
>> xrans=readmatrix('ranexcel.xls')
xrans=
    42    34    41    44    38
     1     4    14    46    69
    78    58    22    13    38
```

These are just examples; MATLAB has many other functions that read from and write to different file formats.

9.2 LOWER-LEVEL FILE I/O FUNCTIONS

When reading from a data file, the **load** function works as long as the data in the file are "regular"—in other words, the same kind of data on every line and in the same format on every line—so that they can be read into a matrix. However, data files are not always set up in this manner. When it is not possible to use **load**, MATLAB has what are called ***lower-level file input functions*** that can be used. The file must be opened first, which involves finding or creating the file and positioning an indicator at the beginning of the file. This indicator then moves through the file as it is being read from. When the reading has been completed, the file must be closed.

Similarly, the **save** function can write or append matrices to a file, but if the output is not a simple matrix, there are lower-level functions that write to files. Again, the file must be opened first and closed when the writing has been completed.

In general, the steps involved are as follows:

- *Open the file.*
- Read from the file, write to the file, or append to the file.
- *Close the file.*

First, the steps involved in opening and closing the file will be described. Several functions that perform the middle step of reading from or writing to the file will be described subsequently.

9.2.1 Opening and Closing a File

Files are opened with the **fopen** function. By default, the **fopen** function opens a file for reading. If another mode is desired, a ***permission*** is used to specify which, for example, writing or appending. The **fopen** function returns -1 if it is not successful in opening the file or an integer value that becomes the ***file identifier*** if it is successful. This file identifier is then used to refer to the file when calling other file I/O functions. The general form is

```
fid=fopen('filename', 'permission');
```

where *fid* is a variable that stores the file identifier (it can be named anything) and the permission includes the following:

r	reading (this is the default)
w	writing
a	appending

After the **fopen** is attempted, the value returned should be tested to make sure that the file was opened successfully. For example, if attempting to open for reading and the file does not exist, the **fopen** will not be successful. As the **fopen** function returns –1 if the file was not found, this can be tested to decide whether to print an error message or to carry on and use the file. For example, if it is desired to read from a file "samp.dat":

```
fid=fopen('samp.dat');
if fid==-1
   disp('File open not successful')
else
   % Carry on and use the file!
end
```

The **fopen** function also returns an error message if it is not successful; this can be stored and displayed. Also, when the first file is opened in a MATLAB session, it will have a file identifier value of 3, because MATLAB assigns three default identifiers (0, 1, and 2) for the ***standard input***, ***standard output***, and ***standard error***. The value of the file identifier can be seen if the output from an **fopen** is not suppressed.

```
>> [fid, msg]=fopen('sample.dat')
fid=
   -1
msg=
No such file or directory
>> if fid==-1
     error(msg)
   else
      % Carry on and use the file!
   end
No such file or directory
>> [fid, msg]=fopen('samp.dat')
fid=
    3
msg=
  0×0 empty char array
```

In the last case there was no error, so the message is an empty character vector.

Files should be closed when the program has finished reading from or writing or appending to them. The function that accomplishes this is the **fclose** function, which returns 0 if the file close was successful or –1 if not. Individual files can be closed by specifying the file identifier or, if more than one file is open, all open files can be closed by passing the string "all" (or character vector 'all') to the **fclose** function. The general forms are:

```
closeresult=fclose(fid);

closeresult=fclose("all")
```

The result from the **fclose** function should also be checked with an **if-else** statement to make sure it was successful, and a message should be printed (if the close was not successful, that might mean that the file was corrupted, and the user would want to know that). Therefore, the outline of the code will be:

```
fid=fopen('filename', 'permission' );
if fid==-1
   disp('File open not successful')
else

   % do something with the file!

   closeresult=fclose(fid);
   if closeresult== 0
      disp('File close successful')
   else
      disp('File close not successful')
   end
end
```

9.2.2 Reading From Files Using fgetl

There are several lower-level functions that read from files. The **fgetl** and **fgets** functions read text from a file one line at a time; the difference is that the **fgets** keeps the newline character if there is one at the end of the line, whereas the **fgetl** function gets rid of it. Both of these functions require first opening the file, and then closing it when finished. Because the **fgetl** and **fgets** functions read one line at a time, these functions are typically inside some form of a loop.

We will concentrate on the **fgetl** function, which reads character vectors from a file one line at a time. Other input functions will be covered in Section 9.2.4. The **fgetl** function affords more control over how the data are read than other input functions. The **fgetl** function reads one line of data from a file into a character vector; text manipulation functions can then be used to manipulate the data. As **fgetl** only reads one line, it is normally placed in a loop that keeps going until the ***end of the file*** is reached. The **fgetl** function returns a character vector or −1 if no more data are found in the file.

A general algorithm for reading from a file into character vectors would be:

- Attempt to open the file
  - Check to ensure the file open was successful.
- If opened, loop until there is no more data
  - For each line in the file:
    - read it into a character vector
    - manipulate the data

- Attempt to close the file
  - Check to make sure the file close was successful.

The following is the generic code to accomplish these tasks:

```
fid=fopen('filename');
if fid==-1
   disp('File open not successful')
else
   % Attempt to read a line and check
   aline=fgetl(fid);
   while aline ~=-1
      % Use text functions to extract numbers,
      %   character vectors, etc. from the line
      % Do something with the data!
      % Attempt to read another line
      aline=fgetl(fid);
  end
  closeresult=fclose(fid);
  if closeresult== 0
     disp('File close successful')
  else
     disp('File close not successful')
  end
end
```

The permission could be included in the call to the **fopen** function. For example:

```
fid=fopen('filename', 'r');
```

but the 'r' is not necessary as reading is the default.

For example, assume that there is a data file "subjexp.dat", which has on each line a number followed by a space followed by a character code. The **type** command can be used to display the contents of this file (as the file does not have the default extension .m, the extension on the file name must be included).

```
>> type subjexp.dat
5.3 a
2.2 b
3.3 a
4.4 a
1.1 b
```

The **load** function would not be able to read this into a matrix because it contains both numbers and text. Instead, the **fgetl** function can be used to read each line as a character vector, and then text functions are used to separate the numbers and characters. For example, the following just reads each line and prints the number with two decimal places and then the rest of the character vector:

fileex.m

```
% Reads from a file one line at a time using fgetl
% Each line has a number and a character
% The script separates and prints them

% Open the file and check for success
fid=fopen('subjexp.dat');
if fid==-1
   disp('File open not successful')
else
   aline=fgetl(fid);
   while aline ~=-1
       % Separate each line into the number and character
       %  code and convert to a number before printing
       [num, charcode]=strtok(aline);
       fprintf('%.2f %s\n', str2double(num), charcode)
       aline=fgetl(fid);
   end

   % Check the file close for success
   closeresult=fclose(fid);
   if closeresult== 0
      disp('File close successful')
   else
      disp('File close not successful')
   end
end
```

The following is an example of executing this script:

```
>> fileex
5.30 a
2.20 b
3.30 a
4.40 a
1.10 b
File close successful
```

In this example, every time the loop action is executed, the **fgetl** function reads one line into a character vector. The function **strtok** is then used to store the number and the character in separate variables, both of which are character vectors (the second variable actually stores the blank space and the letter). If it is desired to perform calculations using the number, the function **str2double** would be used to convert the number stored in the variable into a **double** value as shown.

PRACTICE 9.1

Modify the script *fileex* to sum the numbers from the file. Create your own file in this format first.

9.2.3 Writing and Appending to Files

There are several lower-level functions that can write to files. Like the other low-level functions, the file must be opened first for writing (or appending) and should be closed once the writing has been completed.

We will concentrate on the **fprintf** function, which can be used to write to a file and also to append to a file. To write one line at a time to a file, the **fprintf** function can be used. We have, of course, been using **fprintf** to write to the screen. The screen is the default output device, so if a file identifier is not specified, the output goes to the screen; otherwise, it goes to the specified file. The default file identifier number is 1 for the screen. The general form is:

```
fprintf(fid, 'format', variable(s));
```

The **fprintf** function actually returns the number of bytes that was written to the file, so if it is not desired to see that number, the output should be suppressed with a semicolon as shown here.

Note

that when writing to the screen, the value returned by **fprintf** is not seen, but could be stored in a variable.

The following is an example of writing to a file named "tryit.txt":

```
>> fid=fopen('tryit.txt', 'w');

>> for i=1:3
       fprintf(fid,'The loop variable is %d\n', i);
   end

>> fclose(fid);
```

The permission in the call to the **fopen** function specifies that the file is opened for writing to it. Just like when reading from a file, the results from **fopen** and **fclose** should really be checked to make sure they were successful. The **fopen** function attempts to open the file for writing. If the file already exists, the contents are erased so it is as if the file had not existed. If the file does not currently exist (which would be the norm), a new file is created. The **fopen** could fail, for example, if there isn't space to create this new file.

To see what was written to the file we could then display the contents using **type**.

PRACTICE 9.2

Create a 3 × 5 matrix of random integers, each in the range from 1 to 100. Write the sum of each row to a file called "myrandsums.dat" using **fprintf**. Confirm that the file was created correctly.

The **fprintf** function can also be used to append to an existing file. The permission is 'a', so the general form of the **fopen** would be:

```
fid=fopen('filename', 'a');
```

Then, using **fprintf** (typically in a loop), we would write to the file starting at the end of the file. The file would then be closed using **fclose**. What is written to the end of the file does not have to be in the same format as what is already in the file when appending.

9.2.4 Alternate File Input Functions

The function **fscanf** reads formatted data into a matrix, using conversion formats such as %d for integers, %s for strings, and %f for floats (**double** values). The **textscan** function reads text data from a file and stores the data in a cell array; it also uses conversion formats. The **fscanf** and **textscan** functions can read the entire data file into one data structure. In terms of level, these two functions are somewhat in between the **load** function and the lower-level functions, such as **fgetl**. The file must be opened using **fopen** first and should be closed using **fclose** after the data have been read. However, no loop is required; these functions will read in the entire file automatically into a data structure.

Instead of using the **fgetl** function to read one line at a time, once a file has been opened the **fscanf** function can be used to read from this file directly into a matrix. However, the matrix must be manipulated somewhat to get it back into the original form from the file. The format of using the function is:

```
mat=fscanf(fid, 'format', [dimensions])
```

The **fscanf** reads into the matrix variable *mat* columnwise from the file identified by *fid*. The 'format' includes conversion characters much like those used in the **fprintf** function. The 'format' specifies the format of every line in the file, which means that the lines must be formatted consistently. The dimensions specify the desired dimensions of *mat*; if the number of values in the file are not known, **inf** can be used for the second dimension.

For example, the following would read in from the file *subjexp.dat*; each line contains a number, followed by a space, and then a character.

```
>> type subjexp.dat
5.3 a
2.2 b
3.3 a
4.4 a
1.1 b

>> fid=fopen('subjexp.dat');

>> mat=fscanf(fid,'%f %c',[2, inf])
mat=
    5.3000    2.2000    3.3000    4.4000    1.1000
   97.0000   98.0000   97.0000   97.0000   98.0000

>> fclose(fid);
```

The **fopen** opens the file for reading. The **fscanf** then reads from each line one double and one character and places each pair in separate columns in the matrix (in other words every line in the file becomes a column in the matrix). Note that the space in the format specifier is important: `'%f %c'` specifies that there is a float, a space, and a character. The dimensions specify that the matrix is to have two rows by however many columns are necessary (equal to the number of lines in the file). As matrices store values that are all the same type, the characters are stored as their ASCII equivalents in the character encoding (e.g., 'a' is 97).

Once this matrix has been created, it may be more useful to separate the rows into vector variables and to convert the second back to characters, which can be accomplished as follows:

```
>> nums=mat(1,:);

>> charcodes=char(mat(2,:))
charcodes=
abaab
```

Of course, the results from **fopen** and **fclose** should be checked but were omitted here for simplicity.

PRACTICE 9.3

Write a script to read in this file using **fscanf**, and sum the numbers.

QUICK QUESTION!

Instead of using the dimensions [2, **inf**] in the **fscanf** function, could we use
[**inf** ,2]?

Answer: No, [**inf**, 2] would not work. Because **fscanf** reads each row from the file into a column in the matrix, the number of rows in the resulting matrix are known but the number of columns are not.

QUICK QUESTION!

Why is the space in the conversion specifier '%f %c' important? Would the following also work?

```
>> mat=fscanf(fid,'%f%c',[2, inf])
```

Answer: No, that would not work. The conversion specifier '%f %c' specifies that there is a real number, then a space, then a character. Without the space in the conversion specifier, it would specify a real number immediately followed by a character (which would be the space in the file). Then, the next time it would be attempting to read the next real number, but the file position indicator would be pointing to the character on the first line; the error would cause the **fscanf** function to halt. The end result follows:

```
>> fid=fopen('subjexp.dat');
>> mat=fscanf(fid,'%f%c',[2, inf])
mat=
      5.3000
     32.0000
```

The 32 is the numerical equivalent of the space character ' ', as seen here.

```
>> double(' ')
ans=
     32
```

Another option for reading from a file is to use the **textscan** function. The **textscan** function reads text data from a file and stores the data in column vectors in a cell array. The **textscan** function is called, in its simplest form, as

```
cellarray=textscan(fid, 'format');
```

where the 'format' includes conversion characters much like those used in the **fprintf** function. The 'format' essentially describes the format of columns in the data file, which will then be read into column vectors. For example, to read the file 'subjexp.dat' we could do the following (again, for simplicity, omitting the error-check of **fopen** and **fclose**):

```
>> fid=fopen('subjexp.dat');

>> subjdata=textscan(fid,'%f %c');

>> fclose(fid);
```

The format specifier `'%f %c'` specifies that on each line there is a **double** value followed by a space followed by a character. This creates a *1 x 2* cell array variable called *subjdata*. The first element in this cell array is a column vector of doubles (the first column from the file); the second element is a column vector of characters (the second column from the file), as shown here:

```
>> subjdata
subjdata=
  1×2 cell array
    {5×1 double}    {5×1 char}
>> subjdata{1}
ans=
    5.3000
    2.2000
    3.3000
    4.4000
    1.1000
>> subjdata{2}
ans=
  5×1 char array
     'a'
     'b'
     'a'
     'a'
     'b'
```

To refer to individual values from the vector, it is necessary to index into the cell array using curly braces and then index into the vector using parentheses. For example, to refer to the third number in the first element of the cell array:

```
>> subjdata{1}(3)
ans=
   3.3000
```

A script that reads in these data and echo prints is shown here:

textscanex.m

```
% Reads data from a file using textscan
fid=fopen('subjexp.dat');

if fid==-1
    disp('File open not successful')
else
   % Reads numbers and characters into separate elements
   % in a cell array
   subjdata=textscan(fid,'%f %c');
   len=length(subjdata{1});
   for i= 1:len
       fprintf('%.1f %c\n',subjdata{1}(i),subjdata{2}(i))
   end

   closeresult=fclose(fid);
   if closeresult== 0
      disp('File close successful')
   else
      disp('File close not successful')
   end
end
```

Executing this script produces the following results:

```
>> textscanex
5.3 a
2.2 b
3.3 a
4.4 a
1.1 b
File close successful
```

PRACTICE 9.4

Modify the script *textscanex* to calculate the average of the column of numbers.

9.3 DATA TRANSFER WITH WEB SITES

MATLAB has functions that allow you to access data that are readily available on many websites. Many companies and government agencies put data on their sites. Examples include weather, census, mapping, transportation schedules, and car sharing sites. There are a lot of concepts related to accessing these data, and there is a lot of jargon in this section. To a degree, this goes beyond the scope of this book, but the possibilities for cool applications are endless and so it is hoped that this will spark interest in readers, who will then investigate these topics further.

An ***Application Programming Interface (API)*** allows for communication between devices or computers. Device APIs communicate between devices. Remote or web APIs connect computers; for example, a web API may connect a web application to a database. Some APIs are private, and some are public. A ***RESTful*** (Representational State Transfer) API is a particular type of API.

API calls allow one to retrieve data or to edit data in a database. API calls use HTTP requests. HTTP methods include GET, POST, PUT, and DELETE. API calls combine HTTP request messages, or methods, and the desired structure of the response. For example, a GET request allows one to retrieve data from a database based on parameters. In MATLAB, the function **webread** is used for this. The **webwrite** function retrieves data based on an object; this is a POST request. These functions were introduced in R2014b.

Javascript Object Notation, or JSON, is a standard notation that is used to create an object for a POST request, or to standardize the return format of information in a GET request. JSON uses what are called Key Value pairs, which are similar to structure field names and their values in MATLAB.

The **webread** function reads information from a RESTful web service that is specified by a URL. The URL is the API service ***endpoint***. Assuming that the variable *url* stores the URL of a web service as a character vector, the call

```
wdata=webread(url);
```

will read data from the web service, return the content, and store it in a variable *wdata*. The data returned may be in JSON format. ***Query parameters*** may be passed to the **webread** function in the form of Key Value pairs, to request specified information, for example,

```
wdata=webread(url, Key1, Value1, Key2, Value2);
```

For example, for a stock API, it might be necessary to request information about a particular stock, so, for example:

```
wdata=webread(url, ‘symbol’,’acme’);
```

This might be done in a loop to get information about multiple stocks; the stock names might be in a cell array that is indexed. If calls to the API are made too quickly, there may be errors, so in some cases it may be useful to put a **pause** statement in the loop so that this does not occur. Also, in some cases it might take a while for the data to be read from the web site. It may be useful to put some form of print statement in the loop to let the user know what is going on, e.g.,

```
Retrieving stock data for 'GOOGL'..
Retrieving stock data for 'AAPL'..
```

Images and audio data can also be read from a RESTful web service; see the documentation on the **webread** function and more on images and sounds in Chapter 13.

The format of the input to **webread** and the format of the output from it are dictated by the web service. The **webread** function itself sometimes translates the returned data from JSON to another format, for example, a struct array.

Options in the form of Key Value pairs can be specified using the **weboptions** function. Without any parameters, **weboptions** creates a weboptions object:

```
ans=
  weboptions with properties:

      CharacterEncoding: 'auto'
              UserAgent: 'MATLAB 9.10.0.1602886 (R2021a)'
                Timeout: 5
               Username: ''
               Password: ''
                KeyName: ''
               KeyValue: ''
            ContentType: 'auto'
          ContentReader: []
              MediaType: 'auto'
          RequestMethod: 'auto'
            ArrayFormat: 'csv'
           HeaderFields: []
    CertificateFilename: 'default'
```

If a web service expects a Key name and its value, this can be specified. For example, if a web service expects a value for a Key called *timein*, this could be specified as

```
myopt=weboptions('KeyName', 'timein', 'KeyValue', 10);
```

Another option might specify that the format of the output should be a character vector rather than, for example, JSON:

```
myopt=weboptions('ContentType', 'text');
```

The **webwrite** function can also retrieve information from a web service, using a POST request that is based on an object. Frequently the format of the object is JSON. These requests are more complicated than using **webread**. See the MATLAB documentation for more details and examples.

In R2016b, new functions **jsonencode** and **jsondecode** were introduced that make it easy to convert from MATLAB types to JSON and vice versa. For example, the following takes a struct and encodes it in JSON format and then back to a struct.

```
>> personstruct=struct('Name', 'Harry', 'Age', 33);
>> jsonpers=jsonencode(personstruct)
jsonpers=
    '{"Name":"Harry","Age":33}'
```

```
>> newstr=jsondecode(jsonpers)
newstr=
  struct with fields:

    Name: 'Harry'
    Age: 33
```

There are many examples of web services that are available. To find them, begin by looking at the examples in the documentation on the **webread** function and in general Web Access from MATLAB.

Some APIs can be accessed easily as seen in this section. Other APIs are public but require that some form of access key or authentication be presented. In many cases, you must request an access key from a web service, and once it has been returned to you, you must include this key with your request to the web service. Some of these keys are free, but sometimes you must pay for them.

To find APIs, the best method is to use a search browser. For example, if you are interested in getting weather information, you might search for "weather api". Options for different weather web services will appear in the browser. You must read the information in detail about each web service API, including whether or not you need an access key and if so how to get it, the query parameters that are necessary to retrieve data, and the format of the output that will be returned. If you are interested in a particular company, search for the company name, e.g., "company API". There are endless possibilities. There is so much data out there!

Data Science and Machine Learning Supplement

Built-In Files

There are several .mat files storing data sets that are built into MATLAB. We have seen the census.mat file.

Other built-in .mat files include "accidents.mat," which stores accident data from the 50 United States and Washington, D.C., "patients.mat," which stores 10 features for 100 medical patients, and "wind.mat," which stores position and velocity components of air currents. Statistics and Machine Learning Toolbox™ also stores several .mat files that contain labeled data sets.

There are also built-in .csv files. We have seen the outages.csv file.

```
>> outs=readtable('outages.csv');
>> size(outs)
ans=
     1468     6
```

With six columns, there is too much information to fit on the page, so we will arbitrarily delete the last two columns just to show what the table would look like.

```
>> outs(:, 5:6)=[ ];
>> head(outs)
ans=
8×4 table
    Region              OutageTime             Loss          Customers

 _____________      ________________        ______        ___________
 {'SouthWest'  }    2002-02-01 12:18        458.98        1.8202e+06
 {'SouthEast'  }    2003-01-23 00:49        530.14        2.1204e+05
 {'SouthEast'  }    2003-02-07 21:15         289.4        1.4294e+05
 {'West'       }    2004-04-06 05:44        434.81        3.4037e+05
 {'MidWest'    }    2002-03-16 06:18        186.44        2.1275e+05
 {'West'       }    2003-06-18 02:49             0                 0
 {'West'       }    2004-06-20 14:39        231.29               NaN
 {'West'       }    2002-06-06 19:28        311.86               NaN
```

It is common for the features (the columns) in a table to have labels, but not the rows. The Loss and Customers columns store **double** values. Note that some of them are read in as NaN, which is very common with data sets. The Region column stores cells, so for most ML algorithms this column should be modified to store **categorical** values instead. The OutageTime column stores **datetime** arrays.

Another built-in .csv file is airlinesmall.csv, which, despite the name, is quite large! It has over 120,000 rows and 29 variables.

Data Formats

Data sets come in many different formats, including spreadsheets and images. Data can be ***messy***, meaning that some values may be missing or incorrect. The first step in many ML applications is ***exploratory data analysis***, which involves an initial exploration of the data and may result in modifying the data set in a variety of ways. Another important initial step is to label the data, if it has not been already.

Data can be ***unstructured*** or ***structured***. An example of unstructured data would be a book, which consists of text and images, or a ***clickstream***, which is the sequence of clicks that a user makes when navigating through websites. Structured data are frequently ***rectangular***, meaning it has rows and columns. A spreadsheet is an example, and in MATLAB tables are frequently used in ML applications.

We will concentrate on structured data in a rectangular format, as in the census table above.

The rows are referred to as ***rows*** (!), ***records***, ***cases***, ***instances***, ***examples***, or ***observations***. The columns are called ***features*** (or ***feature vectors***), ***variables***, ***dimensions***, or ***attributes***. We will generally use the terms *rows* and *features*. If the data set is labeled, then one of the columns is the ***output*** (or ***outcome***), and the rest are ***inputs*** (or ***predictors***). The output is typically the last column, and is sometimes also called the ***response***, or the ***target data***.

Data Scrubbing, Feature Analysis, and Feature Engineering

The first step in the ML process is to take raw data and create a data set from it that can be used with a ML algorithm. Preprocessing the raw data to create a usable data set is sometimes referred to as ***data scrubbing***. Data scrubbing involves cleaning up mistakes in the data and missing or incomplete data. This data scrubbing can be a very time-consuming part of the entire process but is a very important step. The data scrubbing should be done after the data have been read in (in our case into MATLAB), not in the original format (for example, not in the .csv file). Note that as of R2019b, tasks in the Live Editor can be used for many data scrubbing operations.

For a given row, if a feature is missing (which frequently results in NaN in MATLAB), there are several methods to fix this. One is simply to delete the row since it contains incomplete information. This reduces the size of the data set, however, and larger data sets are typically recommended. Other methods include replacing the value of that feature with the mean for that feature (or the median or the mode), as we have seen. If outliers are deemed to be mistakes, they are usually removed from the data set. Keep in mind, however, that outliers are not always errors and instead can represent valuable information.

Analyzing the features is called ***feature analysis***. ***Feature engineering*** also includes manipulating the features, for example, by combining multiple features into one and by removing redundancies and irrelevant data. For example, a data set might contain a feature that contains the names of states (e.g., "Virginia") and another feature that is the abbreviation of the state's name (e.g., "VA"). At least one of those feature vectors can be deleted. Other features may simply be irrelevant. In a hospital data base, is the patient's favorite ice cream flavor relevant to any future diagnoses? Well, maybe, but probably not so that feature could be deleted. This is not always straight-forward, so the job that the ***data analyst*** does to create the useable data set is key to the success of the ML process. We have also seen the usefulness of binning to transform real numbers into categories, normalizing features so that one does not dominate over others due to larger numbers, and one-hot encoding to transform categorical data into numerical data.

In many cases, the original data set is very large and contains many features. It may not be obvious at first which features are important predictors of the outcome, and which are not very relevant. Therefore, feature engineering techniques (sometimes called ***feature transformation***) can be used to discover the most relevant features, and to reduce the number of features (***dimensionality reduction***). For example, ***Principal Component Analysis*** (PCA) creates new features that are linear combinations of the original features, with a goal of explaining most of the variation in the original data.

Once the initial data analysis has taken place, and the features have been engineered into a usable data set, it can then be used for ML. Keep in mind, however, that this is an iterative process. Preliminary results from the ML algorithm may indicate that more feature engineering is necessary.

■ Explore Other Interesting Features

Reading from and writing to binary files, using the functions **fread**, **fwrite**, **fseek**, and **frewind**. Note that to open a file to both read from it and write to it, the plus sign must be added to the permission (e.g., 'r+').

Use **help load** to find some example MAT-files in MATLAB.

Email can be sent from MATLAB using the **sendmail** function. In order to do this, the **setpref** function must first be used to set preferences for the email address and for the SMTP server information. See the MATLAB documentation on these functions for more details and examples. Similarly, text messages can be sent from MATLAB.

The **dlmread** function reads from an ASCII-delimited file into a matrix; also investigate the **dlmwrite** function.

The Import Tool to import files from a variety of file formats.

In the MATLAB Product Help, enter "Supported File Formats" to find a table of the file formats that are supported, and the functions that read from them and write to them. ■

SUMMARY

COMMON PITFALLS

- Misspelling a file name, which causes a file open to be unsuccessful.
- Using a lower-level file I/O function, when **load** or **save** could be used.
- Forgetting that **fscanf** reads columnwise into a matrix, so every line in the file is read into a column in the resulting matrix.
- Forgetting that **fscanf** converts characters to their ASCII equivalents.

- Forgetting that **textscan** reads into a cell array (so curly braces are necessary to index).
- Forgetting to use the permission 'a' for appending to a file (which means the data already in the file would be lost if 'w' was used!).

PROGRAMMING STYLE GUIDELINES

- Use **load** when the file contains the same kind of data on every line and in the same format on every line.
- Always close files that were opened.
- Always check to make sure that files were opened and closed successfully.
- Make sure that all data are read from a file; e.g., use a conditional loop to loop until the end of the file is reached rather than using a **for** loop.
- Be careful to use the correct formatting specifier when using **fscanf** or **textscan**.
- Store groups of related variables in separate MAT-files.

MATLAB Functions and Commands

xlswrite
xlsread
csvread
csvwrite
readtable
preview
writetable
writematrix
readmatrix
fopen
fclose
fgetl
fgets
feof
fprintf
fscanf
textscan
webread
webwrite
weboptions
jsonencode
jsondecode

Exercises

1. Create a spreadsheet that has on each line an integer student identification number followed by three quiz grades for that student. Read that information from the spreadsheet into a matrix, and print the average quiz score for each student.
2. A spreadsheet *popdata.xls* stores the population every 20 years for a small town that underwent a boom and then decline. Create this spreadsheet and then read this into a table. Create the variable names shown here (use **renamevars** for this).

Year	Population
1940	4021
1960	8053
1980	14994
2000	9942
2020	3385

3. Create a set of random matrix variables with descriptive names (e.g., *ran2by2int*, *ran3by3double*, etc.) for use when testing matrix functions. Store all of these in a MAT-file.
4. What is the difference between a data file and a MAT-file?
5. Write a script that will prompt the user for the name of a file from which to read. Loop to error-check until the user enters a valid filename that can be opened. (Note: this would be part of a longer program that would actually do something with the file, but for this problem all you have to do is to error-check until the user enters a valid filename that can be read from.)
6. A file called "potentialfilenames.dat" stores names that might be file names. Write a script that will read these potential file names, attempt to open them for reading, and count how many are files that could be opened within the current directory. Close all opened files, but you do not need to error-check this.
7. A set of data files named "exfile1.dat", "exfile2.dat", etc. have been created by a series of experiments. It is not known exactly how many there are, but the files are numbered sequentially with integers beginning with 1. The files all store combinations of numbers and characters, and are not in the same format. Write a script that will count how many lines total are in the files. Note that you do not have to process the data in the files in any way; just count the number of lines.
8. Write a script that will read from a file x and y data points in the following format:

   ```
   x 0 y 1
   x 1.3 y 2.2
   ```

   The format of every line in the file is the letter 'x', a space, the x value, space, the letter 'y', space, and the y value. First, create the data file with 10 lines in this format. Do this by using the Editor/Debugger, then File Save As *xypts.dat*. The script will attempt to open the data file and error-check to make sure it was opened. If so, it uses a **for** loop and **fgetl** to read each line as a character vector. In the loop, it creates x and y vectors for the data points. After the loop, it plots these points and attempts to close the file. The script should print whether or not the file was successfully closed.
9. Modify the script from the previous problem. Assume that the data file is in exactly that format, but do not assume that the number of lines in the file are known. Instead of using a **for** loop, loop until the end of the file is reached. The number of points, however, should be in the plot title.
10. Write a script "custformat" that will read names from a file "customers.txt" in the form "Last, First" (one space in between) and will print them in the form "First Last".
11. Create a data file to store blood donor information for a biomedical research company. For every donor, store the person's name, blood type, Rh factor, and blood pressure information. The Blood type is either A, B, AB, or O. The Rh factor is + or -. The blood pressure consists of two readings: systolic and diastolic (both are **double** numbers). Write a script to read from your file into a data structure and print the information from the file.

12. Create a file “parts_inv.dat” that stores on each line a part number, cost, and quantity in inventory, in the following format:

```
123 5.99 52
```

Use **fscanf** to read this information, and print the total dollar amount of inventory (the sum of the cost multiplied by the quantity for each part).

13. Create a file which stores on each line a letter, a space, and a real number. For example, it might look like this:

```
e 5.4
f 3.3
c 2.2
```

Write a script that uses **textscan** to read from this file. It will print the sum of the numbers in the file. The script should error-check the file open and close, and print error messages as necessary.

14. Write a script to read in division codes and sales for a company from a file that has the following format:

```
A 4.2
B 3.9
```

Print the division with the highest sales.

15. Write a script that will read some baseball statistics from a file “bbstats.dat”. Every line will have a player’s name followed by the number of at bats, hits, and home runs, in that order, in the following format:

```
Jay Rookie 298 111 3
```

The script will print each player’s first name and their batting average, which is hits/at bats.

16. The Wind Chill Factor (WCF) measures how cold it feels with a given air temperature (T, in degrees Fahrenheit) and wind speed (V, in miles per hour). One formula for the WCF follows:

$$\mathrm{WCF} = 35.7 + 0.6\,\mathrm{T} - 35.7\,(\mathrm{V}^{0.16}) + 0.43\,\mathrm{T}\,(\mathrm{V}^{0.16})$$

Create a table showing WCFs for temperatures ranging from −20 to 55 in steps of 5, and wind speeds ranging from 0 to 55 in steps of 5. Write this to a file *wcftable.dat*. Write the script as a live script.

17. Write a script that will loop to prompt the user for *n* circle radii. The script will call a function to calculate the area of each circle, and will write the results in sentence form to a file.

18. Write a script that will read from a file ‘charnum.dat’. Every line in the file will have a single character immediately followed by a number n. It will write each character n times, on separate lines, to a file called ‘charrs.txt’.

19. Create a file that has some college department names and enrollments. For example, it might look like this:

```
Aerospace 201
Mechanical 66
```

Write a script that will read the information from this file and create a new file that has just the first four characters from the department names, followed by the enrollments. The new file will be in this form:

```
Aero 201
Mech 66
```

20. Environmental engineers are trying to determine whether the underground aquifers in a region are being drained by a new spring water company in the area. Well depth data have been collected every year at several locations in the area. Create a data file that stores on each line the year, an alphanumeric code representing the location, and the measured well depth that year. Write a script that will read the data from the file and determine whether or not the average well depth has been lowered.
21. Write a menu-driven program that will read in an employee data base for a company from a file, and do specified operations on the data. The file stores the following information for each employee:
    - Name
    - Department
    - Birth Date
    - Date Hired
    - Annual Salary
    - Office Phone Extension

    You are to decide exactly how this information is to be stored in the file. Design the layout of the file, and then create a sample data file in this format to use when testing your program. The format of the file is up to you. However, space is critical. Do not use any more characters in your file than you have to! Your program is to read the information from the file into a data structure, and then display a menu of options for operations to be done on the data. You may not assume in your program that you know the length of the data file. The menu options are as follows:
    1. Print all of the information in an easy-to-read format to a new file.
    2. Print the information for a particular department.
    3. Calculate the total payroll for the company (the sum of the salaries).
    4. Find out how many employees have been with the company for N years (N might be 10, for example).
    5. Exit the program.
22. Practice with JSON format. Create a nested struct and encode it into JSON format.
23. Read the documentation page on **webread**. There are example API calls; try one of them and examine the structure of the result.
24. Use a browser to find a free API of interest to you. Read the documentation page carefully before attempting to retrieve data from it.

Data Science and Machine Learning

25. Use the **readtable** function to read the file 'outages.csv' into a table. Use the **head** function to examine all six columns (features). Use the **class** function to determine the class of all six features. Use the **categorical** function to convert the Region feature from a cell array to categorical data. Replace the NaN values in the Customers feature with the mean number of Customers (not including the NaN values).
26. There is a built-in Excel file in MATLAB called 'tsunamis.xlsx' that stores information on 162 tsunamis. There are 20 features. Read this into a table using the **readtable** function. Do some feature analysis. Should a feature that stores a lot of NaN values (e.g., Second) be included in your data set? Should rows that are 'very doubtful tsunami' be included? Notice that some NaN values are present in a feature vector because they are not relevant. For example, if the Cause of the tsunami is 'Earthquake', there is a number in the EarthquakeMagnitude feature vector, otherwise it is NaN. Decide what kind of analysis you would like to do with this data, and based on that, create your data set. For example, you may want to try to find correlations in the data only for tsunamis caused by earthquakes.
27. Using the built-in Excel file in MATLAB called 'tsunamis.xlsx', try out the **geobubble** function to create a geographic bubble chart. Use **help geobubble** for more information and an example using this file, and look at the documentation page for **geobubble** for even more examples. Display one of the features from your table using the **geobubble** function, and play with some properties.

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CHAPTER 10

Advanced Functions

KEY TERMS

variable number of arguments
nested functions
anonymous functions
function handle
function function
recursive functions
validation functions
argument block
outer function
inner function
recursion
general (inductive) case
base case
infinite recursion

CONTENTS

Functions were introduced in Chapter 3 and then expanded on in Chapter 6. In this chapter, several advanced features of functions and types of functions are described. All of the functions that we have seen so far have had a well-defined number of input and output arguments, but we see that it is possible to have a ***variable number of arguments***. ***Anonymous functions*** are simple one-line functions that are called using their ***function handle***. Other uses of function handles will also be demonstrated, including ***function functions*** and built-in function functions in the MATLAB® software. ***Nested functions*** are also introduced, which are functions contained within other functions. Finally, ***recursive functions*** are functions that call themselves. A recursive function can return a value or may simply accomplish a task such as printing.

10.1 VARIABLE NUMBERS OF ARGUMENTS

The functions that we have written thus far have contained a fixed number of input arguments and a fixed number of output arguments. For example, in the following function that we have defined previously, there is one input argument and there are two output arguments:

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00010-X

areacirc.m

```
function [area, circum]=areacirc(rad)
% areacirc returns the area and
% the circumference of a circle
% Format: areacirc(radius)

area=pi*rad .* rad;
circum=2*pi*rad;
end
```

However, this is not always the case. It is possible to have a ***variable number of arguments***, both input and output arguments. A built-in cell array **varargin** can be used to store a variable number of input arguments and a built-in cell array **varargout** can be used to store a variable number of output arguments. These are cell arrays because the arguments could be different types, and cell arrays can store different kinds of values in the various elements. The function **nargin** returns the number of input arguments that were passed to the function, and the function **nargout** determines how many output arguments are expected to be returned from a function.

10.1.1 Variable Number of Input Arguments

For example, the following function *areafori* has a variable number of input arguments, either 1 or 2. The name of the function stands for "area, feet or inches". If only one argument is passed to the function, it represents the radius in feet. If two arguments are passed, the second can be a character 'i' indicating that the result should be in inches (for any other character, the default of feet is assumed). One foot = 12 inches. The function uses the built-in cell array **varargin**, which stores any number of input arguments. The function **nargin** returns the number of input arguments that were passed to the function. In this case, the radius is the first argument passed so it is stored in the first element in **varargin**. If a second argument is passed (if **nargin** is 2), it is a character that specifies the units.

areafori.m

```
function area=areafori(varargin)
% areafori returns the area of a circle in feet
% The radius is passed, and potentially the unit of
% inches is also passed, in which case the result will be
% given in inches instead of feet
% Format: areafori(radius) or areafori(radius,'i')

n=nargin; % number of input arguments
radius=varargin{1}; % Given in feet by default
if n== 2
    unit=varargin{2};
    % if inches is specified, convert the radius
    if unit== 'i'
        radius=radius*12;
    end
end
area=pi*radius .^ 2;
end
```

Note that curly braces are used to refer to the elements in the cell array **varargin**.

Some examples of calling this function follow:

```
>> areafori(3)
ans=
  28.2743
>> areafori(1,'i')
ans=
  452.3893
```

In this case, it was assumed that the radius will always be passed to the function. The function header can therefore be modified to indicate that the radius will be passed, and then a variable number of remaining input arguments (either none or 1):

```
areafori2.m
```

```
function area=areafori2(radius, varargin)
% areafori2 returns the area of a circle in feet
% The radius is passed, and potentially the unit of
% inches is also passed, in which case the result will be
% given in inches instead of feet
% Format: areafori2(radius) or areafori2(radius,'i')

n=nargin; % number of input arguments

if n== 2
    unit=varargin{1};
    % if inches is specified, convert the radius
    if unit== 'i'
        radius=radius*12;
    end
end
area=pi*radius .^ 2;
end
```

Note that nargin returns the total number of input arguments, not just the number of arguments in the cell array varargin.

```
>> areafori2(3)
ans=
  28.2743
>> areafori2(1,'i')
ans=
  452.3893
```

There are basically two formats for the function header with a variable number of input arguments. For a function with one output argument, the options are as follows:

```
function outarg=fnname(varargin)

function outarg=fnname(input arguments, varargin)
```

Either some input arguments are built into the function header and **varargin** stores anything else that is passed, or all of the input arguments go into **varargin**.

PRACTICE 10.1

The sum of a geometric series is given by

$$1+r+r^2+r^3+r^4+\ldots+r^n$$

Write a function called *geomser* that will receive a value for *r* and calculate and return the sum of the geometric series. If a second argument is passed to the function, it is the value of *n*; otherwise, the function generates a random integer for *n* (in the range from 5 to 30). Note that loops are not necessary to accomplish this. The following examples of calls to this function illustrate what the result should be:

```
>> g=geomser(2,4) % 1 +2^1 +2^2 +2^3 +2^4
g=
   31
>> geomser(1) % 1+1^1+1^2+1^3+... ?
ans=
      12
```

Note that in the last example, a random integer was generated for *n* (which must have been 11). Use the following header for the function, and fill in the rest:

```
function sgs=geomser(r, varargin)
```

10.1.2 Variable Number of Output Arguments

A variable number of output arguments can also be specified. The function **nargout** can be called to determine how many output arguments were used to call a function. For example, in the function *mysize* below, a matrix is passed to the function. The function behaves like the built-in function **size** in that it returns the number of rows and columns. However, if three variables are used to store the result of calling this function, it also returns the total number of elements:

mysize.m

```
function [row, col, varargout]=mysize(mat)
% mysize returns dimensions of input argument
% and possibly also total # of elements
% Format: mysize(inputArgument)

[row, col]=size(mat);

if nargout== 3
    varargout{1}=row*col;
end
end
```

```
>> [r, c]= mysize(zeros(3))
r=
     3
c=
     3

>> [r, c, elem]= mysize(zeros(3))
r=
     3
c=
     3
elem=
     9
```

In the first call to the *mysize* function, the value of **nargout** was 2, so the function only returned the output arguments *row* and *col*. In the second call, as there were three variables on the left of the assignment statement, the value of **nargout** was 3; thus, the function also returned the total number of elements.

Note

that the function **nargout** does not return the number of output arguments in the function header, but the number of output arguments expected from the function (meaning the number of variables in the vector on the left side of the assignment statement when calling the function).

There are basically two formats for the function header with a variable number of output arguments:

```
function varargout=fnname(input args)

function [output args, varargout]=fnname(input args)
```

Either some output arguments are built into the function header, and **varargout** stores anything else that is returned or all go into **varargout**. The function is called as follows:

```
[variables]=fnname(inputs);
```

QUICK QUESTION!

A temperature in degrees Celsius is passed to a function called *converttemp*. How could we write this function so that it converts this temperature to degrees Fahrenheit, and possibly also to degrees Kelvin, depending on the number of output arguments? The conversions are:

$$F = \frac{9}{5}C + 32$$

$$K = C + 273.15$$

Here are possible calls to the function:

```
>> df=converttemp(17)
df=
   62.6000
>> [df, dk]=converttemp(17)
df=
   62.6000
dk=
   290.1500
```

Answer: We could write the function in two different ways: one with only **varargout** in the function header, and one that has an output argument for the degrees F and also **varargout** in the function header.

Continued

QUICK QUESTION!—CONT'D

converttemp.m

```
function [degreesF, varargout]=converttemp(degreesC)
%converttemp converts temperature in degrees C
% to degrees F and maybe also K
% Format: converttemp(C temperature)

degreesF=9/5*degreesC+32;
n=nargout;
if n == 2
    varargout{1}=degreesC+273.15;
end
end
```

converttempii.m

```
function varargout=converttempii(degreesC)
% converttempii converts temperature in degrees C
% to degrees F and maybe also K
% Format: converttempii(C temperature)

varargout{1}=9/5*degreesC+32;
n=nargout;
if n == 2
    varargout{2}=degreesC+273.15;
end
end
```

10.2 VALIDATING FUNCTION ARGUMENTS

It is possible to declare function input arguments to restrict the input arguments to certain dimensions, types, and/or constraints imposed by ***validation functions***. This is new as of R2019b, and makes use of "must be" validation functions such as **mustBeNumeric**, **mustBePositive**, **mustBeInteger**, **mustBeText**, **mustBeVector**, **mustBeGreaterThan**, etc. For a full list, search "argument validation functions" in the Documentation. Many of these functions were introduced in R2017a, but some have been introduced later (e.g., **mustBeText** in R2020b).

To accomplish this, an ***argument block*** is created within the function body, before any of the function code. The argument block contains argument declarations, in between the keywords **arguments** and **end**. For every input argument that is declared, the name is given, followed by the required dimensions in parentheses, the name of a class, and/or validation functions in curly braces. The format is:

```
arguments
Inputargname (dimensions) classname {validation functions}
end
```

Not all of these are required. Here is an example:

```
testvalid.m
```

```
function testvalid(onenum, posvec)
% First arguments block
arguments
    onenum (1,1) {mustBeNumeric}
    posvec (1,:) {mustBeNumeric, mustBePositive}
end

% Then function code
disp('The vector is: ')
disp(posvec)
result=posvec+onenum;
disp('The result is: ')
disp(result)
end
```

The arguments block specifies that:

- The input argument *onenum* must be a scalar (1 x 1), and it must be numeric.
- The input argument *posvec* must be a row vector (or can be converted to a row vector) containing only positive numbers.

Here are two valid function calls:

```
>> testvalid(33, 2:5)
The vector is:
     2     3     4     5
The result is:
    35    36    37    38

>> testvalid(11, [4; 9; 2])
The vector is:
     4     9     2
The result is:
    15    20    13
```

Note that in the second call, the vector that is passed is a column vector. The arguments block actually changes it to be a row vector for use in the function body.

Here are invalid function calls:

```
>> testvalid(33, 'abc')
Error using testvalid (line 5)
```

```
Invalid argument at position 2. Value must be numeric.
>> testvalid(11,=2:3)
Error using testvalid (line 5)
Invalid argument at position 2. Value must be positive.
```

One class can also be declared for each input argument. Again, if it is possible to convert the input argument to that class, then the class of the input argument will be modified for the rest of the function. Here is an example in which the first argument type must be convertible to the type **uint64**:

testclass.m

```
function outarg=testclass(inarg1, inarg2, inarg3)
arguments
    inarg1 uint64 {mustBeNumeric}
    inarg2
    inarg3 {mustBeNumeric}
end

outarg=inarg1*sum(sum(inarg3));
end
```

In this example call to the function, the first argument is a **double**, but the function converts the type (by rounding it to 2). The result is 2 * (1+2+3+4), or 20.

```
>> testclass(2.1, 'abc', 1:4)
ans=
  uint64
   20
```

10.3 ANONYMOUS FUNCTIONS AND FUNCTION HANDLES

An anonymous function is a very simple, one-line function. The advantage of an anonymous function is that it does not have to be stored in a separate file. This can greatly simplify programs, as often calculations are very simple and the use of anonymous functions reduces the number of code files necessary for a program. Anonymous functions can be created in the Command Window or in any script or user-defined function. The syntax for an anonymous function follows:

```
fnhandlevar = @ (arguments) functionbody;
```

where *fnhandlevar* stores the ***function handle***; it is essentially a way of referring to the function. The handle is returned by the @ operator and then this handle is assigned to the variable *fnhandlevar* on the left. The arguments, in parentheses, correspond to the argument(s) that are passed to the function, just like any other kind of function. The functionbody is the body of the function, which is any valid MATLAB expression. For example, here is an anonymous function that calculates and returns the area of a circle:

```
>> cirarea = @ (radius) pi*radius .^ 2;
```

The function handle variable name is *cirarea*. There is one input argument, *radius*. The body of the function is the expression `pi*radius .^ 2`. The `.^` array operator is used so that a vector of radii can be passed to the function.
The function is then called using the handle and passing argument(s) to it; in this case, the radius or vector of radii. The function call using the function handle looks just like a function call using a function name:

```
>> cirarea(4)
ans=
   50.2655

>> areas=cirarea(1:4)
areas=
    3.1416  12.5664  28.2743  50.2655
```

The type of *cirarea* can be found using the **class** function:

```
>> class(cirarea)
ans=
function_handle
```

Unlike functions stored in code files, if no argument is passed to an anonymous function, the parentheses must still be in the function definition and in the function call. For example, the following is an anonymous function that prints a random real number with two decimal places, as well as a call to this function:

```
>> prtran = @ () fprintf('%.2f\n',rand);
>> prtran()
0.95
```

Typing just the name of the function handle will display its contents, which is the function definition.

```
>> prtran
prtran=
    @ () fprintf('%.2f\n',rand)
```

This is why parentheses must be used to call the function, even though no arguments are passed.

An anonymous function can be saved to a MAT-file and then it can be loaded when needed.

```
>> cirarea = @ (radius) pi*radius .^ 2;
>> save anonfns cirarea
>> clear
>> load anonfns
>> who
Your variables are:
cirarea
>> cirarea
cirarea=
    @ (radius) pi*radius .^ 2
```

Other anonymous functions could be appended to this MAT-file. Even though an advantage of anonymous functions is that they do not have to be saved in individual code files, it is frequently useful to save groups of related anonymous functions in a single MAT-file. Anonymous functions that are used frequently can be saved in a MAT-file and then loaded from this MAT-file in every MATLAB Command Window.

PRACTICE 10.2

Create your own anonymous functions to perform some temperature conversions. Store these anonymous function handle variables in a MAT-file called "tempconverters.mat".

10.4 USES OF FUNCTION HANDLES

Function handles can also be created for functions other than anonymous functions, both built-in and user-defined functions. For example, the following would create a function handle for the built-in **factorial** function:

```
>> facth = @factorial;
```

The @ operator gets the handle of the function, which is then stored in a variable *facth*.

The handle could then be used to call the function, just like the handle for the anonymous functions, as in:

```
>> facth(5)
ans=
   120
```

Using the function handle to call the function instead of using the name of the function does not in itself demonstrate why this is useful, so an obvious question would be why function handles are necessary for functions other than anonymous functions.

10.4.1 Function Functions

One reason for using function handles is to be able to pass functions to other functions – these are called ***function functions***. For example, let us say we have a function that creates an *x* vector. The *y* vector is created by evaluating a function at each of the *x* points, and then these points are plotted.

```
fnfnexamp.m
```

```
function fnfnexamp(funh)
% fnfnexamp receives the handle of a function
% and plots that function of x (which is 1:.25:6)
% Format: fnfnexamp(function handle)

x=1:.25:6;
y=funh(x);
plot(x,y,'ko')
xlabel('x')
ylabel('fn(x)')
title(func2str(funh))
end
```

What we want to do is pass a function to be the value of the input argument *funh*, such as **sin**, **cos**, or **tan**. Simply passing the name of the function does not work:

```
>> fnfnexamp(sin)
Error using sin
Not enough input arguments.
```

Instead, we have to pass the handle of the function:

```
>> fnfnexamp(@sin)
```

This creates the *y* vector as **sin(x)** and then brings up the plot as seen in Fig. 10.1. The function **func2str** converts a function handle to a character vector; this is used for the title.

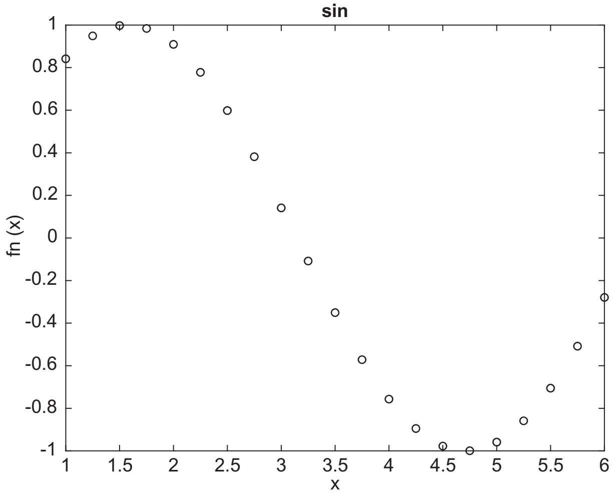


FIGURE 10.1

Plot of **sin** created by passing handle of function to plot.

Passing the handle to the **cos** function instead would graph cosine instead of sine:

```
>> fnfnexamp(@cos)
```

We could also pass the handle of any user-defined or anonymous function to the *fnfnexamp* function. Note that if a variable stores a function handle, just the name of the variable would be passed (not the @ operator). For example, for our anonymous function defined previously,

```
>> fnfnexamp(cirarea)
```

The function **func2str** will return the definition of an anonymous function as a character vector that could also be used as a title. For example:

```
>> cirarea = @ (radius) pi*radius .^ 2;
>> fnname = func2str(cirarea)
fnname =
@(radius)pi*radius.^2
```

There is also a built-in function **str2func** that will convert a string scalar or character vector to a function handle. A string containing the name of a function could be passed as an input argument, and then converted to a function handle.

fnstrfn.m

```
function fnstrfn(funstr)
% fnstrfn receives the name of a function as a string
% it converts this to a function handle and
% then plots the function of x (which is 1:.25:6)
% Format: fnstrfn(function name as string)
x=1:.25:6;
funh=str2func(funstr);
y=funh(x);
plot(x,y,'ko')
xlabel('x')
ylabel('fn(x)')
title(funstr)
end
```

This would be called by passing a string to the function, and would create the same plot as in Fig. 10.1:

```
>> fnstrfn("sin")
```

PRACTICE 10.3

Write a function that will receive as input arguments an *x* vector and a function handle, and will create a vector *y* that is the function of *x* (whichever function handle is passed) and will also plot the data from the *x* and *y* vectors with the function name in the title.

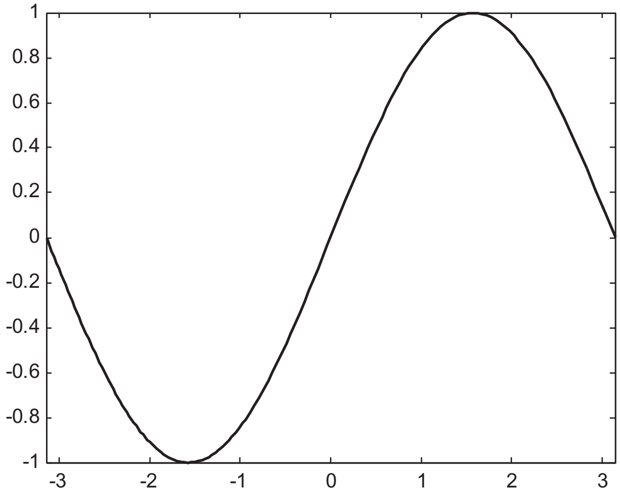


FIGURE 10.2
Plot of **sin** created using **fplot**.

MATLAB has some built-in function functions. One built-in function function is **fplot**, which plots a function between limits that are specified. The form of the call to **fplot** is:

```
fplot(fnhandle, [xmin, xmax])
```

For example, to pass the **sin** function to **fplot** one would pass its handle (see Fig. 10.2 for the result).

```
>> fplot(@sin, [-pi, pi])
```

The **fplot** function is a nice shortcut; it is not necessary to create x and y vectors, and it plots a continuous curve rather than discrete points.

QUICK QUESTION!

Could you pass an anonymous function to the **fplot** function?

Answer: Yes, as in:

```
>> cirarea = @ (radius) pi*radius .^ 2;
>> fplot(cirarea, [1, 5])
>> title(func2str(cirarea))
```

Note that in this case, the @ operator is not used in the call to **fplot**, as *cirarea* already stores the function handle.

The function function **feval** will evaluate a function handle and execute the function for the specified argument. For example, the following is equivalent to **sin(3.2)**:

```
>> feval(@sin, 3.2)
ans =
   -0.0584
```

Another built-in function function is **fzero**, which finds a zero of a function near a specified value. For example:

```
>> fzero(@cos,4)
ans=
   4.7124
```

10.4.2 Timing Functions

The function **timeit** can be used to time functions and is more robust than using **tic** and **toc**. The **timeit** function takes one input argument, which is a function handle; this can be the handle of any type of function. The time is returned in seconds.

```
>> fh = @() prod(1:10000000);
>> timeit(fh)
ans=
   0.0308
```

A warning message may be thrown if the function is too fast.

```
>> fh = @() prod(1:100);
>> timeit(fh)
Warning: The measured time for F may be inaccurate because it is
running too fast. Try measuring something that takes longer.
> In timeit (line 158)
ans=
   1.3993e-06
```

10.5 NESTED FUNCTIONS

Just as loops can be nested, meaning one inside of another, functions can be nested. The terminology for ***nested functions*** is that an ***outer function*** can have within it ***inner functions***. When functions are nested, every function must have an **end** statement. The general format of a nested function is as follows:

```
outer function header

     body of outer function

     inner function header
          body of inner function
     end % inner function

     more body of outer function

end % outer function
```

The inner function can be in any part of the body of the outer function, so there may be parts of the body of the outer function before and after the inner function. There can be multiple inner functions.

Argument validation cannot be performed on nested functions.

The scope of any variable is the workspace of the outermost function in which it is defined and used. That means that a variable defined in the outer function could be used in an inner function (without passing it).

For example, the following function calculates and returns the volume of a cube. Three arguments are passed to it, for the length and width of the base of the cube, and also the height. The outer function calls a nested function that calculates and returns the area of the base of the cube.

Note

that it is not necessary to pass the length and width (*len* and *wid*) to the inner function, as the scope of these variables includes the inner function.

Also notice the colors of *len* and *wid* in the Editor are different, and there is a note that their scope spans both functions when you hover over them.

nestedvolume.m

```
function outvol=nestedvolume(len, wid, ht)
% nestedvolume receives the lenght, width, and
% height of a cube and returns the volume; it calls
% a nested function that returns the area of the base
% Format: nestedvolume(length,width,height)

outvol=base*ht;

function outbase=base
% returns the area of the base
outbase=len*wid;
end % base function

end % nestedvolume function
```

An example of calling this function follows:

```
>> v = nestedvolume(3,5,7)
v =
  105
```

Output arguments are different from variables. The scope of an output argument is just the nested function; it cannot be used in the outer function. In this example, *outbase* can only be used in the *base* function; its value, for example, could not be printed from *nestedvolume*.

A variable defined in the inner function ***could*** be used in the outer function, but if it is not used in the outer function the scope is just the inner function.

Examples of nested functions will be used in the section on Graphical User Interfaces.

10.6 RECURSIVE FUNCTIONS

Recursion is when something is defined in terms of itself. In programming, a ***recursive function*** is a function that calls itself. Recursion is used very commonly in programming, although many simple examples (including some shown in this section) are actually not very efficient and can be replaced by iterative methods (loops or vectorized code in MATLAB). Nontrivial examples go beyond the scope of this book, so the concept of recursion is simply introduced here.

The first example will be of a factorial. Normally, the factorial of an integer *n* is defined iteratively:

```
n!=1*2*3*...*n
```

For example, `4!=1*2*3*4, or 24`.

Another, recursive, definition is:

```
n!=n*(n=1)!                    general case

1!=1                            base case
```

This definition is recursive because a factorial is defined in terms of another factorial. There are two parts to any recursive definition: the ***general (or inductive) case***, and the ***base case***. We say that, in general, the factorial of n is defined as n multiplied by the factorial of (n-1), but the base case is that the factorial of 1 is just 1. The base case stops the recursion.

For example:

```
3!=3*2!
     2!=2*1!
          1!=1
       =2
  =6
```

The way this works is that 3! is defined in terms of another factorial, as 3 * 2!. This expression cannot yet be evaluated because first we have to find out the value of 2!. Therefore, in trying to evaluate the expression 3 * 2!, we are interrupted by the recursive definition. According to the definition, 2! is 2 * 1!. Again, the expression 2 * 1! cannot yet be evaluated because first we have to find the value of 1!. According to the definition, 1! is 1. As we now know what 1! is, we can continue with the expression that was just being evaluated; now we know that 2 * 1! is 2 * 1, or 2. Thus, we can now finish the previous expression that was being evaluated; now we know that 3 * 2! is 3 * 2, or 6.

This is the way that recursion always works. With recursion, the expressions are put on hold with the interruption of the general case of the recursive definition. This keeps happening until the base case of the recursive definition applies. This finally stops the recursion, and then the expressions that were put on hold are evaluated in the reverse order. In this case, first the evaluation of 2 * 1! was completed, and then 3 * 2!.

There must always be a base case to end the recursion, and the base case must be reached at some point. Otherwise, ***infinite recursion*** would occur (theoretically, although MATLAB will stop the recursion eventually).

We have already seen the built-in function **factorial** in MATLAB to calculate factorials, and we have seen how to implement the iterative definition using a running product. Now we will instead write a recursive function called *fact*. The function will receive an integer *n*, which we will for simplicity assume is a positive integer and will calculate *n!* using the recursive definition given previously.

```
fact.m
```

```
function facn=fact(n)
% fact recursively finds n!
% Format: fact(n)
if n == 1
    facn = 1;
else
    facn=n*fact(n-1);
end
end
```

The function calculates one value, using an **if-else** statement to choose between the base and general cases. If the value passed to the function is 1, the function returns 1 as 1! is equal to 1. Otherwise, the general case applies. According to the definition, the factorial of *n*, which is what this function is calculating, is defined as *n* multiplied by the factorial of (*n*-1). So, the function assigns `n*fact(n-1)` to the output argument.

How does this work? Exactly the way the example was sketched previously for 3!. Let us trace what would happen if the integer 3 is passed to the function:

```
fact(3) tries to assign 3*fact(2)
                    fact(2) tries to assign 2*fact(1)
                                       fact(1) assigns 1
                    fact(2) assigns 2
fact(3) assigns 6
```

When the function is first called, 3 is not equal to 1, so the statement

```
facn=n*fact(n-1);
```

is executed. This will attempt to assign the value of 3*fact(2) to *facn*, but this expression cannot be evaluated yet and therefore a value cannot be assigned yet because first the value of fact(2) must be found.

Thus, the assignment statement has been interrupted by a recursive call to the *fact* function. The call to the function fact(2) results in an attempt to assign 2*fact(1), but, again, this expression cannot yet be evaluated. Next, the call to the function fact(1) results in a complete execution of an assignment statement as it assigns just 1. Once the base case has been reached, the assignment statements that were interrupted can be evaluated, in the reverse order.

Calling this function yields the same result as the built-in **factorial** function, as follows:

```
>> fact(5)
ans=
   120

>> factorial(5)
ans=
   120
```

The recursive factorial function is a very common example of a recursive function. It is somewhat of a lame example, however, as recursion is not necessary to find a factorial. A **for** loop can be used just as well in programming (or, of course, the built-in function in MATLAB).

Another, better, example is of a recursive function that does not return anything, but simply prints. The following function *prtwords* receives a sentence, and prints the words in the sentence in reverse order. The algorithm for the *prtwords* function follows:

- Receive a sentence as an input argument.
- Use **strtok** to break the sentence into the first word and the rest of the sentence.
- If the rest of the sentence is not empty (in other words, if there is more to it), recursively call the *prtwords* function and pass to it the rest of the sentence.
- Print the word.

The function definition follows:

prtwords.m

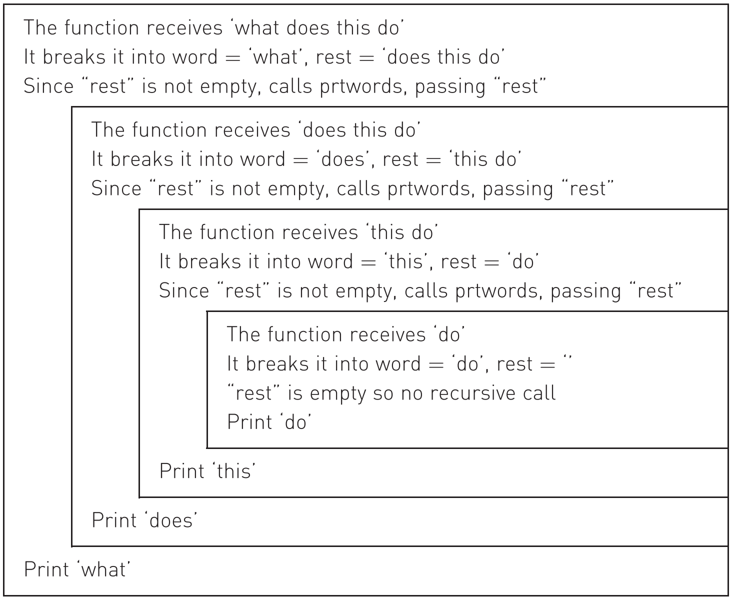
```
function prtwords(sent)
% prtwords recursively prints the words in a
%   sentence in reverse order
% Format: prtwords(sentence)

[word, rest]=strtok(sent);
if ~isempty(rest)
   prtwords(rest);
end
disp(word)
end
```

Here is an example of calling the function, passing the sentence "what does this do":

```
>> prtwords('what does this do')
do
this
does
what
```

An outline of what happens when the function is called follows:



The function receives ‘what does this do’
It breaks it into word = ‘what’, rest = ‘does this do’
Since “rest” is not empty, calls prtwords, passing “rest”

The function receives ‘does this do’
It breaks it into word = ‘does’, rest = ‘this do’
Since “rest” is not empty, calls prtwords, passing “rest”

The function receives ‘this do’
It breaks it into word = ‘this’, rest = ‘do’
Since “rest” is not empty, calls prtwords, passing “rest”

The function receives ‘do’
It breaks it into word = ‘do’, rest = ‘’
“rest” is empty so no recursive call
Print ‘do’

Print ‘this’

Print ‘does’

Print ‘what’

In this example, the base case is when the rest of the sentence is empty, in other words, the end of the original sentence has been reached. Every time the function is called the execution of the function is interrupted by a recursive call to the function until the base case is reached. When the base case is reached, the entire function can be executed, including printing the word (in the base case, the word ‘do’).

Once that execution of the function is completed, the program returns to the previous version of the function in which the word was ‘this’ and finishes the execution by printing the word ‘this’. This continues; the versions of the function are finished in the reverse order, so the program ends up printing the words from the sentence in the reverse order.

PRACTICE 10.4

For the following function,

recurfn.m

```
function outvar=recurfn(num)
% Format: recurfn(number)

if num < 0
   outvar=2;
else
   outvar=4+recurfn(num-1);
end
end
```

what would be returned by the call to the function `recurfn(3.5)`? Think about it, and then type in the function and test it.

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Analyses of One Feature: Minima, Maxima, and Data Spread

We have seen some functions that calculate the central tendency of one feature, for example, the **mean**, **median**, and **mode** of a set of exam scores.

MATLAB has built-in functions for many statistics. Some others that we have already seen include **min** and **max** to find the minimum or maximum value in a data set. These functions can also compare vectors or matrices (with the same dimensions) and return the minimum (or maximum) values from corresponding elements. For example, the following iterates through all elements in the two vectors, comparing corresponding elements, and returning the minimum for each set of corresponding elements:

```
>> x=[3 5 8 2 11];
>> y=[2 6 4 5 10];
>> min(x,y)
ans=
     2     5     4     2    10
```

MATLAB also has functions **mink** and **maxk** that return the minimum and maximum k values in an array. The values that are returned are in sorted order. These functions can be useful in identifying outliers.

```
>> vec=randi(100,1,10)
vec=
    77    80    19    49    45    65    71    76    28    68
>> mink(vec, 3)
ans=
    19    28    45
```

For example, we could write a function that receives a data set represented as a vector, and the value of k, and it would return the minimum k and maximum k values. If we want different k values for the minimum and maximum, we could pass a third argument which would be the value of k for the maximum:

minandmaxk.m

```
function [outmink, outmaxk]=minandmaxk(dataset, k, varargin)
outmink=mink(dataset, k);
if nargin== 3
    outmaxk=maxk(dataset, varargin{1});
else
    outmaxk=maxk(dataset, k);
end
end
```

A property that is useful to know is how spread out the data values are within the data set. The ***standard deviation*** and ***variance*** are ways of determining the spread of the data. The variance is usually defined in terms of the arithmetic mean as:

$$\text{var} = \frac{\sum_{i=1}^{n} (x_i - mean)^2}{n-1}$$

Sometimes, the denominator is defined as *n* rather than *n-1*. The default definition in MATLAB uses *n*-1 for the denominator, so we will use that definition here.

For example, for the vector [8 7 5 4 6], there are *n* = *5* values so *n-1* is 4. Also, the mean of this data set is 6. The variance would be

$$\text{var} = \frac{(8-6)^2 + (7-6)^2 + (5-6)^2 + (4-6)^2 + (6-6)^2}{4}$$

$$= \frac{4+1+1+4+0}{4} = 2.5$$

The built-in function to calculate the variance is called **var**:

```
>> xvals=[8 7 5 4 6];
>> myvar=var(xvals)
myvar=
    2.5000
```

The standard deviation is the square root of the variance:

$$\text{sd} = \sqrt{\text{var}}$$

The built-in function in MATLAB for the standard deviation is called **std**; the standard deviation can be found either as the **sqrt** of the variance or using **std**. The less spread out the numbers are, the smaller the standard deviation will be, as it is a way of determining the spread of the data. Likewise, the more spread out the numbers are, the larger the standard deviation will be. For example, the following shows two data sets that have the same number of values and also the same mean, but the standard deviations are quite different:

```
>> x1=[9 10 9.4 9.6];
>> mean(x1)
ans=
   9.5000
>> std(x1)
ans=
   0.4163

>> x2=[2 17=1.5 20.5];
>> mean(x2)
ans=
   9.5000
```

```
>> std(x2)
ans=
   10.8704
```

The qualifier 'omitnan' can be passed to the **var** and **std** functions in order to omit any NaN values.

■ Explore Other Interesting Features

Other function functions and Ordinary Differential Equation (ODE) solvers can be found using **help funfun**.

The function function **bsxfun**. Look at the example in the documentation page of subtracting the column mean from every element in each column of a matrix.

The ODE solvers include **ode45** (which is used most often), **ode23**, and several others. Error tolerances can be set with the **odeset** function.

Investigate the use of the functions **narginchk** and **nargoutchk**.

The function **nargin** can be used not just when using **varargin**, but also for error-checking for the correct number of input arguments into a function. Explore examples of this. ■

SUMMARY

COMMON PITFALLS

- Thinking that **nargin** is the number of elements in **varargin** (it may be, but not necessarily; **nargin** is the total number of input arguments).
- Trying to pass just the name of a function to a function function; instead, the function handle must be passed.
- Forgetting the base case for a recursive function.

PROGRAMMING STYLE GUIDELINES

- If some inputs and/or outputs will always be passed to/from a function, use standard input arguments/output arguments for them. Use **varargin** and **varargout** only when it is not known ahead of time whether other input/output arguments will be needed.
- Use anonymous functions whenever the function body consists of just a simple expression.
- Store related anonymous functions together in one MAT-file
- Use iteration instead of recursion when possible.

MATLAB Reserved Words

arguments
end (for argument block)

MATLAB Functions and Commands

varargin
varargout
nargin
nargout
mustBeNumeric
mustBePositive
mustBeInteger
mustBeText
mustBeVector
mustBeGreaterThan
func2str
str2func
fplot
feval
fzero
timeit

MATLAB Operators

handle of functions @

Exercises

1. Write a function that will print a random integer. If no arguments are passed to the function, it will print an integer in the inclusive range from 1 to 100. If one argument is passed, it is the max and the integer will be in the inclusive range from 1 to max. If two arguments are passed, they represent the min and max and it will print an integer in the inclusive range from min to max.
2. Write a function *numbers* that will create a matrix in which every element stores the same number *num*. Either two or three arguments will be passed to the function. The first argument will always be the number *num*. If there are two arguments, the second will be the size of the resulting square (n x n) matrix. If there are three arguments, the second and third will be the number of rows and columns of the resulting matrix.
3. The overall electrical resistance of *n* resistors in parallel is given as:

$$R_T = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}\right)^{-1}$$

   Write a function *Req* that will receive a variable number of resistance values and will return the equivalent electrical resistance of the resistor network.
4. Write a function that will receive the radius *r* of a sphere. It will calculate and return the volume of the sphere (4/3 π r^3). If the function call expects two output arguments, the function will also return the surface area of the sphere (4 π r^2).

5. Write a function that will receive the price of an item, and possibly also a discount rate. If a second argument is passed, it would be the discount. For example, 10 would mean a 10% discount from the original price. The function returns the final price.
6. Write a function that will receive as an input argument a temperature in degrees Fahrenheit, and will return the temperature in degrees Celsius and, if two outputs are expected, also in Kelvin. The conversion factors are: C = (F – 32) * 5/9 and K = C + 273.15.
7. Information on some hurricanes is stored in a vector of structures; the name of the vector variable is *hurricanes*. For example, one of the structures might be initialized as follows:

   ```
   struct('Name','Bettylou', 'Avespeed',18,...
          'Size', struct('Width',333,'Eyewidth',22));
   ```

   Write a function *printHurr* that will receive a vector of structures in this format as an input argument. It will print, for every hurricane, its *Name* and *Width* in a sentence format to the screen. If a second argument is passed to the function, it is a file identifier for an output file (which means that the file has already been opened), and the function will print in the same format to this file (and does not close it).
8. The built-in function **date** returns a character vector containing the day, month, and year. Write a function (using the **date** function) that will always return the current day. If the function call expects two output arguments, it will also return the month. If the function call expects three output arguments, it will also return the year.
9. List some built-in functions to which you pass a variable number of input arguments (Note: this is not asking for **varargin**, which is a built-in cell array, or **nargin**.)
10. List some built-in functions that have a variable number of output arguments (or, at least one!).
11. Write a function that will receive a variable number of input arguments: the length and width of a rectangle, and possibly also the height of a box that has this rectangle as its base. The function should return the rectangle area if just the length and width are passed, or also the volume if the height is also passed.
12. Write a function that will return the factorial of the input argument. First, the function must validate that the input argument is a positive integer.
13. Write a function that will concatenate two text input arguments together and return the result. First, the function must validate that both of the input arguments are text.
14. Write an anonymous function to convert a length from feet to yards (there are three feet in a yard). Use it to convert 2, 2.5, 3, 3.5, and 4 feet to yards, all in one expression. (So, two lines of code total: one for the anonymous function, and one to use it.)

15. Create a set of anonymous functions to do length conversions and store them in a file named *lenconv.mat*. Call each a descriptive name, such as *cmtoinch* to convert from centimeters to inches.
16. An approximation for a factorial can be found using Stirling's formula:

$$n! \approx \sqrt{2\pi n}\left(\frac{n}{e}\right)^n$$

Write an anonymous function to implement this.
17. Why would you want to use an anonymous function?
18. Write an anonymous function to implement the following quadratic: `3x^2-2x+5`. Then, use **fplot** to plot the function in the range from=6 to 6.
19. Write a function that will receive data in the form of x and y vectors, and a handle to a plot function and will produce the plot. For example, a call to the function would look like `wsfn(x,y,@bar)`.
20. Write a function *plot2fnhand* that will receive two function handles as input arguments, and will display in two Figure Windows plots of these functions, with the function names in the titles. The function will create an x vector that ranges from 1 to n (where n is a random integer in the inclusive range from 4 to 10). For example, if the function is called as follows

```
>> plot2fnhand(@sqrt, @exp)
```

and the random integer is 5, the first Figure Window would display the **sqrt** function of x=1:5, and the second Figure Window would display **exp(x)** for x=1:5.
21. Use **feval** as an alternative way to accomplish the following function calls:

```
abs(-4)
size(zeros(4))
```

Use **feval** twice for this one!
22. Write a function to calculate the volume of a cone. The volume V is V=AH, where A is the area of the circular base (A=πr^2 where r is the radius) and H is the height. Use a nested function to calculate A.
23. The two real roots of a quadratic equation $ax^2+bx+c=0$ (where a is nonzero) are given by

$$\frac{-b \pm \sqrt{D}}{2*a}$$

where the discriminant $D=b^2 - 4*a*c$. Write a function to calculate and return the roots of a quadratic equation. Pass the values of a, b, and c to the function. Use a nested function to calculate the discriminant.
24. A recursive definition of a^n where *a* is an integer and *n* is a non-negative integer follows:

$$
\begin{aligned}
a^n &= 1 \quad \text{if } n == 0 \\
&= a * a^{n-1} \quad \text{if } n > 0
\end{aligned}
$$

Write a recursive function called *mypower*, which receives *a* and *n* and returns the value of a^n by implementing the previous definition. Note: The program should NOT use ^ operator anywhere; this is to be done recursively instead! Test the function.

25. What does this function do:

```
function outvar = mystery(x,y)
if y == 1
   outvar = x;
else
   outvar = x + mystery(x,y-1);
end
```

Give one word to describe what this function does with its two arguments.

26. The Fibonacci numbers is a sequence of numbers F_i:

```
0    1    1    2    3    5    8    13    21    34 ...
```

where F_0 is 0, F_1 is 1, F_2 is 1, F_3 is 2, and so on. A recursive definition is:

$$
\begin{aligned}
F_0 &= 0 \\
F_1 &= 1 \\
F_n &= F_{n-2} + F_{n-1} \text{ if } n > 1
\end{aligned}
$$

Write a recursive function to implement this definition. The function will receive one integer argument n, and it will return one integer value that is the n^{th} Fibonacci number. Note that in this definition, there is one general case but two base cases. Then, test the function by printing the first 20 Fibonacci numbers.

27. Use **fgets** to read character vectors from a file and recursively print them backwards.

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28. The ***Euclidean distance*** between two points (x1, y1) and (x2, y2) is given by:

E = sqrt((x1 – x2) ^ 2 + (y1 – y2) ^ 2)

The Manhattan distance is

M = abs(x1 – x2) + abs(y1 – y2)

The Manhattan distance between points is used in some machine learning algorithms because it is faster and easier to calculate than the Euclidean distance. Write a function "ptdist" that will receive the x and y coordinates of two points, and will return the Euclidean distance between them. If two output arguments are expected, the function will also return the Manhattan distance (but, it will do this only if two output arguments are expected).

29. Modify the *minandmaxk* function so that if the function is called with three variables on the left-hand side of an assignment, it will also return the original data set without the minimum and maximum k values. Note: one easy way to do this is to use the **setdiff** function. The **setdiff** function receives two vectors as input arguments, and returns a vector consisting of all of the values that are contained in the first vector argument but not the second.
30. Recall that the precision for a classification model measures how accurately the positive outcome was predicted. The precision is the TP divided by the sum of TP+FP. Write an anonymous function to find the precision.

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CHAPTER 11

Introduction to Object-Oriented Programming and Graphics

KEY TERMS

procedural languages
object-oriented languages
classes
hybrid languages
abstract data types
objects
properties
methods
class definition
instances
instantiation
inheritance
parent/child
superclass/subclass
value classes
handle classes
graphics objects
object handle
primitive objects
root object
constructor function
ordinary method
overloading
attributes
copy constructor
destructor function
events
event-driven programming
listeners
callback

CONTENTS

Most programming languages are either ***procedural*** or ***object-oriented***. Procedural programs are comprised of ***functions***, each of which performs a task. Object-oriented programs use ***classes***, which contain both data and functions to manipulate the data. ***Hybrid languages*** can utilize both of these programming paradigms. All of our programs so far have been procedural, but the MATLAB® software uses objects in its graphics, and thus has object-oriented programming (OOP) capabilities.

In this chapter, we first introduce some of the concepts and terminologies of OOP using graphics objects and show how to manipulate plot properties using this system. Later we show how user-defined classes can be created.

11.1 OBJECT-ORIENTED PROGRAMMING

This short section is intended to introduce the very basic ideas behind OOP as well as some of the terminology that is used. This section is very dense in terms of the terminology. It is hoped that by introducing the terms once here, and

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then giving examples in the next two sections, the terms will be easier to understand.

Built-in data types have certain capabilities associated with them. For example, we can perform mathematical operations such as adding and dividing with number types such as **double**. When a variable is created that stores a value of a particular type, operations can then be performed that are suitable for that type.

Similarly, ***abstract data types*** are data types that are defined by both data and operational capabilities. In MATLAB, these are called ***classes.*** Classes define both the data and the functions that manipulate the data. Once a class has been defined, ***objects*** can be created of the class.

To define a class, both the data and the functions that manipulate the data must be defined. The data are called ***properties*** and are similar to variables in that they store the values. The functions are called ***methods***. A ***class definition*** consists of the definition of the properties, and the definition of the methods.

Once a class has been defined, ***objects*** can be created from the class. The objects are called ***instances*** of the class and an object that is created is an ***instantiation*** of the class. The properties and methods of the object can be referenced using the object name, the dot operator, and the name of the property or method.

Inheritance is when one class is derived from another. The initial class is called the ***base***, ***parent***, or ***superclass***, and the derived class is called the ***derived***, ***child***, or ***subclass.*** A subclass is a new class that has the properties and methods of the superclass (this is what is called ***inheritance***), plus it can have its own properties and methods. The methods in a subclass can override methods from the superclass if they have the same name.

MATLAB has built-in classes, and also allows for user-defined classes. There are two types of classes in MATLAB: ***value classes*** and ***handle classes***. The differences are explained in Section 11.3. MATLAB uses handle classes to implement graphical objects used in plots.

11.2 USING OBJECTS WITH GRAPHICS AND PLOT PROPERTIES

MATLAB uses graphics in all of its figures. All figures consist of ***graphics objects***, each of which is referenced using an ***object handle***. The object handles store objects, which are derived from a superclass called **handle**.

Graphics objects include ***primitive objects***, which are basic building blocks of plots, as well as the axes used to orient the objects. The graphics primitives include objects such as lines and text. For example, a plot that uses straight line segments uses the **line** graphics primitive. More of the graphics primitives are discussed in Section 12.3. The objects are organized hierarchically, and there are properties associated with each object.

The computer screen is called the ***root object*** and is referenced using the function **groot** (which is short for "graphics root"). When plots are made, they appear in the Figure Window; the Figure Window itself appears on the computer screen. The hierarchy in MATLAB can be summarized as follows:

```
Root (screen)           Parent
                           |
Figure Window              |
                           |
    Axes                   |
                           ↓
Primitive objects       Children
```

In other words, the Figure Window is in the screen; it includes Axes, which are used to orient graphics primitive objects, which are the building blocks of plots.

Objects and Properties

A Figure Window is an object; the data in objects are stored in properties. Just calling the **figure** function will bring up a blank Figure Window and return its handle; by assigning the handle of this Figure Window to an object variable, the properties can then be referenced. For example, if no other figures have been created yet, the following will create Fig. (1).

```
>> f=figure
f =
  Figure (1) with properties:

    Number: 1
      Name: ''
     Color: [0.9400 0.9400 0.9400]
  Position: [440 378 560 420]
     Units: 'pixels'

Show all properties
```

By default, only a few of the properties are listed; what is shown are the names of the properties and the values for this instance of the object; these include:

- the figure number: 1
- the name of the figure: none was given so this is an empty character vector
- the color: given as a vector storing the values of the red, green, and blue components of the color
- the position of the Figure Window within the screen, specified in the units of pixels (which is shown next); this is a vector consisting of four values: the number of pixels that the lower left corner of the Figure Window is

from the left of the screen, the number of pixels that the lower left corner of the Figure Window is from the bottom of the screen, the length in pixels, and the height in pixels

- the units: pixels

For the Color property, the three numbers in the vector are real numbers in the range from 0 to 1. Zero for a color component means none of that color, whereas one is the brightest possible hue. All zeros represent black, and all ones represent the color white. The default Color property value of `[0.94 0.94 0.94]` is a very light gray.

By clicking on the "all properties" link, all of the properties can be seen. As long as the Figure Window is not closed, the handle *f* can be used to refer to the Figure Window, but when the Figure Window is closed, the handle is deleted. Another method of viewing the properties is to pass the handle to the **get** function.

```
>> get(f)
```

This will show a very long list of property names and values. You may not understand most of these properties; do not worry about it! Notice, however, that the Parent of this figure is the Root object, and that there are no Children since there is nothing in this Figure Window.

QUICK QUESTION!

What would the following display:

```
>> f
```

Answer: It would display the same abbreviated list of properties as was shown when the handle was first created.

PRACTICE 11.1

Call the **groot** function and store the resulting handle in an object variable. What are the dimensions of your screen?

(Note that pixels are a fixed size and do not necessarily correspond exactly to the actual number of pixels on the screen.)

Note

that this is the same as the notation to refer to a field in a structure, but it is not a structure; this is directly referencing a property within an object.

The dot notation is used to reference or change a property of an object. The format for this is:

```
objecthandle.PropertyName
```

For example,

```
>> f.Color
ans =
    0.9400    0.9400    0.9400
```

The following modifies the Color property to a darker gray.

```
>> f.Color=[0.5 0.5 0.5]
```

The **get** and **set** functions can also be used.

The **get** function can also be used to retrieve just one particular property; for example, the Units property, as follows.

```
>> get(f, 'Units')
ans =
    'pixels'
```

The function **set** can be used to change property values. For example, the position of the Figure Window could be modified as follows.

```
>> set(f,'Position',[400 450 600 550])
```

Using the dot notation is preferable to using **get** and **set**.

For the figure object stored in *f*, its built-in class is matlab.ui.Figure; "ui" is the abbreviation for "user interface" and is used in many graphics names. This can be seen using the **class** function.

```
>> class(f)
ans =
    'matlab.ui.Figure'
```

Recall that a class definition consists of the data (properties) and functions to manipulate the data (methods). There are built-in functions **properties** and **methods** that display the properties and methods for a particular class. For example, for the figure referenced by the handle *f*, we can find the properties; note that they are not listed in alphabetical order as with **get** and that only the names of the properties are returned (not the values).

```
>> properties(f)
Properties for class matlab.ui.Figure:
    Position
    OuterPosition
    InnerPosition
    Units
    Renderer
    RendererMode
    Visible
    Color
          etc.
```

The methods for the figure *f* are as follows.

```
>> methods(f)

Methods for class matlab.ui.Figure:

Figure                              getUnitsService
ProcessButtonEventForUIComponent    isprop
addlistener                         java
addprop                             ne
```

```
double                          reset
eq                              scroll
findobj                         set
get

Static methods:

loadobj

Methods of matlab.ui.Figure inherited from handle.
```

Again, much of this will not make sense but notice that the methods are derived from the superclass **handle**. The methods, or functions, that can be used with the object *f* include **get** and **set**. Also, the methods **eq** and **ne** are defined; these are equivalent to the equality (==) and inequality (~=) operators. That means that the equality and inequality operators can be used to determine whether two figure handles are equal to each other or not.

QUICK QUESTION!

Given two figure objects

```
>> f=figure(1);
>> g=figure(2);
```

Assuming that both Figure Windows are still open, what would be the value of the following expression?

```
>> f== g
```

Answer: This would be false. However, consider the following, which demonstrates that all of the color components of the two figures are the same, and that if one figure handle variable is assigned to another, they are equivalent.

```
>> f.Color == g.Color
ans =
     1      1      1
>> h = f;
>> f == h
ans =
     1
```

The various plot functions return a handle for the plot object, which can then be stored in a variable. In the following, the **plot** function plots a **sin** function in a Figure Window and returns the object handle. This handle will remain valid as long as the object exists.

Note

Notice that the plot is generated using the **line** primitive object. As with the Figure Window, the properties can be viewed and modified using the dot notation.

```
>> x=-2*pi: 1/5 : 2*pi;
>> y=sin(x);
>> hl=plot(x,y)
hl =
  Line with properties:

              Color: [0 0.4470 0.7410]
          LineStyle: '-'
          LineWidth: 0.5000
             Marker: 'none'
         MarkerSize: 6
    MarkerFaceColor: 'none'
              XData: [1x63 double]
              YData: [1x63 double]
              ZData: [1x0 double]

  Show all properties
```

For example, we can find that the parent of the plot is an Axes object.

```
>> axhan = hl.Parent
ans =
  Axes with properties:

             XLim: [-8 8]
             YLim: [-1 1]
               etc.
```

The objects, their properties, what the properties mean, and valid values can be found in the MATLAB Help Documentation. Search for Graphics Object Properties to see a list of the property names and a brief explanation of each.

QUICK QUESTION!

How could you change the x-axis limit to `[-10 10]`?

Answer: `>> axhan.XLim=[-10 10]`

Note that this modifies the axes in the Figure Window. Using the dot notation in an assignment statement will show the new value of *axhan*.

For example, the Color property is a vector that stores the color of the line as three separate values for the Red, Green, and Blue intensities, in that order. Each value is in the range from 0 (which means none of that color) to 1 (which is the brightest possible hue of that color). In the previous plot example, the Color was [0 0.4470 0.7410], which means no red, some green, and a lot of blue; in other words, the line drawn for the **sin** function was a royal blue hue. This is the default color for line plots.

Note
that in earlier versions of MATLAB, the default color was [0 0 1], or full blue.

More examples of possible values for the Color vector include:

[1 0 0] is red
[0 1 0] is green
[0 0 1] is blue
[1 1 1] is white
[0 0 0] is black
[0.5 0.5 0.5] is a shade of gray

Changing the line width in the figure makes it easier to see the line and its color, as shown in Fig. 11.1. Also, tab completion is available for class properties and methods; for example, if you are not sure of the exact property name for the line width, typing “hl.Li” and then hitting the tab key would display the options.

```
>> hl.LineWidth=4;
```

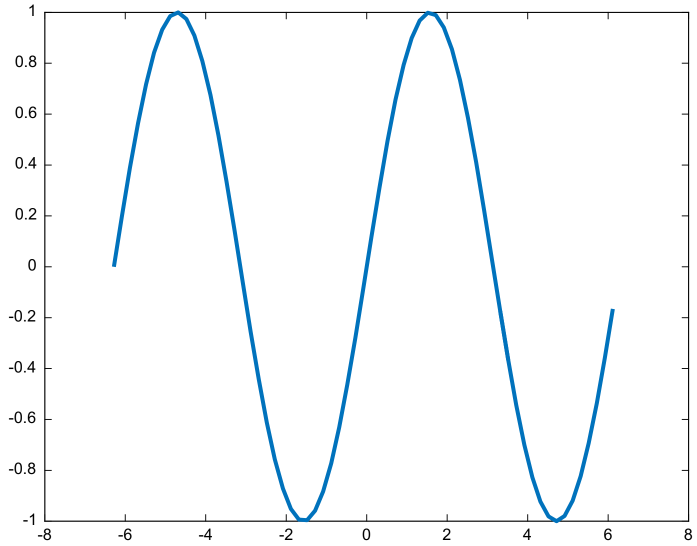


FIGURE 11.1
Line plot of sin with width of 4.

PRACTICE 11.2

Create *x* and *y* vectors, and use the **plot** function to plot the data points represented by these vectors. Store the handle in a variable and do not close the Figure Window! Inspect the properties and then change the line width and color. Next, put markers for the points and change the marker size and edge color.

In addition to handles for objects, the built-in functions **gca** and **gcf** return the handles for the current axes and figure, respectively (the function names stand for "get current axes" and "get current figure"). In the following example, two Figure Windows are opened. The current figure and the current axes are the most recently created.

```
>> x = -pi: 0.1: pi;
>> f1 = figure(1);
>> p1 = plot(x,sin(x));
>> f2 = figure(2);
>> p2 = plot(x,cos(x), Color=[0 1 1]);
>> curfig=gcf
curfig=
  Figure (2) with properties:
   Number: 2
     Name: ''
    Color: [0.9400 0.9400 0.9400]
 Position: [440 378 560 420]
    Units: 'pixels'

  Show all properties
```

The Children property of the current figure stores the axes that orient the plot; these axes are also returned by the **gca** function.

```
>> curfig.Children
ans =
  Axes with properties:

             XLim: [-4 4]
             YLim: [-1 1]
           XScale: 'linear'
           YScale: 'linear'
    GridLineStyle: '-'
         Position: [0.1300 0.1100 0.7750 0.8150]
            Units: 'normalized'

  Show all properties
>> curfig.Children==gca
ans =
     1
```

Within the axes, the Line primitive was used to create the plot. This can be referenced using the dot operator twice. The variable *curfig* stores the handle of the current figure; its Children property stores the current axes, and the Children property of the axes is the Line primitive.

```
>> curfig.Children.Children
ans=
  Line with properties:

              Color: [0 1 1]
          LineStyle: '-'
          LineWidth: 0.5000
             Marker: 'none'
         MarkerSize: 6
    MarkerFaceColor: 'none'
              XData: [1x63 double]
              YData: [1x63 double]
              ZData: [1x0 double]

  Show all properties
```

Note that the Color property was specified in the original plot.

Thus, the hierarchy is: Figure Window -> Axes -> Line.

11.3 USER-DEFINED CLASSES AND OBJECTS

There are many examples of built-in classes in MATLAB, including the **handle** class used by plot functions. It is also possible for users to define classes, and then create or instantiate objects of those classes.

11.3.1 Class Definitions

Classes are defined using the keyword **classdef**. The class definition is organized by blocks, and typically at a minimum contains properties (the data) using the keyword **properties** and methods (the functions that act on the data) using the keyword **methods**. One special case of a method is a ***constructor function*** that initializes the properties. Class definitions are stored in code files with the same name as the class; the constructor function also is given the same name.

Every block begins with the keyword and ends with **end**. The organization of a basic class definition, in which there are two properties and one method, which is a constructor function, follows.

MyClassName.m

```
classdef MyClassName

   properties
       prop1
       prop2
   end

   methods

     % Constructor function
     function obj=MyClassName(val1, val2)
               obj.prop1=val1;
               obj.prop2=val2;
     end

     % Other methods that operate on properties

   end
end
```

The class definition is stored in a code file with the same name as the class. Within the **classdef** block, there are blocks for **properties** and **methods**. In the **properties** block, the names of all properties are given. It is also possible to assign default values for the properties using the assignment operator; if this is not done, MATLAB initializes each to the empty vector.

The constructor function must have the same name as the class. It only returns one output argument, which is the initialized object. If no constructor function is defined, MATLAB creates one that uses the default values given in the

properties definition, if any, or empty vectors if not. It is best to write the constructor function to allow for the case in which no input arguments are passed, using **nargin** to check to determine how many arguments were passed to the function.

The following is a simple class definition in which there are two properties: x, which is not initialized so the default value is the empty vector and y, which is initialized to 33. The class has one constructor function; if two arguments are passed to it, they are stored in the two properties. If not, the default values are used.

SimpleClass.m

```
classdef SimpleClass

    properties
        x
        y = 33;
    end

    methods

        function obj = SimpleClass(val1, val2)
            if nargin == 2
               obj.x = val1;
               obj.y = val2;
            end
        end
    end

end
```

Once the class has been defined, objects can be created or instantiated by assigning the name of the class. For example, the following instantiates an object named *myobject*; because the output is not suppressed, the property names and their values are shown:

```
>> myobject=SimpleClass
myobject=
  SimpleClass with properties:

  x: []
  y: 33
```

Instantiating this object automatically calls the constructor function; because no arguments were passed, the default values were used for the properties.

In the following example, input arguments are passed to the constructor.

```
>> newobject=SimpleClass(4, 22)
newobject=
  SimpleClass with properties:

    x: 4
    y: 22
```

The properties and methods can be seen using the **properties** and **methods** functions:

```
>> properties(myobject)
Properties for class SimpleClass:
    x
    y
>> methods(myobject)

Methods for class SimpleClass:

SimpleClass
```

The properties can be accessed using the dot operator to either display or modify their values.

```
>> myobject.x=11
myobject=
  SimpleClass with properties:

    x: 11
    y: 33
```

We will now modify the class definition, making the constructor function more general, and adding a new method.

```
SimpleClassii.m
```

```
classdef SimpleClassii

    properties
        x
        y=33;
    end

    methods
        function obj=SimpleClassii(varargin)
            if nargin==0
                obj.x=0;
            elseif nargin==1
                obj.x=varargin{1};
            else
                obj.x=varargin{1};
                obj.y=varargin{2};
            end
        end

        function outarg=ordMethod(obj, arg1)
            outarg=obj.x+obj.y+arg1;
        end
    end
end
```

In the class *SimpleClassii*, there are two methods. The constructor, which has the same name as the class, is general in that it accepts any number of input arguments. If no arguments are passed, the property *x* is initialized to 0 (*y* is not initialized since a default value was already assigned to it in the **properties** block). If only one input argument is passed, it is assumed to be the value of the property *x*, and is assigned to *obj.x*. If two or more input arguments are passed, the first is the value of *x* and the second is the value to be stored in *y*. Although it is best to use **nargin** and **varargin** to allow for any number of input arguments, future examples assume the correct number of input arguments for simplicity. If the properties are to be a certain type, the constructor function should also check and ensure that the input arguments are the correct type and either typecast them or change them if not.

The following examples demonstrate instantiating two objects of the class *SimpleClassii*.

```
>> objA=SimpleClassii
objA=
  SimpleClassii with properties:

   x: 0
   y: 33

>> objB=SimpleClassii(4, 9)
objB=
  SimpleClassii with properties:

   x: 4
   y: 9
```

QUICK QUESTION!

What would the value of the properties be for the following:

```
>> ob=SimpleClassii(1,-6, 7, 200)
```

Answer:

```
x:1
y:-6
```

The last two arguments to the constructor were ignored.

Every time an object is instantiated, the constructor function is automatically called. Therefore, there are two ways of initializing properties: in the property definition block, and by passing values to the constructor method.

The second method in SimpleClassii is an example of an ***ordinary method***. The method *ordMethod* adds the values of the input argument, the *x* property, and the *y* property together and returns the result. When calling this method, the object to be used must always be passed to the method, which is why there are two input arguments in the function header: the object and the value to be summed with the properties.

There are two ways in which the method *ordMethod* can be called. One way is by explicitly passing the object to be used:

```
>> resultA=ordMethod(objA, 5)
resultA=
    38
```

The other way is by using the dot operator with the object, as follows:

```
>> resultB=objB.ordMethod(11)
resultB=
    24
```

Both of these methods are identical in their effect; they both pass the object to be used and the value to be added. Notice that, regardless of how the method is called, there are still two input arguments in the function header: one for the object (whether it is passed through the argument list or by using the dot operator) and one for the value to be added. Although it is common for the object to be the first input argument, it is not necessary to do so.

The **ismethod** function, introduced in R2020a, can be used to determine whether a character vector (or string) is the name of a method for a particular object.

11.3.2 Overloading Functions and Operators

By default, MATLAB creates an assignment operator for classes, which allows one object of the class to be assigned to another. This performs *memberwise* assignment, which means it assigns each property individually. Thus, one object can be assigned to another using the assignment operator. Other operators, however, are not defined automatically for classes. Instead, the programmer has the power to define operators. For example, what would it mean for one object to be less than another? The programmer has the power to define "<" any way they want! Of course, it makes sense for the operator to be defined in a way that is consistent with the definition for MATLAB classes. For example, it makes sense to define the equality operator to determine whether two objects are equal to each other or not (and that would typically be memberwise). An error message will be thrown if an operator is used that has not been defined.

Recall that all operators have a functional form. For example, the expression `a+b` can also be written as **plus(a,b)**. When defining an operator for a user-defined class, a member function is defined with the function name for the operator, e.g., **plus**. This is called ***overloading***, as it gives another definition for an existing function. Which function is used (the built-in or user-defined) depends on the context, which means the types of the arguments that are used in the expression.

In addition to the operator functions, it is also possible to overload other functions for a class. For example, one function that is frequently overloaded is the function **disp**. By creating a class member function **disp**, one can customize the way in which object properties are displayed. One aspect of overloading the **disp** function is that when the assignment operator is used to assign a value to an object or an object property, and the semicolon is not used to suppress the output, the **disp** function is automatically called to display the properties; therefore, the format of the output that is created in the overloaded **disp** function will be seen with every unsuppressed assignment.

To illustrate some of these concepts, a class to represent a rectangle, *Rectangle*, will be developed. There are two properties, for the length and width of the rectangle. There are four methods:

- a constructor function, or method, *Rectangle*
- an ordinary method *rectarea* that calculates the area of a Rectangle object
- two overloaded functions:
  - *disp*, which displays the properties in a formatted sentence
  - *lt*, which is the function for the less than operator

What does it mean for one Rectangle object to be less than another? In the following definition, the *lt* function returns **true** if the area of one Rectangle object is less than another. However, this is our choice. Depending on the application, it may make more sense to define it using just the length, just the width, or perhaps based on the perimeters of the Rectangle objects. This is a cool thing about classes; the programmer can define these operator functions in any way desired.

Rectangle.m

```
classdef Rectangle

    properties
        len=0;
        width=0;
    end

    methods

        function obj = Rectangle(l, w)
            if nargin == 2
                obj.len=l;
                obj.width=w;
            end
        end

        function outarg=rectarea(obj)
            outarg=obj.len*obj.width;
        end

        function disp(obj)
            fprintf('The rectangle has length %.2f', obj.len)
            fprintf(' and width %.2f\n', obj.width)
        end


        function out=lt(obja, objb)
            out=rectarea(obja) < rectarea(objb);
        end
    end
end
```

For simplicity, the constructor only checks for two input arguments; it does not check for a variable number of arguments, nor does it verify the types of the input arguments. If **nargin** is not 2, the default values from the properties block are used.

Here are examples of instantiating *Rectangle* objects, both using the constructor function and using the assignment operator that MATLAB provides for classes:

```
>> rect1=Rectangle(3,5)
rect1=
The rectangle has length 3.00 and width 5.00
>> rect2=rect1;
>> rect2.width=11
rect2=
The rectangle has length 3.00 and width 11.00
```

Notice that the overloaded *disp* function in the class definition is used for displaying the objects when the output is not suppressed. It can also be called explicitly.

```
>> rect1.disp
The rectangle has length 3.00 and width 5.00
```

As the *lt* operator was overloaded, it can be used to compare *Rectangle* objects.

```
>> rect1 < rect2
ans =
     1
```

Other operators, for example, **gt** (greater than), however, have not been defined within the class so they cannot be used, and MATLAB will throw an error message.

```
>> rect1 > rect2
Undefined operator '>' for input arguments of
type 'Rectangle'.
```

Care must be taken when overloading operator functions. The function in the class definition takes precedence over the built-in function, when objects of the class are used in the expression.

QUICK QUESTION!

Could we mix types in the expression? For example, what if we wanted to know whether the area of *rect1* was less than 20, could we use the expression

```
rect1 < 20 ?
```

Answer: No, not with the overloaded *lt* function as written, which assumes that both arguments are *Rectangle* objects. The following error message would be generated:

```
>> rect1 < 20
Undefined function 'rectarea' for input
  arguments of type 'double'.
Error in < (line 30)
out=rectarea(obja) < rectarea(objb);
```

However, it is possible to rewrite the function to handle this case. In the following modified version, the type of each of the input arguments is checked. If the argument is not a *Rectangle* object, the type is checked to see whether it is the type **double**. If it is, then the input argument is modified to be a rectangle with the number specified as the length and a width of 1 (so the area will be calculated correctly). Otherwise, the argument is simply typecast to be a *Rectangle* object so that no error is thrown (another option would be to print an error message).

```
function out=lt(inp1, inp2)
    if ~isa(inp1,'Rectangle')
        if isa(inp1, 'double')
            inp1=Rectangle(inp1,1);
        else
            inp1=Rectangle;
        end
    end
    if ~isa(inp2,'Rectangle')
        if isa(inp2, 'double')
            inp2=Rectangle(inp2,1);
        else
            inp2=Rectangle;
        end
    end
    out=rectarea(inp1) < rectarea(inp2);
end
```

With the modified function, expressions mixing Rectangle objects and double values can now be used:

```
>> rect1 < 20
ans =
        1
```

11.3.3 Inheritance and the Handle Class

Inheritance is when one class is derived from another. The initial class is called the ***superclass*** and the derived class is called the ***subclass***. A subclass is a new class that has the properties and methods of the superclass, plus it can have its own properties and methods. The methods in a subclass can override methods from the superclass if they have the same name.

11.3.3.1 Subclasses

The syntax for the subclass definition includes the "<" operator followed by the name of the superclass in the first line of the code file. (Note: this is not the less than operator!) The subclass inherits all of the properties and methods of the superclass, and then its own properties and methods can be added. For example, a subclass might inherit two properties from the superclass, and then also define one of its own. The constructor function would initialize all three properties, as seen in the example that follows.

MySubclass.m

```
classdef MySubclass < Superclass

    properties
        prop3
    end

    methods

      % Constructor function
      function obj=MySubclass(val1, val2,val3)
                obj@Superclass(val1,val2)
                obj.prop3=val3;
      end

      % Other methods that operate on properties

    end
end
```

The first line in the constructor uses the syntax obj@Superclass in order to call the constructor method of the super class to initialize the two properties defined in the super class.

For example, our class *Rectangle* can be a superclass for a subclass *Box*. The subclass *Box* inherits the *len* and *width* properties and has its own property *height*. In the following class definition for *Box*, there is also a constructor function named *Box* and an ordinary method to calculate the volume of a *Box* object.

Box.m

```
classdef Box < Rectangle

    properties
        height=0;
    end

    methods
        function obj=Box(l,w,h)
            if nargin < 3
                l=0;
                w=0;
                h=0;
            end
            obj@Rectangle(l,w)
            obj.height=h;
        end

        function out=calcvol(obj)
            out=obj.len*obj.width*obj.height;
        end
    end
end
```

The values of all three properties should be passed to the constructor function. If not, the input arguments are all assigned default values. Next, the *Box* constructor calls the *Rectangle* constructor to initialize the *len* and *width* properties. The syntax for the call to the *Rectangle* constructor is:

```
obj@Rectangle(l,w)
```

Note that this call to the Rectangle constructor must be executed first, before other references to the object properties. Finally, the constructor initializes the *height* property.

The following is an example of instantiating a *Box* object. Notice that since the result of the assignment is not suppressed, the *disp* function from the *Rectangle* class is called. All three of the properties were initialized, but only the length and width were displayed.

```
>> mybox=Box(2,5,8)
mybox =
The rectangle has length 2.00 and width 5.00
>> mybox.height
ans =
     8
```

To remedy this, we would have to overload the *disp* function again within the *Box* class.

```
function disp(obj)
   fprintf('The box has a length of %.2f,',obj.len)
   fprintf(' width %.2f\nand height %.2f\n',...
              obj.width,obj.height)
end
```

```
>> mybox=Box(2,5,8)
mybox=
The box has a length of 2.00, width 5.00
and height 8.00
```

11.3.3.2 Value and Handle Classes

There are two types of classes in MATLAB: ***value classes*** and ***handle classes***. Value classes are the default; so far, the classes that have been demonstrated have all been value classes. Handle classes are subclasses that are derived from the abstract class **handle**, which is a built-in class. The class definition for a **handle** class begins with:

```
classdef MyHandclass < handle
```

There is a very fundamental difference between value classes and handle classes. With value classes, if one object is copied to another, they are completely independent; changing one does not affect the other. With handle classes, on the other hand, if one handle object is copied to another it does not copy the data; instead, it creates a reference to the same data. All objects refer to the same data (the properties).

User-defined classes can be either value classes or handle classes. Built-in classes are also either value classes or handle classes. For example, built-in numeric types such as **double** are value classes, whereas plot objects are handle objects.

Because **double** is a value class, we can assign one **double** variable to another – and then changing the value of one does not affect the other.

```
>> num = 33;
>> value = num;
>> value = value+4
value =
     37
>> num
num =
     33
```

On the other hand, plot object handles are handle objects. When assigning one plot handle variable to another, they both refer to the same plot.

```
>> x=0: 0.1 : pi;
>> plothan=plot(x,sin(x));
>> handleb=plothan;
```

Both variables *plothan* and *handleb* refer to the same plot; they are not different plots. As a result, a property such as the line width could be changed by either

```
>> plothan.LineWidth=3;
```

or

```
>> handleb.LineWidth=3;
```

Either of these would accomplish the same thing, changing the line width in the one plot to 3.

As an example of a user-defined **handle** class, let us modify the value class *Rectangle* to be a handle class called *HandleRect* (and simplify a bit by not overloading the **lt** function).

HandleRect.m

```
classdef HandleRect < handle

    properties
        len=0;
        width=0;
    end

    methods

        function obj=HandleRect(l, w)
            if nargin== 2
                obj.len=l;
                obj.width=w;
            end
        end
        function outarg=rectarea(obj)
            outarg=obj.len*obj.width;
        end

        function disp(obj)
            fprintf('The rectangle has length %.2f', obj.len)
            fprintf(' and width %.2f\n', obj.width)
        end
    end
end
```

By instantiating an object, we can find the properties and methods as follows.

```
>> HRectangle=HandleRect(3,5)
HRectangle=
The rectangle has length 3.00 and width 5.00
>> properties(HRectangle)
Properties for class HandleRect:
    len
    width
>> methods(HRectangle)

Methods for class HandleRect:

 HandleRect disp         rectarea

Methods of HandleRect inherited from handle.
```

By clicking on the underlined Methods link, the inherited methods can be seen.

```
Methods for class handle:

addlistener    findobj    gt        lt      listener
delete         findprop   isvalid   ne
eq             ge         le        notify
```

Notice that these inherited methods include overloaded operator functions for the operators >, <, >=, <=,==, and ~=. Because the assignment operator is defined automatically for all classes, and the equality operator is overloaded for handle classes, we can assign one *HandleRect* object to another and then verify that they are identical.

```
>> HRecA=HandleRect(2,7.5)
HRecA=
The rectangle has length 2.00 and width 7.50
>> HRecB=HRecA
HRecB=
The rectangle has length 2.00 and width 7.50
>> HRecA== HRecB
ans =
     1
```

QUICK QUESTION!

What would happen if the value of *HRecA.len* was changed to 6?

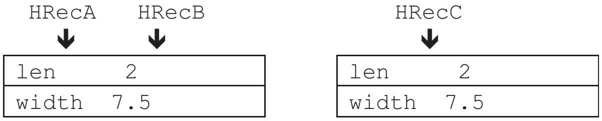
Answer:

```
>> HRecA.len=6;
>> HRecA
HRecA=
The rectangle has length 6.00 and width 7.50
>> HRecB
HRecB=
The rectangle has length 6.00 and width 7.50
```

However, if we then create another object HRecC with the same properties as HRecA and HRecB, HRecC is not equal to either HRecA or HRecB.

```
>> HRecC=HandleRect(2,7.5)
HRecC=
The rectangle has length 2.00 and width 7.50
>> HRecA== HRecC
ans =
     0
```

This illustrates one of the important concepts about handle classes: assigning one object to another does not make a new copy; instead, it creates another reference to the same object. However, instantiating an object by calling the constructor function does create a new object, even if it happens to have the same properties as other object(s). The following is an illustration of the three *HandleRect* objects that have been created:



Because both *HRecA* and *HRecB* refer to the same object, changing a property using one of the instances will change that property for both *HRecA* and *HRecB* but will not affect *HRecC*.

```
>> HRecA.len=11;
>> HRecB.len
ans =
     11
>> HRecC.len
ans =
     2
```

PRACTICE 11.3

The **gt**, **lt**, **le**, **ge** functions are overloaded in **handle** classes for the operators >, <, <=, and >= respectively. Create a **handle** class with multiple properties, instantiate at least two objects of this class, and design experiments with the objects to determine whether these overloaded operators are implemented memberwise or not.

Because handle class objects are references to the locations in which the objects are stored, there are differences between handle and value classes in the ways that objects are passed to functions, and in the manner in which functions can change objects. We will create two simple classes, a value class *valClass*, and a handle class *hanClass*, to illustrate the differences. Both will have just one double property *x*. There will be four methods; for simplicity, none of them error-check:

- a simple constructor
- a function *add* that receives two objects, adds the x properties together, and returns an object in which the x property is the sum of the two inputs
- a function *timestwo* that receives one object, and returns an object in which the property is the property of the input argument multiplied by two
- a function *timesthree* that receives one object, multiplies its property by three but does not return anything

The constructor and *add* functions behave similarly in the value and handle classes. In both classes, the *add* function receives two input arguments which are objects and returns an object which is distinct from the input objects. The other two functions, however, behave differently in *valClass* and *hanClass*. We will first examine the value class.

valClass.m

```
classdef valClass

    properties
        x=0;
    end

    methods
        function obj=valClass(in)
            if nargin== 1
                obj.x=in;
            end
        end

        function out=add(obja, objb)
            out=valClass(obja.x+objb.x);
        end

        function outobj=timestwo(inobj)
            outobj=valClass(inobj.x*2);
        end

        function timesthree(obj)
            % Note: this function does not
            % accomplish anything; MATLAB
            % flags the following line
            obj.x=obj.x*3;
        end
    end
end
```

Note

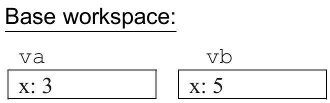
that the *add* and *timestwo* functions call the *valClass* constructor to make the output a *valClass* object.

Instantiating two objects and calling the *timestwo* function create the following result.

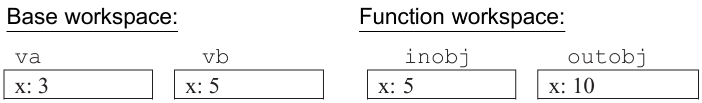
```
>> va=valClass(3);
>> vb=valClass(5);
>> vmult2=timestwo(vb)
vmult2=
  valClass with properties:

    x: 10
>> vb
vb =
  valClass with properties:

    x: 5
```

Note that in the base workspace, initially there are two objects *va* and *vb*. While the function is executing, the function's workspace has the input argument *inobj* and output argument *outobj*. These are all separate objects. The value of the object *va* was passed to the input object *inobj*, and a separate output argument is created in the function, which is then returned to the object *vmult2* in the assignment statement. At this point, the function's workspace would no longer exist but the base workspace would now have *va*, *vb*, and *vmult*.

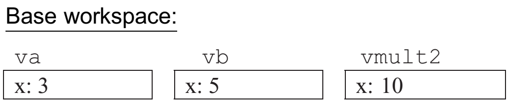
Before the function call to *timestwo*, we have:



While the *timestwo* function is executing, we have:



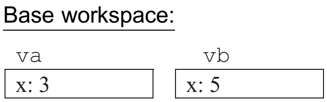
After *timestwo* has stopped executing and has returned the object, we have:



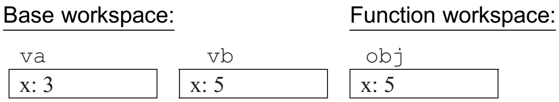
Now let us examine the behavior of the *timesthree* function, which does not return any output argument, so the call cannot occur in an assignment statement.

```
>> clear
>> va=valClass(3);
>> vb=valClass(5);
>> timesthree(vb)
>> va
va =
  valClass with properties:

    x: 3
>> vb
vb =
  valClass with properties:

    x: 5
```

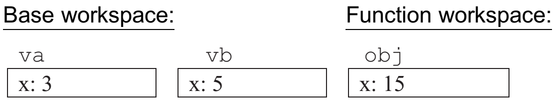
Before the function call to *timesthree*, we have:



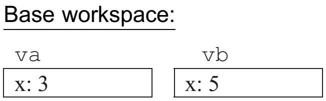
Initially in the *timesthree* function, we have:



Once the assignment statement in the *timesthree* function has executed, we have:



After *timesthree* has stopped executing, we have:



Within the body of the function, the value of the input argument was modified. However, that value was not returned. It was also a separate object from the two objects in the base workspace. Therefore, the function accomplished nothing, which is why MATLAB flags it. It appears to behave as though it is a handle class method, as we will see next.

The next example is similar but is a **handle** class rather than a value class. Let us examine the *timestwo* and *timesthree* functions in the following **handle** class.

hanClass.m

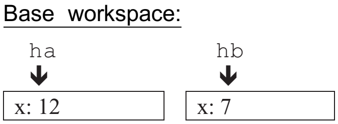
```
classdef hanClass < handle

    properties
        x=0;
    end

    methods

        function obj=hanClass(in)
            if nargin== 1
                obj.x=in;
            end
        end

        function out=add(obja, objb)
            out=hanClass(obja.x+objb.x);
        end

        function outobj=timestwo(inobj)
            outobj=hanClass(inobj.x*2);
        end

        function timesthree(obj)
            obj.x=obj.x*3;
        end
    end
end
```

Instantiating two objects and calling the *timestwo* function create the following result.

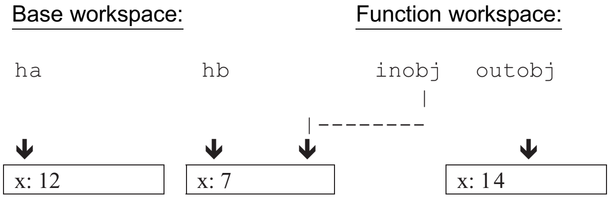
```
>> ha=hanClass(12);
>> hb=hanClass(7);
>> hmult2=timestwo(hb)
hmult2=
  hanClass with properties:

    x: 14
>> hb
hb =
  hanClass with properties:

    x: 7
>> ha
ha =
  hanClass with properties:

    x: 12
```

Note that in the base workspace, there are two objects, *ha* and *hb*. While the function is executing, there are also the input argument *inobj* and output argument *outobj*. The value of the object *hb*, which is a reference to the object, was passed to the input object *inobj*, which means that *inobj* refers to the same object. Within the body of the function, a separate object *outobj* is created.

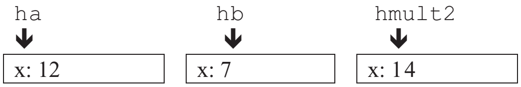
Before the function call to *timestwo*, we have:



While the *timestwo* function is executing, we have:



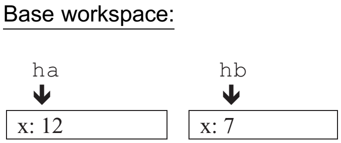
After *timestwo* has stopped executing and has returned the object, we have:



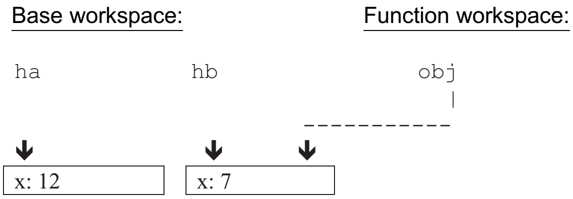
Now let us examine the behavior of the *timesthree* function. As with the value class, this function does not return any output argument, so calls to it cannot occur in an assignment statement. However, this function does accomplish something; it modifies the object passed as an input argument.

```
>> clear
>> ha=hanClass(12);
>> hb=hanClass(7);
>> timesthree(hb)
>> ha
ha =
  hanClass with properties:

    x: 12
>> hb
hb =
  hanClass with properties:

    x: 21
```

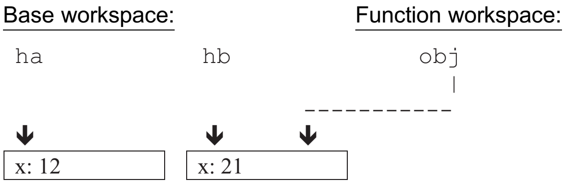
Before the function call to *timesthree*, we have:



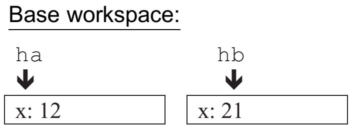
While the *timesthree* function begins, we have:



Once the *timesthree* function executes its assignment statement, we have:



After *timesthree* has stopped executing and has returned the object, we have:



Thus, because handle class objects store references, passing a handle class object to a function can allow the function to modify its properties (without returning anything). This cannot happen with value class objects.

Notice that errors will occur for both the value and handle classes if the *timesthree* functions are called in assignment statements because these functions do not return any values.

```
>> vmult3=timesthree(vb)
Error using valClass/timesthree
Too many output arguments.

>> hmult3=timesthree(hb)
Error using hanClass/timesthree
Too many output arguments.
```

11.3.4 Property Definition Blocks

The behaviors of, and access to, classes, properties, and methods can be controlled by what are called ***attributes***. The attributes are specified in parentheses in the first line of any block.

There are several attributes that relate to properties. One of the most important attributes is access to the properties. There are three types of access to properties:

- **public**: access is possible from anywhere; this is the default
- **private**: access is possible only by methods in this class

- **protected**: access is possible only by methods in this class or any of its subclasses

The attributes that control the access to properties are:

- **GetAccess**: read access, which means the ability to determine the values of properties
- **SetAccess**: write access, which means the ability to initialize or modify values of properties
- **Access**: both read and write access

In the case in which different properties are to have different attributes, multiple property definition blocks can be defined. So far, because we have not specified, both the read and write access to all properties in our class definitions have been public. This means that we have been able to see, and to modify, the values of the properties for example from the Command Window.

The following is an example of a value class in which one property, *num*, is public, and the other property, *word*, has public GetAccess but protected SetAccess.

valAttributes.m

```
classdef valAttributes

    properties
        num = 0;
    end

    properties (SetAccess=protected)
        word='hello';
    end

    methods
        function obj = valAttributes(n,w)
            if nargin == 2
                obj.num = n;
                obj.word = w;
            end
        end

    end
end
```

Once an object has been instantiated using the constructor, the property *num* can be queried and modified (because Access is public by default).

```
>> valA=valAttributes(3, 'hi')
valA=
  valAttributes with properties:

     num: 3
    word: 'hi'
>> valA.num
ans=
    3
```

```
>> valA.num=14
valA=
  valAttributes with properties:

     num: 14
    word: 'hi'
```

The property *word*, however, can be queried (because GetAccess is public by default) but it cannot be changed (because SetAccess was set to protected). Only methods within the class (or subclasses if defined) can change the word property.

```
>> valA.word
ans =
hi

>> valA.word='ciao'
You cannot set the read-only property 'word' of valAttributes.
```

This is a very useful aspect of objects. Protecting objects by only allowing class methods to modify them is a very powerful tool. One example of this is to error-check property values.

Although the access attributes are the most commonly used, there are other attributes that can be set (e.g., Constant for values that are to be constant for all objects). A table of all attributes can be found by searching the documentation for Property Attributes.

11.3.5 Method Types

There are different types of methods that can be defined in class definitions; we have already seen constructor functions, ordinary methods, and overloading functions. As with properties, there are also attributes that control the behavior of methods.

11.3.5.1 Constructor Functions

As we have seen, all classes should have constructor functions, which initialize the properties in an object. If a class definition does not include a constructor, MATLAB will initialize the properties to either default values provided in the property definition block, or to empty vectors. Constructor functions always have the same name as the class, and return only the initialized object; this is true for both value and handle classes. Constructor functions should be general and should allow for the case in which no input arguments are passed by creating default property values. To be truly general, the types of the input arguments should also be checked to make sure that they are the correct types for the properties. Overloading the set.PropertyName functions for all properties allows for even more control over all functions that set the properties, including the constructor function.

If the class being defined is a subclass, the constructor function of the superclass must be called to initialize its properties. MATLAB automatically makes implicit calls to the superclass constructors using no arguments when the class is defined as a subclass in the class definition line. It is also possible to explicitly call the constructors and pass arguments to be the property values; this is necessary if the superclass constructors require that input arguments be passed.

Some languages have what are called ***copy constructor*** functions, which allow an object to be constructed by copying all properties of one object into another. MATLAB does not have a copy constructor, but it would be possible to write a constructor function so that it checks to see whether the input argument is an object of the class type, and if so, copy the properties. The beginning of a simplified version of such a constructor for a class *MyClass* might be:

```
MyClass.m
```

```
function obj=MyClass(varargin)
if nargin == 1
    val = varargin{1};
    if isa(val, 'MyClass')
        % Copy all properties
        obj.Prop=val.Prop;
    else
        % etc.

    end
end
end
```

11.3.5.2 Access Methods

MATLAB has special access methods that allow you to query a property and to assign a value to a property. These methods have special names that include the name of the property:

```
get.PropertyName
set.PropertyName
```

These methods cannot be called directly, and they do not show in the list of functions returned by the **methods** function. Instead, they are automatically called whenever a property is queried or an attempt is made to assign a value to a property. They can, however, be overloaded.

One reason to overload the set.PropertyName method is to be able to error-check to make sure that only correct values are being assigned to a property. For example, the following is a simple value class in which the property is a grade that should be in the inclusive range from 0 to 100; the *set.grade* function ensures this.

valSet.m

```
classdef valSet
    properties
        grade=0;
    end

    methods

        function obj=valSet(in)
            if nargin== 1
                obj.grade=in;
            end
        end

        function obj=set.grade(obj,val)
            if val >= 0 && val <= 100
                obj.grade=val;
            else
                error('Grade not in range')
            end
        end
    end
end
```

The *set.grade* function restricts values for the *grade* property to be in the correct range, both when instantiating objects and when attempting to modify an object. Note that the input and output argument names for the object must be the same. The **error** function throws an error message.

```
>> valobj=valSet(98)
valobj=
  valSet with properties:

    grade: 98
>> badobj=valSet(105)
Error using valSet/set.grade (line 18)
Grade not in range
Error in valSet (line 10)
                obj.grade=in;
>> valobj.grade=99
valobj=
    valSet with properties:

    grade: 99
>> valobj.grade=-5
Error using valSet/set.grade (line 18)
Grade not in range
```

The *set.grade* function would be slightly different in a handle class because the function can modify properties of an object without returning the object. An equivalent example for a handle class follows; note that the function does not return any output argument.

hanSet.m

```
classdef hanSet < handle
    properties
        grade=0;
    end

    methods

        function obj=hanSet(in)
            if nargin == 1
               obj.grade=in;
            end
        end

        function set.grade(obj,val)
            if val >= 0 && val <= 100
                obj.grade=val;
            else
                error('Grade not in range')
            end
        end
    end
end
```

Note that the **get** and **set** method blocks cannot have any attributes.

11.3.5.3 Method Attributes

As with property attributes, method attributes are defined in parentheses in the first line of the method block. In the case in which different methods are to have different attributes, multiple method definition blocks can be defined.

There are several attributes that relate to methods. These include **Access**, which controls from where the method can be called. There are three types of access to methods:

- **public**: access is possible from anywhere; this is the default
- **private**: access is possible only by methods in this class
- **protected**: access is possible only by methods in this class or any of its subclasses

All of the methods in the examples shown thus far have been public. This means, for example, that we have been able to call our class methods from the Command Window. It is very common, however, to restrict access so that only methods within the class itself (or, any subclasses) can call other methods.

Besides **Access**, other method attributes include the following, all of which are the type **logical** and have a default value of **false**.

- **Abstract**: If true, there is no implementation of the method
- **Hidden**: If true, the method is not seen in lists of methods
- **Sealed**: If true, the method cannot be redefined in a subclass
- **Static**: If true, the method is a static method which means that it is not called by any particular object; static methods are the same for all objects in the class

Static methods are not associated with any object. One reason to have a static method is to perform calculations that are typical for the class (e.g., conversion of units). The following is a simple example.

StatClass.m

```
classdef StatClass
    methods (Static)
        function out=statex(in)
            out=in*10;
        end
    end
end
```

As static methods are not associated with any instantiation of the class, they are therefore called with the name of the class, not by any object.

```
>> StatClass.statex(4)
ans =
     40
```

11.3.5.4 Destructor Functions

Just as constructor functions create objects, ***destructor functions*** destroy objects. In MATLAB, destructor functions are optional. If a destructor function is defined within a class, this is accomplished by overloading the **delete** function. There are specific rules that make an overloaded **delete** function a destructor function: the function must have just one input argument, which is an object of the class, and it must not have any output arguments. Also, it cannot have the value **true** for the attributes **Sealed**, **Static**, or **Abstract**. The reason for having a class destructor function is to be able to “clean up”. For example, if the class opens a file, the destructor function might make sure that the file is closed properly.

11.3.6 Events and Listeners

In addition to the properties and methods blocks that are normally in a class definition, handle classes (but not value classes) can also have an **events** block. ***Events*** are some type of action that takes place; ***event-driven programming*** is when an event triggers an action. In handle classes in MATLAB, there are three main concepts:

- *event*: an action, such as changing the value of a property or the user clicking the mouse
- *listener*: something that detects an event and initiates an action based on it
- *callback*: a function that is called by the listener as a result of the event

There are two methods defined in the handle class that are used with events:

- **notify**: notifies listener(s) when an event has occurred
- **addlistener**: adds a listener to an object, so that it will know when an event has occurred

Examples of these concepts will be provided later in the section on Graphical User Interfaces (GUIs). GUIs are graphical objects that the user manipulates (e.g., a push button). When the user pushes a button, for example, that is an event that can cause a callback function to be called to perform a specified operation.

11.3.7 Advantages of Classes

There are many advantages to using OOP and instantiating objects versus using procedural programming and data structures such as structs. Creating one's own classes offers more control over behaviors. Because operators and other functions can be overloaded, programmers can define them precisely as needed. Also, by redefining the set.PropertyName methods, the range of values that can be assigned is strictly controlled.

Another advantage of objects is that when using struct.field, if a fieldname is not spelled correctly in an assignment statement, for example,

```
struct.feild=value;
```

this would just create a new field with the incorrect fieldname, and add it to the structure! If this was attempted with a class object, however, it would throw an error.

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Range and Quartiles

The *range* of a data set is the difference between the maximum and minimum values. In MATLAB, the function **range** will return this value, and the **bounds** function returns the minimum and maximum values. For example, for the vector *svec*:

```
svec =
    44    236    248    285    290    355    401    447

>> range(svec)
ans =
   403
```

```
>> [l, h]=bounds(svec)
l =
    44
h =
    447
```

Quartiles are points that divide an ordered data set into four groups. The second quartile, Q2, is the median of the data set. It cuts the data set in half. The first quartile, Q1, cuts the lower half of the data set in half. Q3 cuts the upper half of the data set in half. For sorted vectors that have an even number of values, this is straightforward. However, for vectors with an odd number of values, there are several possibilities: either calculate without the median, with the median in both halves, or the average of the above two methods (this is the method used by MATLAB). The ***interquartile range*** is defined as Q3 – Q1; MATLAB has a function **iqr** to compute this.

Similarly, ***percentiles*** are points that divide an ordered set into 100 groups. The function **prctile** calculates these. For example, the 50th percentile is the same as the median:

```
>> prctile(svec,50)== median(svec)
ans =
      1
```

Quantiles are also points that divide a sorted set but are referenced by fractions. There is a **quantile** function:

```
>> iqr(svec)
ans =
     136
>> quantile(svec, 0.75)=quantile(svec, 0.25)
ans =
     136
>> quantile(svec, 0.5)== median(svec)
ans =
   logical
     1
>> quantile(svec, 0.6)== prctile(svec, 60)
ans =
   logical
     1
```

Data Visualization: Using Plot Properties

Data visualization is very important in ML, and we have seen in this chapter that by storing handles of plot objects, their properties can be queried and modified. For example, the following script simulates a data set as the vector *svec* from above, and computes the values of Q1, Q2, and Q3. It plots the data points, and straight lines to show the quartiles using the **yline** function.

```
Q2 = median(svec);
Q1 = quantile(svec, 0.25);
```

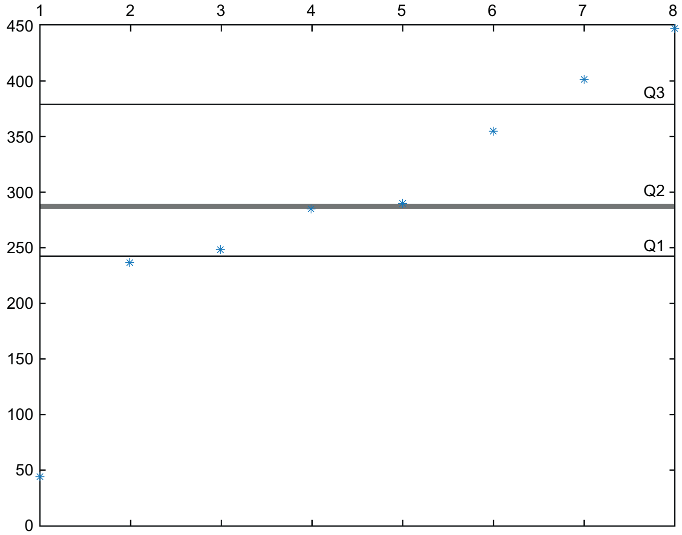

FIGURE 11.2
X-axis on top.

```
    Q3 = quantile(svec, 0.75);
    IQR = iqr(svec);
    qp = plot(svec, '*');
    ylq1 = yline(Q1, 'Label', 'Q1');
    ylq2 = yline(Q2, 'Label', 'Q2');
    ylq3 = yline(Q3, 'Label', 'Q3');
```

This brings up the Figure Window shown in Fig. 11.2. By storing the handles of the plot objects in variables, the properties can be manipulated. For example, we can make the line for Q2 wider than the others, then get the current axes and put the x axis location on top instead of on bottom:

```
    >> ylq2.LineWidth=3;
    >> gh=gca;
    >> gh.XAxisLocation='top';
```

■ Explore Other Interesting Features

Investigate creating a directory for a class so that not all methods have to be in the same file as the class definition.

Investigate the Constant attribute.

Investigate the built-in class Map, and the Map containers which are data structures that utilize key/value pairs and allow for indexing using the keys. ■

SUMMARY

COMMON PITFALLS

- Confusing value and handle classes
- Not realizing that constructor functions are called automatically when objects are instantiated

PROGRAMMING STYLE GUIDELINES

- Use the dot notation to reference properties instead of **get** and **set**.
- Use **nargin** to check the number of input arguments to a constructor function.
- Write constructor functions to allow for no input arguments.
- Call an ordinary method by using the dot operator with the object rather than explicitly passing the object.

MATLAB Keyword
classdef

MATLAB Functions and Commands		
line	properties	gca
groot	methods	gcf
get	eq	ismethod
set	ne	

MATLAB Operators
dot operator for object properties and methods

Exercises

1. Create a **double** variable. Use the functions **methods** and **properties** to see what are available for the class **double**.
2. Create a simple **plot** and store the handle in a variable. View the Color property.
3. Create a simple plot, for example, using:

```
>> y=[3  7  2  9  4  6  2  3];
>> plothan=plot(y)
```

Create the following character vectors, and then use them to change the Color and Marker properties to a random color and a random marker. Also make the LineWidth 3.

```
>> somecolors='bgrcmyk';
>> somemarkers='.ox+*sd';
```

4. Create a **bar** chart and store the handle in a variable. Experiment with the BarWidth property. Make the FaceColor yellow and the EdgeColor red.
5. Create a class *circleClass* that has a property for the radius of the circle and a constructor function. Make sure that there is a default value for the radius, either in the properties block or in the constructor. Instantiate an object of your class and use the **methods** and **properties** functions.
6. Add ordinary methods to *circleClass* to calculate the area and circumference of the circle.
7. Use **ismethod** to determine whether or not **eq** is a method for circleClass.
8. Create a class that will store the price of an item in a store, as well as the sales tax rate. Write an ordinary method to calculate the total price of the item, including the tax.
9. Create the *Rectangle* class from this chapter. Add a function to overload the **gt** (greater than) operator. Instantiate at least two objects and make sure that your function works.
10. Create a class *MyCourse* that has properties for a course number, number of credits, and grade. Overload the **disp** function to display this information.
11. Construct a class named *Money* that has five properties for dollars, quarters, dimes, nickels, and pennies. Include an ordinary function *equivtotal* that will calculate and return the equivalent total of the properties in an object (e.g., 5 dollars, 7 quarters, 3 dimes, 0 nickels, and 6 pennies is equivalent to $7.11). Overload the **disp** function to display the properties.
12. Write a program that creates a class for complex numbers. A complex number is a number of the form a+bi, where a is the real part, b is the imaginary part, and $i=\sqrt{-1}$. The class *Complex* should have properties for the real and imaginary parts. Overload the **disp** function to print a complex number.
13. A Student class is being written. There are two properties: an integer student ID number, and a string final grade for a course. So far, for methods, there is a constructor function. You are to add two more methods: and overloaded **disp** function that displays the student ID and grade, and an overloaded **mean** function that changes the grade (whatever it is) to an F (yes, truly mean!). The format should be as shown here:

```
>> studa=Student(456,'B+')
studa=
Student 456 has earned a B+
>> studa=mean(studa)
studa=
Student 456 has earned a F
```

```
>> disp(studa)
Student 456 has earned a F
>>
```

14. Create a base class *Square* and then a derived class *Cube*, similar to the Rectangle/Box example from the chapter. Include methods to calculate the area of a square and volume of a cube.
15. Create a base class named *Point* that has properties for x and y coordinates. From this class derive a class named *Circle* having an additional property named *radius*. For this derived class, the *x* and *y* properties represent the center coordinates of a circle. The methods of the base class should consist of a constructor, an *area* function that returns 0, and a distance function that returns the distance between two points (sqrt($(x2-x1)^2+(y2-y1)^2$)). The derived class should have a constructor and an override function named *area* that returns the area of a circle. Write a script that has two objects of each class and calls all of the methods.
16. Take any value class (e.g., *MyCourse* or *Square*) and make it into a handle class. What are the differences?
17. Create a class that stores information on a company's employees. The class will have properties to store the employee's name, a 10-digit ID, their department, and a rating from 0 to 5. Overwrite the *set.propertyname* function to check that each property is the correct class and that:

    - The employee ID has 10 digits
    - The department is one of the following codes: HR (Human Resources), IT (Information Technology), MK (Marketing), AC (Accounting), or RD (research and Development)
    - The rating is a number from 0 to 5.

    The rating should not be accessible to anyone without a password. Overwrite the *set.rating* and *get.rating* functions to prompt the user for a password. Then, write a function that returns the rating.
18. Create a handle class that logs the times a company's employees arrive and leave at work. The class must have the following characteristics. As the employer, you do not want your employees to access the information stored. The class will store date, hour, minute, second, and total time as properties. The constructor function will input the data from the *clock* function, which returns a vector with format [year month day hour minute second]. Each time an employee arrives or leaves, they must call a method *LogTime* that will store the new times with the old times. For example, property hour will be
    Hour 1
    Hour 2
    Hour 3
    Include a method *calcPay* that calculates the money owed if it is assumed that the employees are paid $15/hour. In order to do this, call a separate method that calculates the time elapsed between the last two time entries. Use the

function **etime**. This method should only be available to call by *calcPay*, and the existence of *calcPay* should only be known to the coder.

19. You head a team developing a small satellite in competition for a NASA contract. Your design calls for a central satellite that will deploy sensor nodes. These nodes must remain within 30 km of the satellite to allow for data transmission. If they pass out of range, they will use an impulse of thrust propulsion to move back toward the satellite. Make a *Satellite* class with the following properties:

    - *location*: An [X Y Z] vector of coordinates, with the satellite as the origin.
    - *magnetData*: A vector storing magnetic readings.
    - *nodeAlerts*: An empty string to begin with, stores alerts when nodes go out of range.

    Satellite also has the following methods:

    - *Satellite*: The constructor, which sets location to [0 0 0] and magnetData to 0.
    - *retrieveData*: Takes data from a node, extends the magnetData vector.

    Then, make the *sensorNode* class as a subclass of Satellite. It will have the following properties:

    - *distance*: The magnitude of the distance from the satellite. Presume that a node's location comes from on-board, real-time updating GPS (i.e., do not worry about updating node.location).
    - *fuel*: Sensor nodes begin with 100 kg of fuel.

    sensorNode also has the following methods:

    - *sensorNode*: The constructor.
    - *useThrust*: Assume this propels node toward satellite. Each usage consumes 2 kg of fuel. If the fuel is below 5 kg, send an alert message to the satellite.
    - *checkDistance*: Check the magnitude of the distance between
    - useMagnetometer: Write this as a stub. Have the "magnetometer reading" be a randomized number in the range 0 to 100.
    - *sendAlert*: set the "nodeAlerts" Satellite property to the string 'Low fuel'.

    First, treat both classes as value classes. Then, adjust your code so that both are handle classes. Which code is simpler?

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20. Create a plot and store the handle in a variable. Store the result from **gca** in a variable, also. Use this to examine the properties of the tick marks on the x and y axes. Using the Help Documentation for MATLAB, search for Axes Properties to find lists of the axes properties, and the possible values for each. Change the tick length and the tick direction. Change the rotation of the x tick label.
21. Create a **scatter** plot of random points. Draw straight lines to show the values of Q1 and Q3 and put the interquartile range in the title of the plot.

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CHAPTER 12

Advanced Plotting Techniques

KEY TERMS

histogram
stem plot
pie chart
area plot
scatter plot
bubble plot
bin
animation
plot properties
primitive objects
core objects
text box

CONTENTS

In Chapter 3, we introduced the use of the function **plot** in the MATLAB® software to get simple, two-dimensional (2D) plots of x and y points represented by two vectors *x* and *y*. We have also seen some functions that allow customization of these plots. In Chapter 11, we introduced handle classes, object handles, and methods of examining and modifying plot object properties. In this chapter we will explore other types of plots, ways of customizing plots, and some applications that combine plotting with functions and file input. Additionally, animation, three-dimensional (3D) plots, and core graphics primitives will be introduced.

In the latest versions of MATLAB, the PLOTS tab can be used to very easily create advanced plots. The method is to create the variables in which the data are stored and then select the PLOTS tab. The plot functions that can be used are then highlighted; simply clicking the mouse on one will plot the data using that function and open the Figure Window with that plot. For example, by creating *x* and *y* variables, and highlighting them in the Workspace Window, the 2D plot types will become visible. If, instead, *x*, *y*, and *z* variables are highlighted, the 3D plot types will become available. These are extremely fast methods for users to create plots in MATLAB. However, as this text focuses on programming concepts, the programmatic methodologies will be explained in this chapter.

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00012-3

12.1 PLOT FUNCTIONS AND CUSTOMIZING PLOTS

So far, we have used **plot** to create 2D plots and **bar** to create bar charts, and we have seen the use of **xline** and **yline**. We have seen how to clear the Figure Window using **clf**, and how to create and number Figure Windows using **figure**. Labeling plots has been accomplished using **xlabel**, **ylabel**, **title**, **subtitle**, and **legend**, and we have also seen how to customize the strings passed to these functions using **sprintf**. The **axis** function changes the axes from the defaults that would be taken from the data in the *x* and *y* vectors to the values specified. Finally, the **grid** and **hold** toggle functions print grids or not, or lock the current graph in the Figure Window so that the next plot will be superimposed.

Another function that is very useful with all types of plots is **subplot**, which creates a matrix of plots in the current Figure Window, as we have seen in Chapter 5 (and **sgtitle**, which puts a title on the Figure Window). The **sprintf** function is frequently used to create customized axis labels and titles within the matrix of plots.

Besides **plot** and **bar**, there are many other plot types, such as ***histograms***, ***stem plots***, ***pie charts***, and ***area plots***, as well as other functions that customize graphs. Described in this section are some of the other plotting functions.

12.1.1 Bar, Barh, Area, Stem, and Scatter Functions

The functions **bar**, **barh**, **area**, and **stem** essentially display the same data as the **plot** function, but in different forms. The **bar** function draws a bar chart (as we have seen before), **barh** draws a horizontal bar chart, **area** draws the plot as a continuous curve and fills in under the curve that is created, and **stem** draws a stem plot. A ***scatter plot***, or ***bubble plot***, creates a plot using circle markers, using **scatter**.

For example, the following script creates a Figure Window that uses a *2* × *2* **subplot** to demonstrate four plot types using the same data points (see Fig. 12.1).

subplottypes.m

```
% Subplot to show plot types

year=2018:2022;
pop=[0.9 1.4 1.7 1.3 1.8];
subplot(2,2,1)
scatter(year,pop)
title('scatter')
xlabel('Year')
ylabel('Population (mil)')
axis padded
subplot(2,2,2)
```

```
bar(year,pop)
title('bar')
xlabel('Year')
ylabel('Population (mil)')
subplot(2,2,3)
area(year,pop)
title('area')
xlabel('Year')
ylabel('Population (mil)')
subplot(2,2,4)
stem(year,pop)
title('stem')
xlabel('Year')
ylabel('Population (mil)')
axis padded
sgtitle('4 Plot types')
```

Note that the third argument in the call to the **subplot** function is a single index into the matrix created in the Figure Window; the numbering is row wise (in contrast to the normal column wise unwinding that MATLAB uses for matrices).

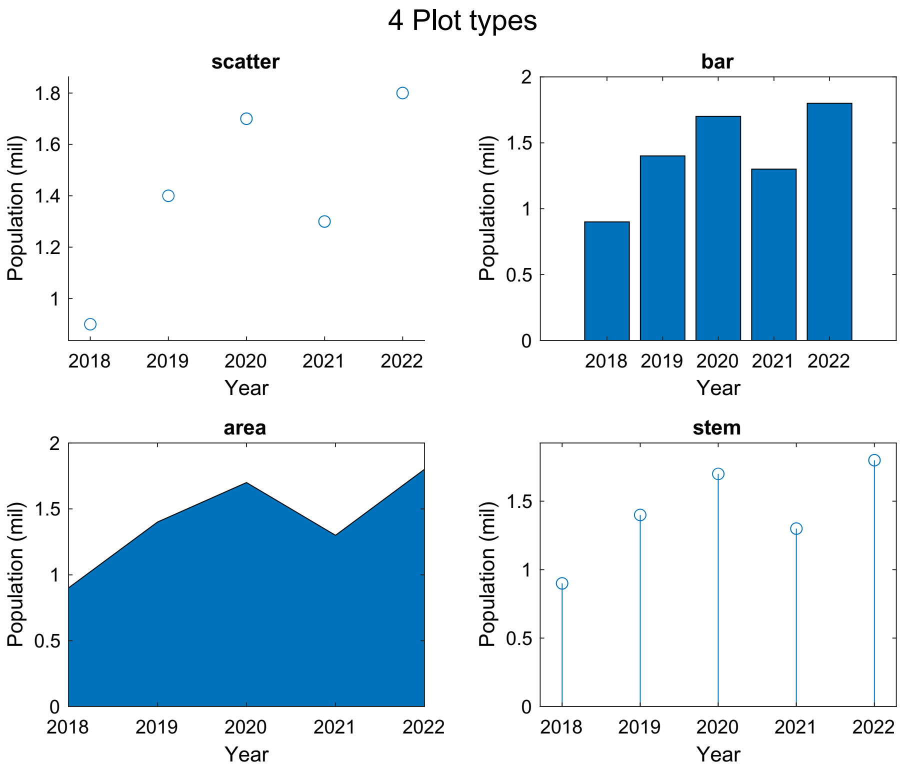


FIGURE 12.1

Subplot to display **scatter**, **bar**, **area**, and **stem** plots.

QUICK QUESTION!

Could we produce this **subplot** using a loop?

Answer: Yes, we can store the names of the plots in a cell array. These names are put in the titles, and also converted to function handles so that the functions can be called.

loopsubplot.m

```
% Demonstrates evaluating plot type names in order to
% use the plot functions and put the names in titles

year = 2018:2022;
pop=[0.9 1.4 1.7 1.3 1.8];
titles = {'scatter', 'bar', 'area', 'stem'};
for i = 1:4
    subplot(2,2,i)
    fn = str2func(titles{i});
    fn(year,pop)
    title(titles{i})
    xlabel('Year')
    ylabel('Population (mil)')
end
```

QUICK QUESTION!

What are some different options for plotting more than one graph?

Answer: There are several methods, depending on whether you want them in one Figure Window superimposed (using **hold on**), in a matrix in one Figure Window (using **subplot**), or in multiple Figure Windows (using **figure(n)**).

For a matrix, the **bar** and **barh** functions will group together the values in each row. For example:

```
>> groupages=[8 19 43 25; 35 44 30 45]
groupages=
     8     19     43     25
    35     44     30     45
>> bar(groupages)
>> xlabel('Group')
>> ylabel('Ages')
```

produces the plot shown in Fig. 12.2.

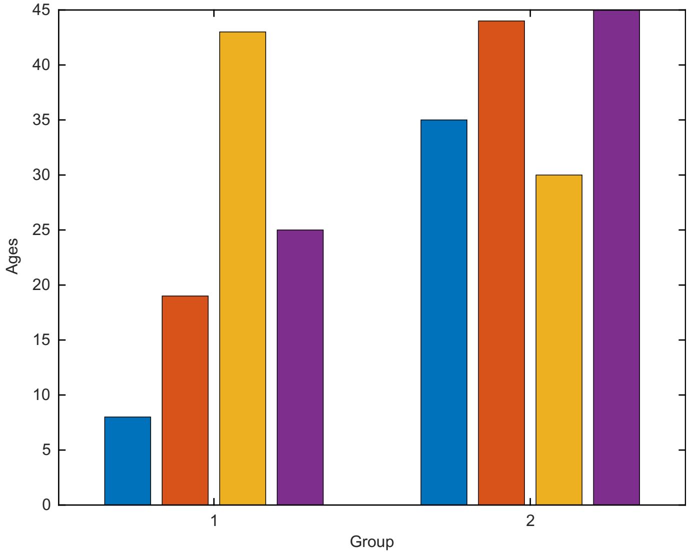


FIGURE 12.2
Data from a matrix in a bar chart.

Note that MATLAB groups together the values in the first row and then in the second row. It cycles through colors to distinguish the bars. The "stacked" option will stack rather than group the values, so the "y" value represented by the top of the bar is the sum of the values from that row (shown in Fig. 12.3).

```
>> bar(groupages,'stacked')
>> xlabel('Group')
>> ylabel('Ages')
```

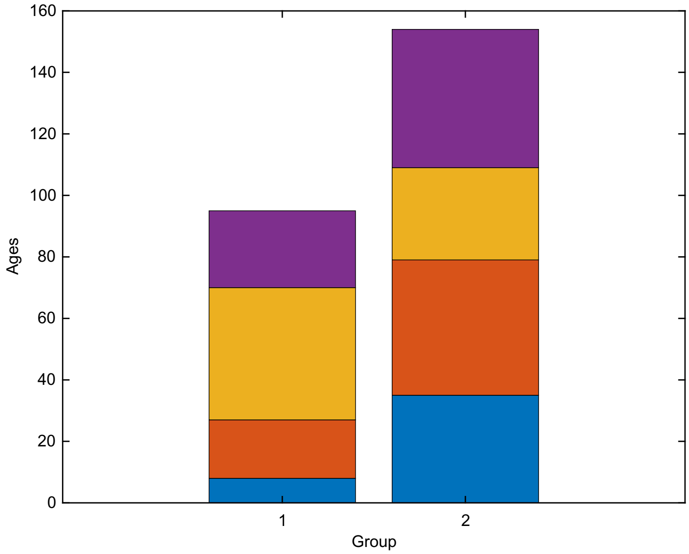


FIGURE 12.3
Stacked bar chart of matrix data.

PRACTICE 12.1

Create a file that has two lines with *n* numbers in each. Use **load** to read this into a matrix. Then, use **subplot** to show the **barh** and stacked **bar** charts side by side. Put labels "Groups" for the two groups and "Values" for the data values on the axes (note the difference between the x and y labels for these two plot types).

12.1.2 Histograms and Pie Charts

A ***histogram*** is a particular type of bar chart that shows the frequency of occurrence of values within a vector. Histograms use what are called ***bins*** to collect values that are in given ranges. MATLAB has a function to create a histogram, **histogram**. Calling the function with the form **histogram(vec)** by default takes the values in the vector *vec* and puts them into bins; the number of bins is determined by the **histogram** function (or **histogram(vec,n)** will put them into *n* bins) and plots this, as shown in Fig. 12.4.

```
>> quizzes=[10 8 5 10 10 6 9 7 8 10 1 8];
>> histogram(quizzes)
>> xlabel('Grade')
>> ylabel('#')
>> title('Quiz Grades')
```

In this example, the numbers range from 1 to 10 in the vector, and there are 10 bins in the range from 1 to 10. The heights of the bins represent the number of values

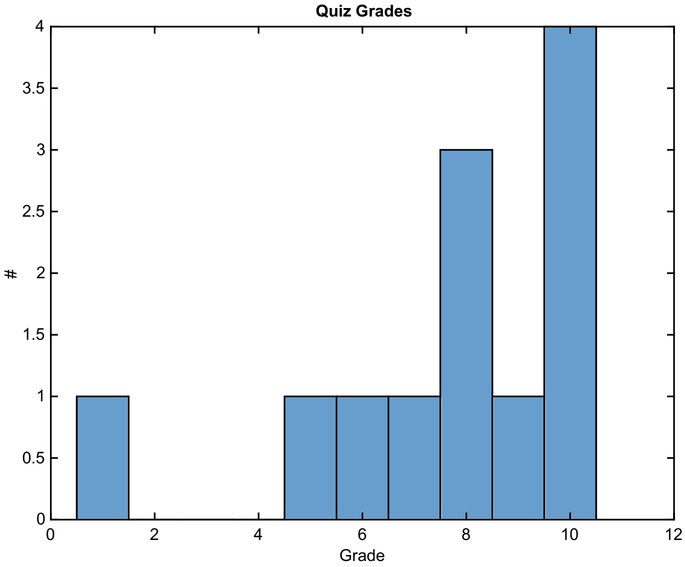


FIGURE 12.4
Histogram of data.

that fall within that particular bin. The handle of a **histogram** can also be stored in an object variable; the properties can then be inspected and/or modified.

```
>> hhan=histogram(quizzes)
hhan =
  Histogram with properties:

            Data: [10 8 5 10 10 6 9 7 8 10 1 8]
          Values: [1 0 0 0 1 1 1 3 1 4]
         NumBins: 10
        BinEdges: [0.5000 1.5000 2.5000 3.5000 4.5000
              5.5000 6.5000 7.5000 8.5000 9.5000 10.5000]
        BinWidth: 1
       BinLimits: [0.5000 10.5000]
   Normalization: 'count'
       FaceColor: 'auto'
       EdgeColor: [0 0 0]

Show all properties
```

Histograms are used for statistical analyses on data.

MATLAB has a function, **pie,** that will create a pie chart. Calling the function with the form **pie(vec)** draws a pie chart using the percentage of each element of *vec* of the whole (the sum). It shows these starting from the top of the circle and going around counterclockwise. For example, the first value in the vector [11 14 8 3 1], 11, is 30% of the sum, 14 is 38% of the sum, and so forth, as shown in Fig. 12.5.

```
>> pie([11 14 8 3 1])
```

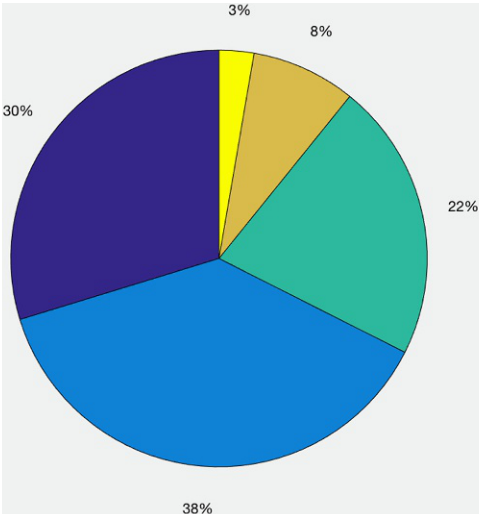


FIGURE 12.5
Pie chart showing percentages.

As of R2020a, it is possible to create format specifiers for the percentages. Labels can also be passed to the **pie** function; these labels will appear instead of the percentages (shown in Fig. 12.6). The labels can be either a cell array of character vectors or a string array.

```
>> pie([11 14 8 3 1], {'A','B','C','D', 'F'})
```

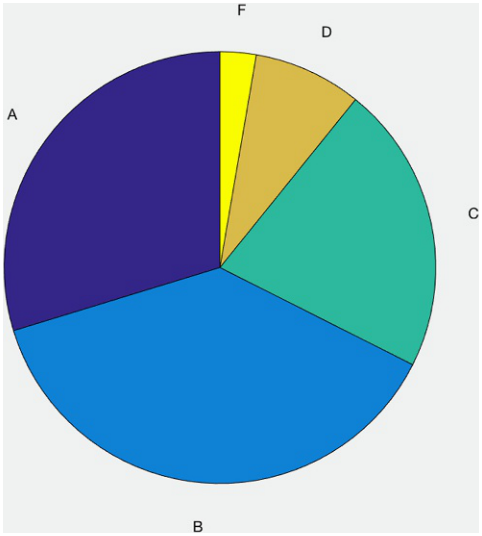


FIGURE 12.6
Pie chart with labels from a cell array.

PRACTICE 12.2

A chemistry professor teaches three classes. These are the course numbers and enrollments:

```
CH 101  111
CH 105   52
CH 555   12
```

Use **subplot** to show this information using **pie** charts: the **pie** chart on the right should show the percentage of students in each course, and on the left the course numbers. Put appropriate titles on them.

12.1.3 Log Scales

The **plot** function uses linear scales for both the x and y axes. There are several functions that instead use logarithmic scales for one or both axes: the function **loglog** uses logarithmic scales for both the x and y axes, the function **semilogy** uses a linear scale for the x-axis and a logarithmic scale for the y-axis, and the function **semilogx** uses a logarithmic scale for the x-axis and a linear scale for the y-axis. The following example uses **subplot** to show the difference, for example, between using the **plot** and **semilogy** functions, as seen in Fig. 12.7.

```
>> subplot(1,2,1)
>> plot(logspace(1,10))
>> title('plot')
>> subplot(1,2,2)
>> semilogy(logspace(1,10))
>> title('semilogy')
```

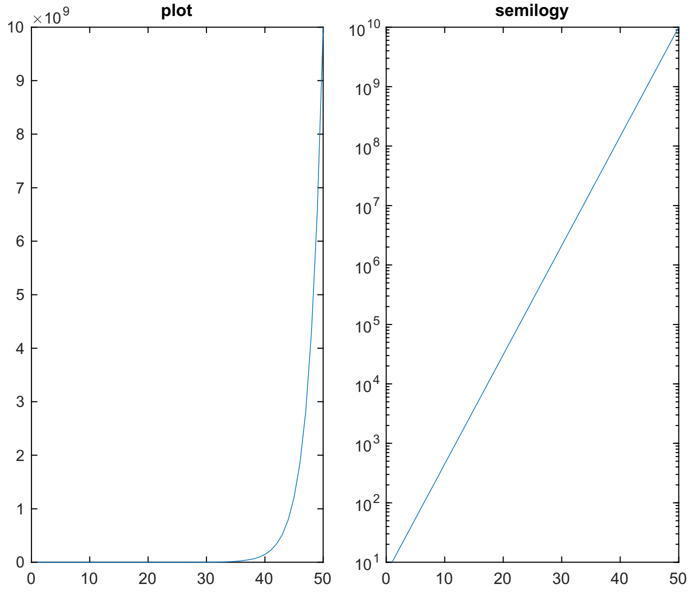


FIGURE 12.7
Plot versus semilogy.

12.1.4 Animation

There are several ways to ***animate*** a plot. These are visuals, so the results cannot really be shown here; it is necessary to type these into MATLAB to see the results.

We will start by animating a plot of **sin(x)** with the vectors:

```
>> x=-2*pi : 1/100 : 2*pi;
>> y=sin(x);
```

This results in enough points that we will be able to see the result using the built-in **comet** function, which shows the plot by first showing the point (x(1),y(1)), and then moving on to the point (x(2),y(2)), and so on, leaving a trail (like a comet!) of all of the previous points.

```
>> comet(x,y)
```

The end result looks similar to the result of **plot(x,y)**, although the color will be different.

Another way of animating is to use the built-in function **movie**, which displays recorded movie frames. The frames are captured in a loop using the built-in function **getframe** and are stored in a matrix. For example, the following script again animates the **sin** function. The **axis** function is used so that MATLAB will use the same set of axes for all frames, and using the **min** and **max** functions on the data vectors *x* and *y* will allow us to see all points. It displays the "movie" once in the **for** loop, and then again when the movie function is called.

```
sinmovie.m
```

```
% Shows a movie of the sin function
clear

x = -2*pi: 1/5 : 2*pi;
y = sin(x);
n = length(x);

for i = 1:n
    plot(x(i),y(i),'r*')
    axis([min(x)-1 max(x)+1 min(y)-1 max(y)+1])
    M(i)=getframe;
end
movie(M)
```

12.1.5 Customizing Plots

There are many ways to customize figures in the Figure Window. Clicking on the Plot Tools icon in the Figure Window itself will bring up the Property Editor and Plot Browser, with many options for modifying the current plot. Additionally, there are ***plot properties*** that can be modified from the defaults in the plot functions, using the dot operator, as we have seen. Bringing up the documentation page for the function name will show all of the options for that particular plot function.

For example, the **bar** and **barh** functions by default have a "width" of 0.8 for the bars. When called as **bar(x,y)**, the width of 0.8 is used. If, instead, a third argument is passed, it is the width, for example **barh(x,y,width)**. The following script uses **subplot** to show variations on the width. A width of 0.6 results in more space between the bars because the bars are not as wide. A width of 1 makes the bars touch each other, and with a width greater than 1, the bars actually overlap. The results are shown in Fig. 12.8.

barwidths.m

```
% Subplot to show varying bar widths

year=2016:2020;
pop=[0.9 1.4 1.7 1.3 1.8];

for i=1:4
    subplot(1,4,i)
    % width will be 0.6, 0.8, 1, 1.2
    barh(year,pop,0.4+i*.2)

    title(sprintf('Width=%.1f',0.4+i*.2))
    xlabel('Population (mil)')
    ylabel('Year')
end
```

Alternatively, the BarWidth property can be modified.

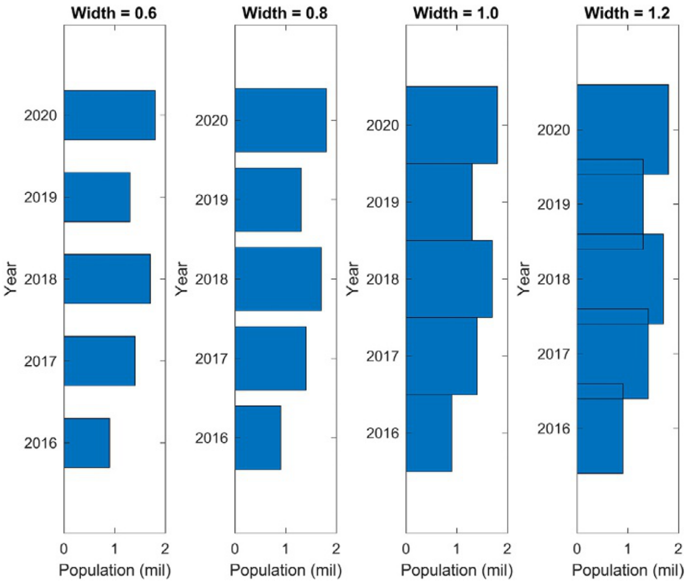


FIGURE 12.8

Subplot demonstrates varying widths in a bar chart.

PRACTICE 12.3

Use **help area** to find out how to change the base level on an **area** chart (from the default of 0).

As another example of customizing plots, pieces of a pie chart can be "exploded" from the rest. In this case, two vectors are passed to the **pie** function: first the data vector, then a **logical** vector; the elements for which the **logical** vector is **true** will be exploded from (separated from) the pie chart. A third argument, a cell array of labels, can also be passed. The result is seen in Fig. 12.9.

```
>> gradenums=[11 14 8 3 1];
>> letgrades={'A','B','C','D','F'};
>> which = gradenums == max(gradenums)
which =
     0     1     0     0     0
>> pie(gradenums,which,letgrades)
>> title(sprintf('Largest Fraction of Grades: %c',...
letgrades{which}))
```

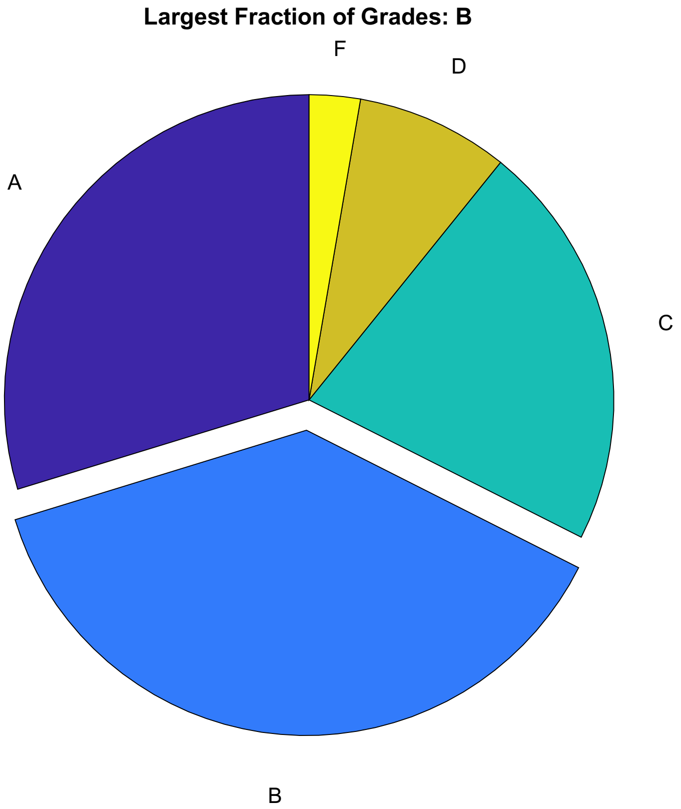


FIGURE 12.9
Exploding pie chart.

12.2 3D PLOTS

MATLAB has functions that will display 3D plots. Many of these functions have the same name as the corresponding 2D plot function with a '3' at the end. For example, the 3D line plot function is called **plot3**. Other functions include **bar3**, **bar3h**, **pie3**, **comet3**, and **stem3**.

Vectors representing x, y, and z coordinates are passed to the **plot3** and **stem3** functions. These functions show the points in 3D space. Clicking on the rotate 3D icon and then in the plot allows the user to rotate to see the plot from different angles. Also, using the **grid** function makes it easier to visualize, as shown in Fig. 12.10. The function **zlabel** is used to label the z-axis.

```
>> x = 1:5;
>> y = [0-2 4 11 3];
>> z = 2:2:10;
>> plot3(x,y,z,'k*')
>> grid
>> xlabel('x')
>> ylabel('y')
>> zlabel('z')
>> title('3D Plot')
```

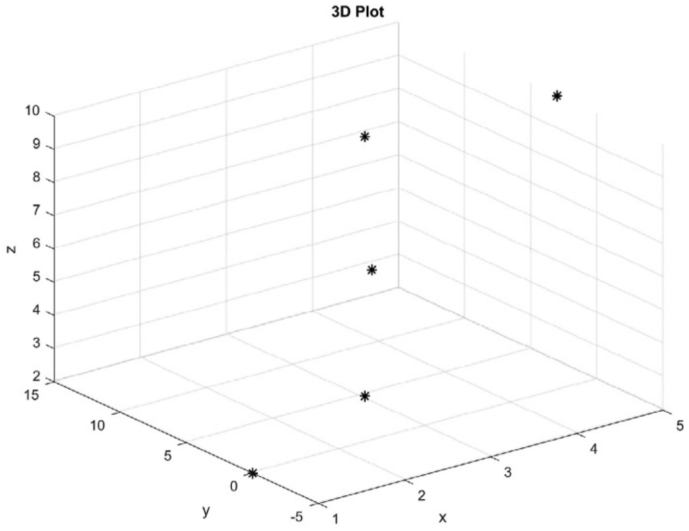


FIGURE 12.10

Three-dimensional plot with a grid.

Displaying the result of an animated plot in three dimensions is interesting. For example, try the following using the **comet3** function:

```
>> t = 0:0.001:12*pi;
>> comet3(cos(t), sin(t), t)
```

Other interesting 3D plot types include **mesh** and **surf**. The **mesh** function draws a wireframe mesh of 3D points, whereas the **surf** function creates a surface plot by using color to display the parametric surfaces defined by the points. MATLAB has several functions that will create the matrices used for the (x,y,z) coordinates for specified shapes (e.g., **sphere** and **cylinder**).

For example, passing an integer *n* to the **sphere** function creates *n+1 x n+1 x*, *y*, and *z* matrices, which can then be passed to the **mesh** function (Fig. 12.11) or the **surf** function (Fig. 12.12).

```
>> [x,y,z] = sphere(15);
>> size(x)
ans =
    16      16
>> mesh(x,y,z)
>> title('Mesh of sphere')
```

Additionally, the **colorbar** function displays a colorbar to the right of the plot, showing the range of colors.

Note

that more options for colors will be described in Chapter 13.

```
>> [x,y,z]=sphere(15);
>> sh=surf(x,y,z);
>> title('Surf of sphere')
>> colorbar
```

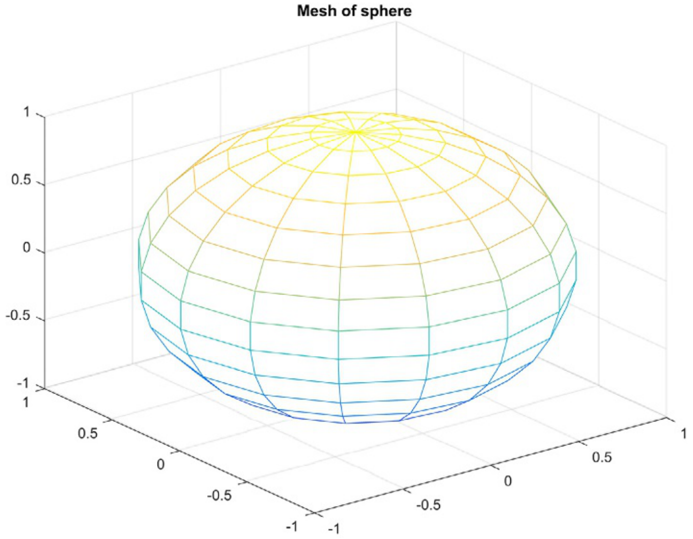


FIGURE 12.11

Mesh plot of sphere.

The **meshgrid** function can be used to create (x,y) points for which z=f(x,y); then the *x*, *y*, and *z* matrices can be passed to **mesh** or **surf**. For example, the following creates a surface plot of the function cos(x)+sin(y), as seen in Fig. 12.13.

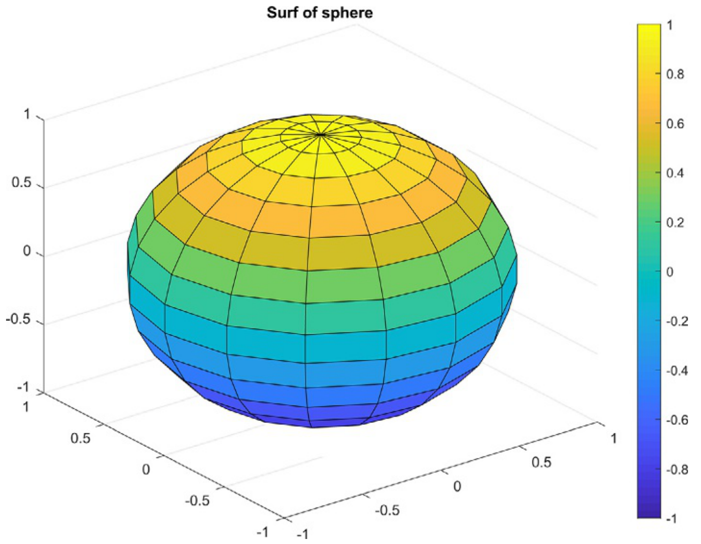


FIGURE 12.12

Surf plot of sphere.

```
>> [x, y]=meshgrid(-2*pi: 0.1: 2*pi);
>> z = cos(x)+sin(y);
>> surf(x,y,z)
>> title('cos(x)+sin(y)')
>> xlabel('x')
>> ylabel('y')
>> zlabel('z')
```

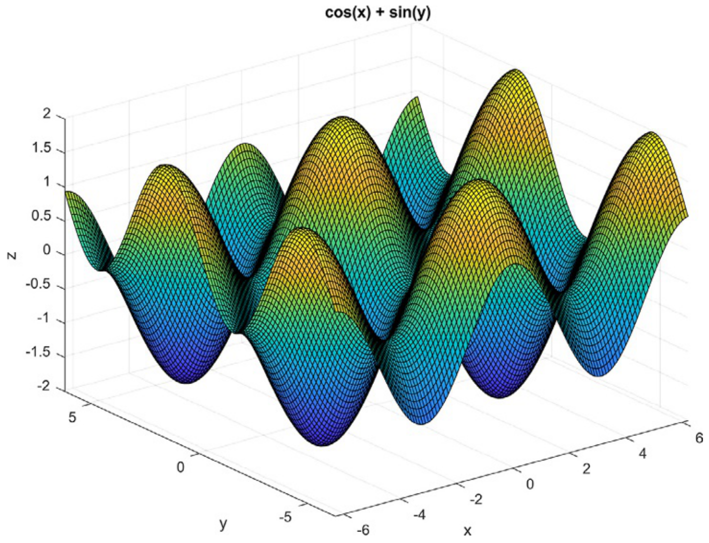


FIGURE 12.13

Use of **meshgrid** for f(x,y) points.

12.3 PRIMITIVE GRAPHICS OBJECTS

Primitive objects, or ***core objects*** in MATLAB, are the very basic graphics primitives. A description can be found under the MATLAB help. In the documentation, search for Graphics and Graphics Objects. The primitive objects include:

- `line`
- `text`
- `rectangle`
- `patch`
- `image`

These are all built-in functions; **doc** can be used to find out how each function is used. The first four of these core objects will be described in this section; images will be described in Section 13.1.

A **line** is a core graphics object, which is what is used by the **plot** function. The following is an example of creating a line object, setting some properties, and saving the handle in a variable *hl*:

```
>> x = -2*pi: 1/5 : 2*pi;
>> y = sin(x);
>> hl = line(x,y,'LineWidth', 6, 'Color', [0.5 0.5 0.5])
hl =

  Line with properties:

              Color: [0.5000 0.5000 0.5000]
          LineStyle: '-'
          LineWidth: 6
             Marker: 'none'
         MarkerSize: 6
    MarkerFaceColor: 'none'
              XData: [1x63 double]
              YData: [1x63 double]
              ZData: [1x0 double]

  Show all properties
```

As seen in Fig. 12.14, this draws a reasonably thick gray line for the **sin** function. As before, the handle will be valid as long as the Figure Window is not closed.

As another example, the following uses the **line** function to draw a circle. First, a white Figure Window is created. The x and y data points are generated, and then the **line** function is used, specifying a dotted red line with a line width of 4. The **axis** function is used to make the axes square, so the result looks like a circle, but

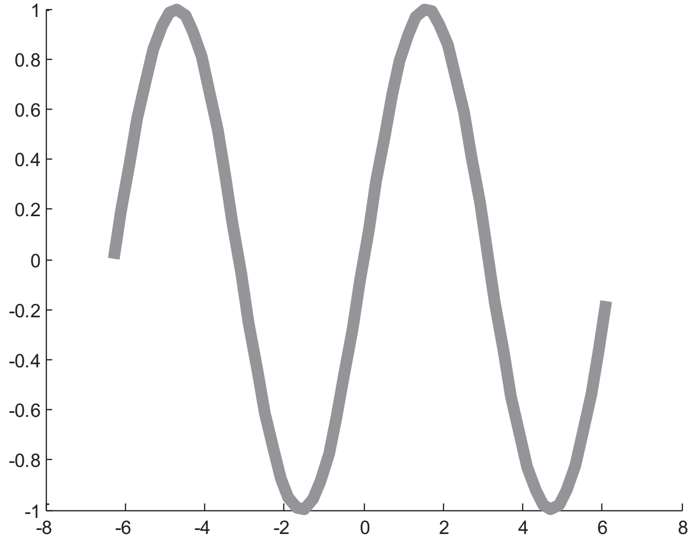


FIGURE 12.14

A **line** object with modified line width and color.

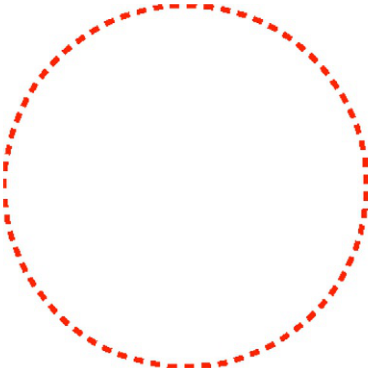


FIGURE 12.15

Use of line to draw a circle.

then removes the axes from the Figure Window (using **axis square** and **axis off**, respectively). The result is shown in Fig. 12.15.

```
>> figure('Color',[1 1 1])
>> pts = 0:0.1:2*pi;
>> xcir = cos(pts);
>> ycir = sin(pts);
>> line(xcir, ycir, 'LineStyle',':', ...
       'LineWidth',4,'Color','r')
>> axis square
>> axis off
```

The **text** graphics function allows text to be printed in a Figure Window, including special characters that are printed using `\specchar`, where "specchar" is the actual name of the special character. The format of a call to the **text** function is

```
text(x,y,'text string')
```

where *x* and *y* are the coordinates on the graph of the lower left corner of the ***text box*** in which the text string appears. The special characters include letters of the Greek alphabet, arrows, and characters frequently used in equations. For example, Fig. 12.16 displays the Greek symbol for **pi** and a right arrow within the text box.

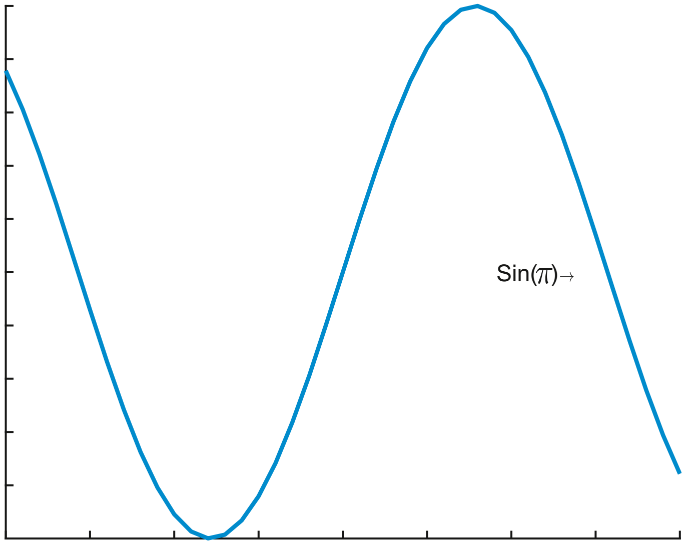


FIGURE 12.16

A **line** object with a text box.

```
>> x = -4:0.2:4;
>> y = sin(x);
>> hp = line(x,y,'LineWidth',3);
>> thand = text(2,0,'Sin(\pi)\rightarrow')
thand =

  Text (Sin(\pi)\rightarrow) with properties:

                 String: 'Sin(\pi)\rightarrow'
               FontSize: 10
             FontWeight: 'normal'
               FontName: 'Helvetica'
                  Color: [0 0 0]
    HorizontalAlignment: 'left'
               Position: [2 0 0]
                  Units: 'data'

  Show all properties
```

Some of the other properties are shown here.

```
>> thand.Extent
ans =
    2.0000    -0.0380    0.6636    0.0730
>> thand.EdgeColor
ans =
    'none'
>> thand.BackgroundColor
ans =
    'none'
```

Although the Position specified was (2,0), the Extent is the actual extent of the text box, which cannot be seen as the BackgroundColor and EdgeColor are not specified. These can be modified. For example, the following produces the result seen in Fig. 12.17.

```
>> thand.BackgroundColor = [0.8 0.8 0.8];
>> thand.EdgeColor = [1 0 0];
```

The **gtext** function allows you to move your mouse to a particular location in a Figure Window, indicating where text should be displayed. As the mouse is moved into the Figure Window, cross hairs indicate a location; clicking on the mouse will display the text in a box with the lower left corner at that location. The **gtext** function uses the **text** function in conjunction with **ginput**, which allows you to click the mouse at various locations within the Figure Window and store the x and y coordinates of these points.

Another core graphics object is **rectangle**, which can have curvature added to it (!!). Just calling the function **rectangle** without any arguments brings up a Figure Window (shown in Fig. 12.18), which, at first glance, does not seem to have anything in it:

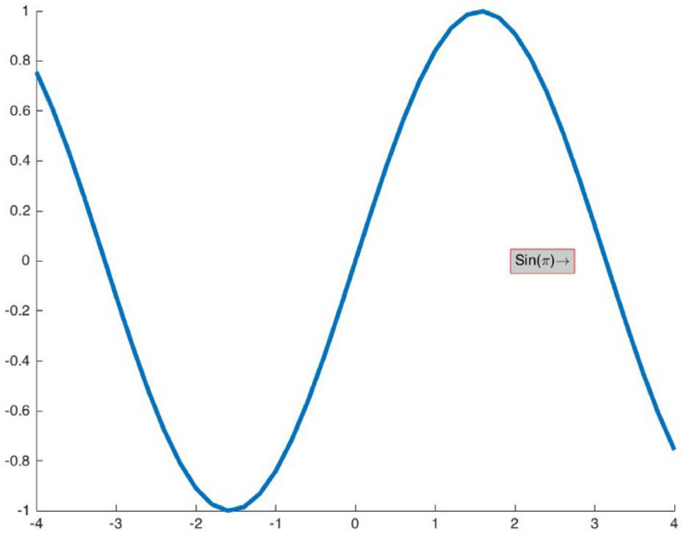


FIGURE 12.17

Text box with a modified edge color and background color.

```
>> recthand=rectangle
recthand=
  Rectangle with properties:

    FaceColor: 'none'
    EdgeColor: [0 0 0]
    LineWidth: 0.5000
    LineStyle: '-'
    Curvature: [0 0]
     Position: [0 0 1 1]

 Show all properties
```

The Position of a rectangle is [x y w h], where x and y are the coordinates of the lower left point, w is the width, and h is the height. The default rectangle has a Position of [0 0 1 1]. The default Curvature is [0 0], which means no curvature. The values range from [0 0] (no curvature) to [1 1] (ellipse). A more interesting rectangle object is seen in Fig. 12.19.

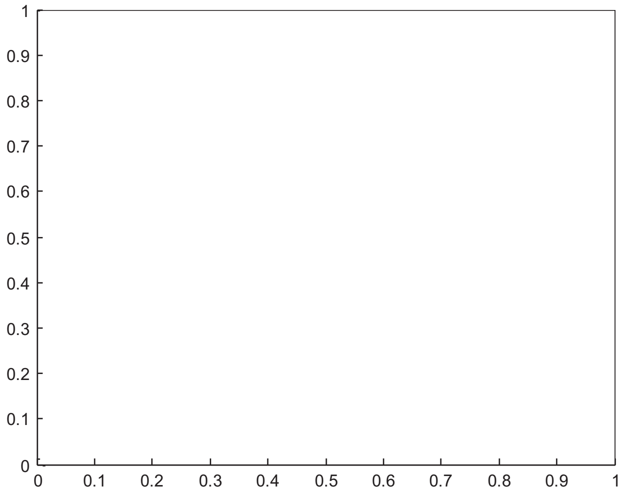


FIGURE 12.18
A **rectangle** object.

Note that properties can be set when calling the **rectangle** function, and also subsequently using the dot operator, as follows:

```
>> rh = rectangle('Position', [0.2, 0.2, 0.5, 0.8],...
     'Curvature',[0.5, 0.5]);
>> axis([0 1.2 0 1.2])
>> rh.LineWidth = 3;
>> rh.LineStyle = ':';
```

This creates a curved rectangle and uses dotted lines.

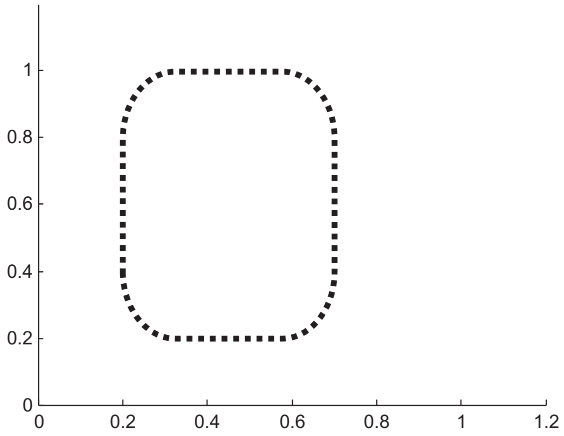


FIGURE 12.19
Rectangle object with curvature.

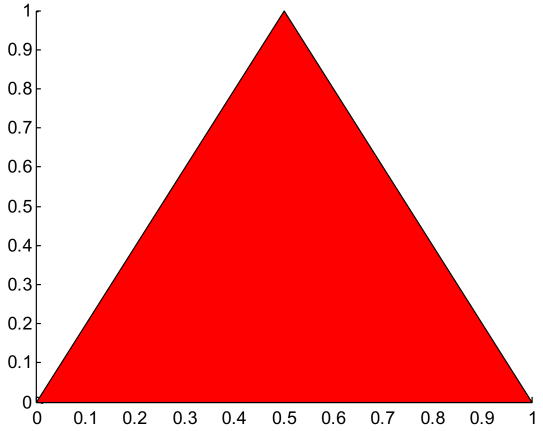


FIGURE 12.20
Simple patch.

The **patch** function is used to create a patch graphics object, which is made from 2D polygons. A simple patch in 2D space, a triangle, is defined by specifying the coordinates of three points as shown in Fig. 12.20; in this case, the color red is specified for the polygon.

```
>> x = [0 1 0.5];
>> y = [0 0 1];
>> hp = patch(x,y,'r')
hp =
  Patch with properties:

    FaceColor: [1 0 0]
    FaceAlpha: 1
    EdgeColor: [0 0 0]
    LineStyle: '-'
        Faces: [1 2 3]
     Vertices: [3x2 double]

  Show all properties
```

The Vertices property stores the three points given by the x and y data vectors.

```
>> hp.Vertices
ans =
         0         0
    1.0000         0
    0.5000    1.0000
```

The Faces property tells how the vertices are connected to create the patch. The vertices are numbered; the first point (0,0) is vertex 1, the point (1,0) is vertex 2, and the last point (0.5, 1) is vertex 3. The Faces property specifies connecting vertex 1 to 2 to 3 (and then by default back to 1). Another method of creating a patch is to specifically use the Vertices and Faces properties.

One way of calling **patch** is `patch(fv)`, where *fv* is a structure variable with field names that are names of properties, and the values are the property values, for example, fields called *Vertices* and *Faces*. For example, consider a patch object that consists of three connected triangles, and has five vertices given by the coordinates:

(1)	(0, 0)
(2)	(2, 0)
(3)	(1, 2)
(4)	(1,-2)
(5)	(3, 1)

The order in which the points are given is important because the faces describe how the vertices are linked. To create these vertices in MATLAB and define faces that connect them, we use a structure variable and then pass it to the **patch** function; the result is shown in Fig. 12.21.

```
mypatch.Vertices = [...
    0 0
    2 0
    1 2
    1 -2
    3 1];
mypatch.Faces = [
    1 2 3
    2 3 5
    1 2 4];
```

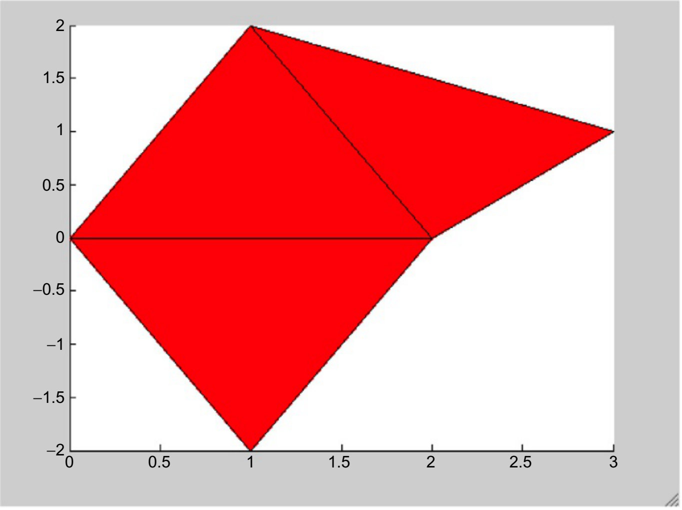


FIGURE 12.21
Patch object.

```
patchhan=patch(mypatch, 'FaceColor', 'r',...
    'EdgeColor','k');
```

The face color is set to red and the edge color to black.

To vary the colors of the faces of the polygons, the FaceColor property is set to 'flat', which means that every face has a separate color. The *mycolors* variable stores three colors in the rows of the matrix by specifying the red, green, and blue components for each; the first is blue, the second is cyan (a combination of green and blue), and the third is yellow (a combination of red and green). The property FaceVertexCData specifies the color data for the vertices, as seen in Fig. 12.22.

```
>> mycolors = [0 0 1; 0 1 1; 1 1 0];
>> patchhan = patch(mypatch, 'FaceVertexCData', ...
               mycolors, 'FaceColor','flat');
```

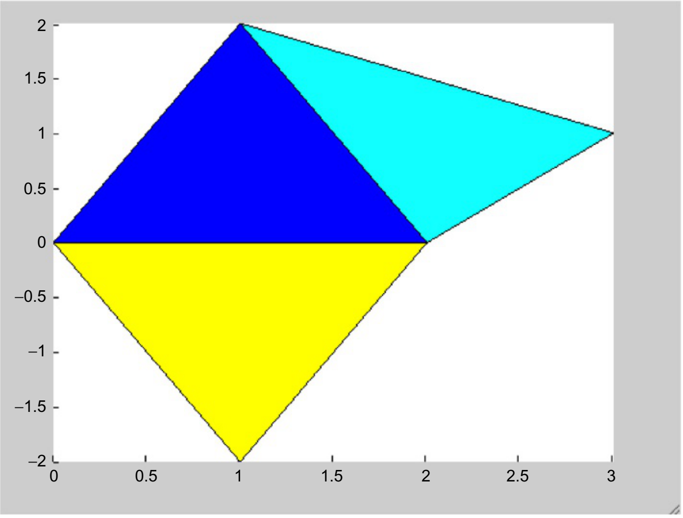


FIGURE 12.22
Varying patch colors.

12.4 PLOT APPLICATIONS

In this section, we will show some examples that integrate plots and many of the other concepts covered to this point in the book. For example, we will have a function that receives an *x* vector, a function handle of a function used to create the *y* vector, and a cell array of plot types as character vectors and will generate the plots, and we will also show examples of reading data from a file and plotting them.

12.4.1 Plotting From a Function

The following function generates a Figure Window (seen in Fig. 12.23) that shows different types of plots for the same data. The data are passed as input arguments (as an x vector and the handle of a function to create the y vector) to the function, as is a cell array with the plot type names. The function generates the Figure Window using the cell array with the plot type names. It creates a function handle for each using the **str2func** function.

plotxywithcell.m

```
function plotxywithcell(x, fnhan, rca)
% plotxywithcell receives an x vector, the handle
% of a function (used to create a y vector), and
% a cell array with plot type names; it creates
% a subplot to show all of these plot types
% Format: plotxywithcell(x,fn handle, cell array)

lenrca = length(rca);
y = fnhan(x);
for i = 1:lenrca
    subplot(1,lenrca,i)
    funh = str2func(rca{i});
    funh(x,y)
    title(upper(rca{i}))
    xlabel('x')
    ylabel(func2str(fnhan))
end
end
```

For example, the function could be called as follows:

```
>> anfn = @ (x) x .^ 3;
>> x = 1:2:9;
>> rca = {'bar', 'area', 'plot'};
>> plotxywithcell(x, anfn, rca)
```

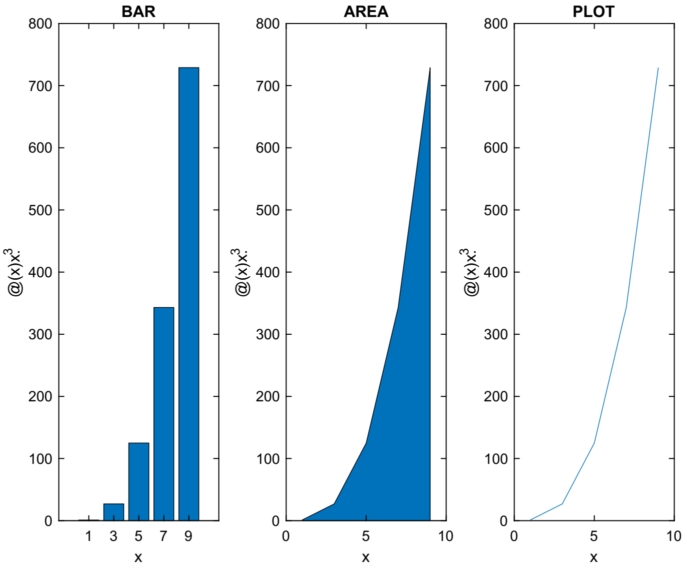


FIGURE 12.23

Subplot showing different file types with their names as titles.

The function is general and works for any number of plot types stored in the cell array.

12.4.2 Plotting File Data

It is often necessary to read data from a file and plot them. Normally, this entails knowing the format of the file. For example, let us assume that a company has two divisions, A and B. Assume that the file "ab21.dat" contains four lines, with the sales figures (in millions) for the two divisions for each quarter of the year 2021. For example, the file might look like this (and the format will be exactly like this):

```
A5.2B6.4
A3.2B5.5
A4.4B4.3
A4.5B2.2
```

The following script reads in the data and plots the data as bar charts in one Figure Window. The script prints an error message if the file open is not successful or if the file close was not successful. The **axis** command is used to force the x-axis to range from 0 to 3 and the y-axis from 0 to 8, which will result in the axes shown here. The numbers 1 and 2 would show on the x-axis rather than the division labels A and B by default. The **xticklabels** function changes the XTickLabel property of the axes to use the character vectors in the cell array as labels on the tick marks on the x-axis.

plotdivab.m

```
% Reads sales figures for 2 divisions of a company one
% line at a time as char vectors, and plots the data
fid = fopen('ab21.dat');
if fid == -1
    disp('File open not successful')

else
    for i = 1:4
       % Every line is of the form A#B#; this separates
       % the characters and converts the #'s to actual
       % numbers
       aline = fgetl(fid);
       aline = aline(2:length(aline));
       [compa, rest]=strtok(aline,'B');
       compa = str2double(compa);
       compb = rest(2:length(rest));
       compb = str2double(compb);

       % Data from every line is in a separate subplot
       subplot(1,4,i)
       bar([compa,compb])
       xticklabels({'A', 'B'})
       axis([0 3 0 8])
       ylabel('Sales (millions)')
```

```
        title(sprintf('Quarter %d',i))
    end
    closeresult = fclose(fid);
    if closeresult ~= 0
        disp('File close not successful')
    end
end
```

Running this produces the subplot shown in Fig. 12.24.

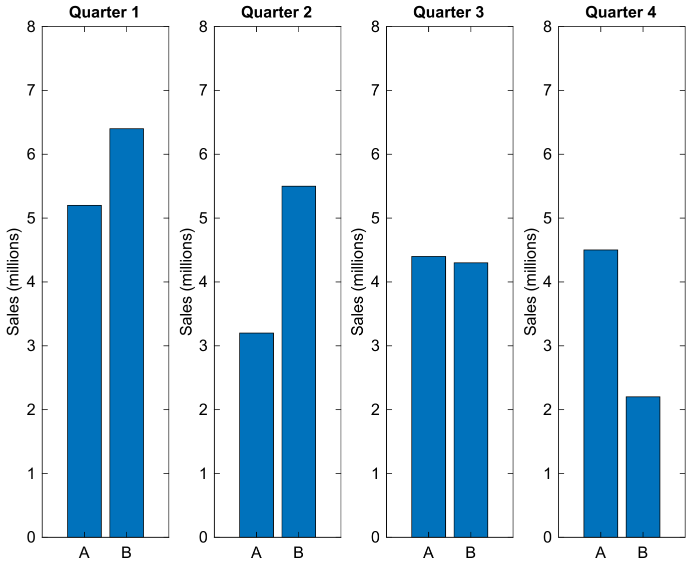


FIGURE 12.24
Subplot with customized x-axis tick labels.

12.5 SAVING AND PRINTING PLOTS

Once any plot has been created in a Figure Window, there are several options for saving it, printing it, and copying and pasting it into a report. When the Figure Window is open, choosing Edit and then Copy Figure will copy the Figure Window so that it can then be pasted into a word processor. Choosing File and then Save As allows you to save in different formats, including common image types, such as .jpg, .tif, and .png. Another option is to save it as a .fig file, which is a Figure file type used in MATLAB. If the plot was not created programmatically, or the plot properties have been modified using the plot tools icon, choosing File and then Generate Code will generate a script that will re-create the plot.

Choosing File and then Print allows you to print the file on a connected printer. The **print** command can also be used in MATLAB programs. The line

```
print
```

in a script will print the current Figure Window using default formats. Options can also be specified (see the Documentation page on **print** for the options). Also, by specifying a file name, the plot is saved to a file rather than printed. For example, the following would save a plot as a .tif file with 400 dots per inch in a file named 'plot.tif':

```
print -dtiff -r400 plot.tif
```

Data Science and Machine Learning Supplement

Fitting Polynomial Curves / Linear Regression

Recall that regression is a supervised Machine Learning algorithm that predicts continuous data (real numbers). In this section, we will describe fitting a curve to continuous data and the underlying regression algorithm.

Simple curves are ***polynomials*** of different ***degrees*** or ***orders***. The degree is the integer of the highest exponent in the expression. For example:

- a straight line is a first order (or degree 1) polynomial of the form $ax+b$, or, more explicitly, $ax^1 + b$.
- a quadratic is a second order (or degree 2) polynomial of the form ax^2+bx+c.
- a cubic (degree 3) is of the form ax^3+bx^2+cx+d.

MATLAB represents a polynomial as a row vector of coefficients. For example, the polynomial $x^3 + 2x^2 - 4x+3$ would be represented by the vector `[1 2-4 3]`. The polynomial $2x^4 - x^2 + 5$ would be represented by `[2 0-1 0 5]`; note the zero terms for x^3 and x^1.

The function **polyval** will evaluate a polynomial *p* at *x*; the form is **polyval(p,x)**. The argument x can be a scalar or a vector. For example, the polynomial $-2x^2 + x +4$ is evaluated at x values 1, 2, and 3:

```
>> p=[-2 1 4];
>> polyval(p,1:3)
ans =
     3    -2    -11
```

In many applications, continuous properties are ***sampled***, to result in discrete (x, y) points. ***Interpolation*** means estimating the values in between recorded data points. ***Extrapolation*** is estimating outside of the bounds of the recorded data. One way to do this is to fit a curve to the data and use this for the estimations. Curve fitting is finding the curve that "best fits" the data.

Simple curves are polynomials of different degrees, as described previously. Thus, curve fitting involves finding the best polynomials to fit the data. Finding the best straight line that goes through data would mean finding the values of *a* and *b* in the equation `ax+b`.

MATLAB has a function to do this called **polyfit**. The function **polyfit** finds the coefficients of the polynomial of the specified degree that best fits the data using a least squares algorithm. There are three arguments passed to the function: *x* and *y* vectors that represent the data, and the degree of the desired polynomial. For example, to fit a straight line (degree 1) through the points representing temperatures, the call to the **polyfit** function would be:

```
>> x = 1:10;
>> y = [2, 2.7, 3.1, 4, 4.5, 5.3, 5.9, 6.4, 7.1, 9];
>> coefs = polyfit(x,y,1)
coefs =
    0.7079    1.1067
```

which says that the best straight line is of the form `0.7079x+1.1067`.
The function **polyval** can then be used to evaluate the polynomial at specified values. For example, we could evaluate at every value in the *x* vector:

```
>> linepts=polyval(coefs, x);
```

This results in *y* values for each point in the *x* vector, and stores them in a vector called *linepts*. The points and the line can be plotted together, for example,

```
>> phan=plot(x,y,'k*', x, linepts)
phan=
  21 Line array:

  Line
  Line
```

By storing the result of the plot in a handle variable, the plot objects (in this case, lines) can be accessed so that the properties can be queried and modified. In this case, there is a Line array; phan(1) is the first thing plotted, the individual points, and phan(2) is the straight line. Modifying a few properties:

```
>> phan(1).MarkerSize = 10;
>> phan(2).LineWidth = 3;
```

results in the plot shown in Fig. 12.25.

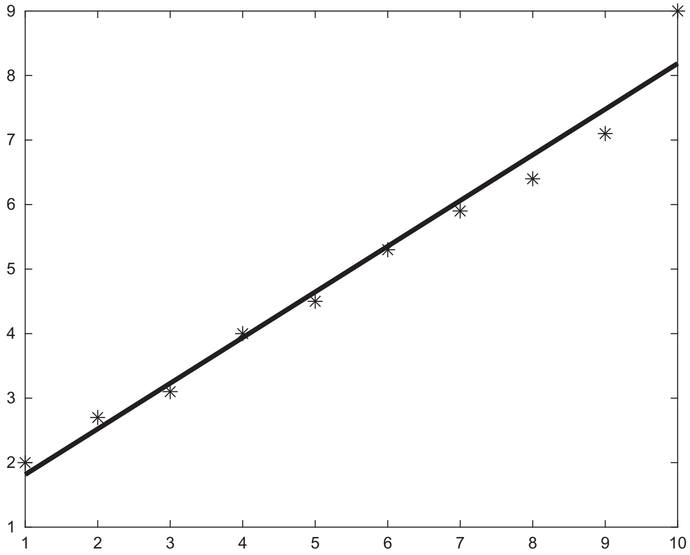


FIGURE 12.25
Straight line fit.

To estimate the values of y at x values that were not sampled, **polyval** can be used for discrete *x* points. Therefore, **polyval** can be used to interpolate between the given data points and also to extrapolate beyond the given data points.

```
>> polyval(coefs, 8.5)
ans =
    7.1236
>> polyval(coefs, 11)
ans =
    8.8933
```

The better the curve fit, the more accurate these interpolated and extrapolated values will be.

The **polyfit** function uses the ***least squares regression*** method. To find the equation of the straight line y = mx + b that best fits using a least squares regression, the equations for m and b are:

$$\mathrm{m} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}$$

$$\mathrm{b} = \bar{y} - m\bar{x}$$

where n is the number of points in x and y, all summations are from i = 1 to n, and $\bar{y}$ and $\bar{x}$ represent the means of the vectors y and x. The least squares fit minimizes the sum of the squares of the differences between the actual data and the data predicted by the line.

■ Explore Other Interesting Features

There are many built-in plot functions in MATLAB, and many ways to customize plots. Use the Help facility to find them. Here are some specific suggestions for functions to investigate.

Investigate the **peaks** function, and the use of the resulting matrix as a test for various plot functions.

Investigate how to show confidence intervals for functions using the **errorbar** function.

Find out how to set limits on axes using **xlim**, **ylim**, and **zlim**.

The **plotyy** function allows y axes on both the left and the right of the graph. Find out how to use it, and how to put different labels on the two y axes.

Investigate how to use the **gtext** and **ginput** functions.

Investigate the 3D functions **meshc** and **surfc**, which put contour plots under the mesh and/or surface plots.

Investigate using the **datetick** function to use dates to label tick lines. Note that there are many options!

Investigate the use of **pie** charts with categorical arrays. ■

SUMMARY

COMMON PITFALLS

- Closing a Figure Window prematurely: the properties can only be set if the Figure Window is still open!

PROGRAMMING STYLE GUIDELINES

- Always label plots.
- Take care to choose the type of plot in order to highlight the most relevant information.

MATLAB Functions and Commands

barh
area
stem
scatter
histogram
pie
loglog
semilogy
semilogx
comet
movie
getframe
plot3
bar3
bar3h
pie3
comet3
stem3
zlabel
mesh
surf
sphere
cylinder
colorbar
line
text
gtext
ginput
rectangle
patch
xticklabels
print

Exercises

1. Create a data file that contains 10 numbers. Write a script that will load the vector from the file, and use **subplot** to do an **area** plot and a **stem** plot with these data in the same Figure Window (Note: a loop is not needed). Prompt the user for a title for each plot.
2. Do a quick survey of your friends to find ice cream flavor preferences. Display this information using a **pie** chart.
3. Create a matrix variable. Display the numbers from the matrix using a subplot as both a **bar** chart and a stacked bar.
4. The number of faculty members in each department at a certain College of Engineering are as follows: `ME 22,BM 45,CE 23,EE 33.`Experiment with at least three different plot types to graphically depict this information. Make sure that you have appropriate titles, labels, and legends on your plots. Which type(s) work best, and why?
5. Create a simple pie chart:

   ```
   >> v=[11 33 5];
   >> ph=pie(v)
   ```

   Notice that the result is a graphics array, consisting of three patch primitives and three text primitives. So, ph is an array that can be indexed. Use the properties to change the face color of one of the patches, for example, ph(1).
6. Experiment with the **comet** function: try the example given when **help comet** is entered and then animate your own function using **comet**.
7. Experiment with the **comet3** function: try the example given when **help comet3** is entered and then animate your own function using **comet3**.
8. Experiment with the **scatter** and **scatter3** functions.
9. Use the cylinder function to create *x*, *y*, and *z* matrices and pass them to the surf function to get a surface plot. Experiment with different arguments to cylinder.
10. Experiment with **contour** plots.
11. Generate an ellipsoid using the **ellipsoid** function and then plot using **surf**.

12. Create an x vector, and then two different vectors (y and z) based on x. Plot them with a legend. Use **help legend** to find out how to position the legend itself on the graph, and experiment with different locations.
13. Create an x vector that has 30 linearly spaced points in the range from -2π to 2π, and then y as **sin(x)**. Do a **stem** plot of these points, and store the handle in a variable. Change the face color of the marker.
14. Write a script that will draw the line y=x between x=2 and x=5, with a random line width between 1 and 10.
15. Write a script that will plot the data points from y and z data vectors, and store the handles of the two plots in variables *yhand* and *zhand*. Set the line widths to 3 and 4 respectively. Set the colors and markers to random values (create character vectors containing possible values and pick a random index).
16. Write a function *plotexvar* that will plot data points represented by x and y vectors which are passed as input arguments. If a third argument is passed, it is a line width for the plot, and if a fourth argument is also passed, it is a color. The plot title will include the total number of arguments passed to the function.
17. A file *houseafford.dat* stores on its three lines years, median incomes, and median home prices for a city. The dollar amounts are in thousands. For example, it might look like this:

```
2014 2015 2016 2017 2018 2019 2020 2021
72 74 74 77 80 83 89 93
250 270 300 310 350 390 410 380
```

Create a file in this format, and then **load** the information into a matrix. Create a horizontal stacked bar chart to display the information, with an appropriate title. Note: use the 'XData' property to put the years on the axis as shown in Fig. 12.26.

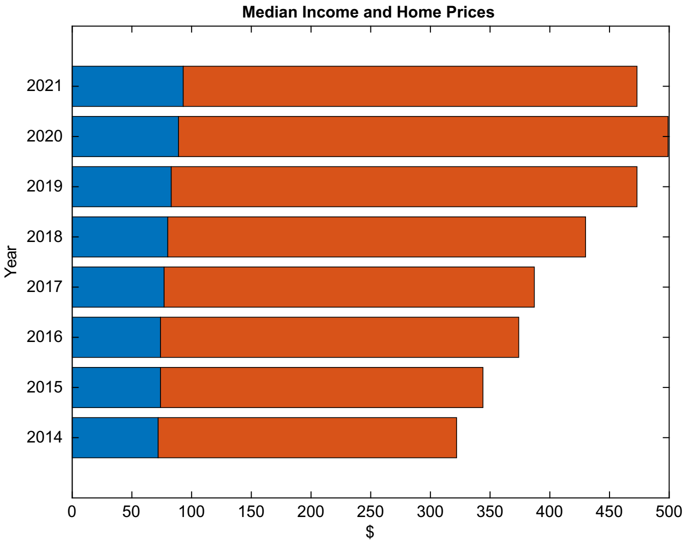


FIGURE 12.26

Horizontal stacked bar chart of median incomes and home prices.

18. Create a graph, and then use the **text** function to put some text on it, including some \specchar commands to increase the font size and to print some Greek letters and symbols.
19. Create a rectangle object, and use the axis function to change the axes so that you can see the rectangle easily. Change the Position, Curvature, EdgeColor, LineStyle, and LineWidth. Experiment with different values for the Curvature.
20. Write a script that will display rectangles with varying curvatures and line widths. The script will, in a loop, create a 2 by 2 subplot showing rectangles. In all, both the x and y axes will go from 0 to 1.4. Also, in all, the lower left corner of the rectangle will be at (0.2, 0.2), and the length and width will both be 1. The line width, i, is displayed in the title of each plot. The curvature will be [0.2, 0.2] in the first plot, then [0.4, 0.4], [0.6,0.6], and finally [0.8,0.8].
21. Write a script that will start with a rounded rectangle. Change both the x and y axes from the default to go from 0 to 3. In a **for** loop, change the position vector by adding 0.1 to all elements 10 times (this will change the location and size of the rectangle each time). Create a movie consisting of the resulting rectangles. The final result should look like the plot shown in Fig. 12.27.
22. A hockey rink looks like a rectangle with curvature. Draw a hockey rink, as in Fig. 12.28.

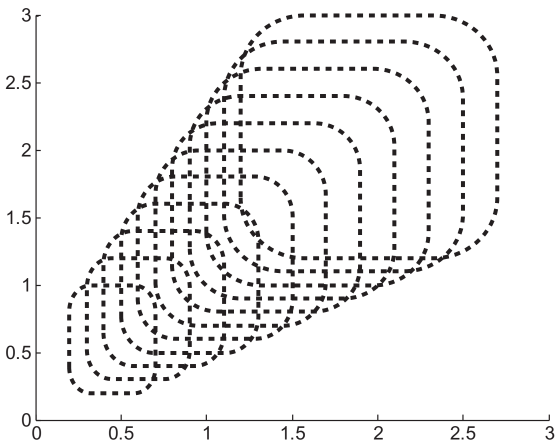


FIGURE 12.27

Curved rectangles produced in a loop.

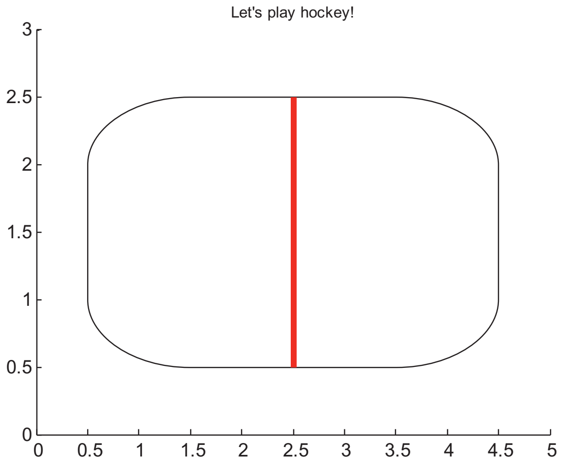


FIGURE 12.28

Hockey rink.

23. Given the following script:

```
fw.Vertices=[0 0; 0 4; 2 4; 3 2];
fw.Faces=[1 2 3 4];
fwinner=patch(fw,'FaceColor','g', 'EdgeColor','k');
ml=line([0 2], [4 4],'Color',[0 0.4 0], 'LineWidth',5);
axis([0 3 0 5])
text(1,4.2,'Monstah')
```

Sketch the figure that would result from executing the script. Indicate properties by describing them and/or using arrows. MakShow the axes and draw some tick labels to indicate the positions of objects. Note: the default LineWidth is 0.5.

24. Given the following script:

```
rechan = rectangle('Position',[2,2,3,3], 'Curvature',[1 1]);
obj1 = line([2.5,4.5], [2.5,4.5], 'Color','r');
obj2 = line([2.5,4.5], [4.5,2.5], 'Color','r');
texhan = text(3.2,3.5,'Cell Phones');
set([obj1, obj2, rechan], 'LineWidth', 3)
axis([1 6 1 6])
```

Draw a sketch of the Figure Window that would result from executing the script.

25. Assume that the Figure Window from the previous script is still open. For each of the following expressions, show the result.

```
gr=groot;
gr.Children== gcf

rechan.Parent== texhan.Parent

obj2.LineWidth
```

26. Using the **patch** function, create a black box with unit dimensions (therefore, there will be eight vertices and six faces). Set the edge color to white so that when you rotate the figure, you can see the edges.
27. Write a function *plotline* that will receive x and y vectors of data points, and use the **line** primitive to display a line using these points. If only the x and y vectors are passed to the function, it will use a line width of 5; otherwise, if a third argument is passed, it is the line width.
28. Investigate the **polyshape** function.
29. The **nsidedpoly** function creates a polygon (a polyshape object) with n sides. Create an 8-sided polyshape object and plot it; investigate its properties.
30. The **xticks** function can be used to create custom tick marks. Create a plot of sin(x) where x ranges from at least –7 to 7, and then change the x ticks with xticks(-2*pi: pi: 2*pi).

Data Science and Machine Learning

31. Create x and y vectors that are negatively correlated (y falls when x rises). Use **polyfit** to fit a straight line through the points. Plot both the original data points and the line on one graph. Estimate the y value when x is 8.5 using **polyval**, and plot that point as a large (MarkerSize of 20) red circle on the graph.

CHAPTER 13

Sights and Sounds

KEY TERMS

apps
Graphical User Interfaces
GUIs
image processing
sound processing
pixels
true color
RGB
colormap
event
callback function
event-driven programming
components
sound wave
sampling frequency

CONTENTS

The MATLAB® product has functions that manipulate images, audio, or sound files. MATLAB also has the capability to produce sophisticated ***apps***, and also ***Graphical User Interfaces***, or ***GUIs***. Apps utilize object-oriented programming to allow users to graphically interact with programs using graphical objects such as push buttons and sliders.

This chapter starts with the introduction of ***image processing*** functions and the two basic methods for representing color in images.

Next, the topic of creating apps is introduced. Because the focus of this book is programming concepts, the programming aspects of creating GUIs are the main part of this section. GUIs in MATLAB use procedural code. The object-based App Designer was introduced in R2016a and since then, much more functionality has been included. The use of App Designer is illustrated with several examples.

The chapter ends with a brief introduction to some of the ***sound processing*** functions.

13.1 IMAGE PROCESSING

Color images are represented as grids, or matrices, of picture elements called ***pixels***. In MATLAB, an image is represented by a matrix in which each element

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00013-5

corresponds to a pixel in the image. Each element that represents a particular pixel stores the color for that pixel. There are two basic ways in which the color can be represented:

- ***True-color*** or ***RGB***, in which the three color components are stored (red, green, and blue, in that order) in layers in a three-dimensional matrix
- Index into a ***colormap***, in which the value stored for each pixel is an integer that refers to a row in another matrix called a colormap; the colormap stores the red, green, and blue components of colors in three separate columns

Thus, for an image that has $m \times n$ pixels, there are two methods for representing color.

In the true-color or RGB method, all of the information is stored in one 3D matrix with the size $m \times n \times 3$. The first two indices represent the coordinates of the pixel. The third index is the color component, so `(:,:,1)` is the red, `(:,:,2)` is the green, and `(:,:,3)` is the blue component.

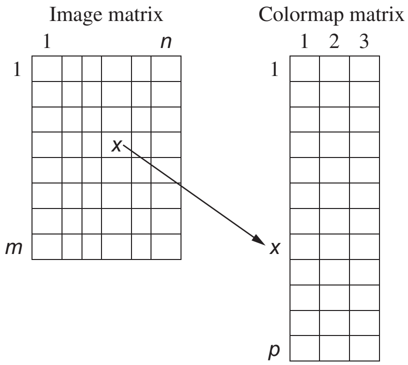
The colormap method instead uses two separate matrices: the image matrix is a 2D matrix with a size of $m \times n$. Every element in this matrix of integers is an index into a colormap matrix, which is the size $p \times 3$ (where p is the number of colors available in that particular colormap). Each row in the colormap has three numbers representing one color: first the red, then the green, and then the blue component.

Typically colormaps use **double** values in the range from 0 to 1, and RGB matrices use the type **uint8**. These conventions are used in the next two sections that introduce these methods.

13.1.1 Colormaps

When an image is represented using a colormap, there are two matrices:

- The colormap matrix, which has dimensions $p \times 3$, where p is the number of available colors; every row stores a separate color by storing three real numbers in the range from 0 to 1, representing the red, green, and blue components of the color.
- The image matrix, with dimensions $m \times n$; every element stores a color. To accomplish this, every element is an index into a particular row in the colormap, which means that it is an integer in the range 1 to p.



MATLAB has several built-in colormaps that are named; these can be seen and can be set using the built-in function **colormap**. The reference page on **colormap** displays them. Calling the function **colormap** without passing any arguments will return the current colormap. The default colormap is a map named **parula**, which has 256 colors. In versions of MATLAB before R2014b, the default was the colormap named **jet**, which is still an available colormap. A colormap named **turbo** was introduced in R2020b, which has similar colors to **jet**.

The following stores the current colormap in a variable *map*, gets the size of the matrix (which will be the number of rows in this matrix or, in other words, the number of colors, by three columns), and displays the last five rows in this colormap. If the current colormap is the default **parula**, the following will be the result:

```
>> map=colormap;
>> [r, c]=size(map)
r =
   256
c =
     3
>> map(252:256, :)
ans =
    0.9692    0.9609    0.1061
    0.9711    0.9667    0.1001
    0.9730    0.9724    0.0938
    0.9749    0.9782    0.0872
    0.9769    0.9839    0.0805
```

Note

that **parula** is actually a function that returns a colormap matrix. Passing no arguments results in the 256 × 3 matrix shown here.

This shows that there are 256 rows or, in other words, 256 colors, in this particular colormap. It also shows that the last five colors are shades of yellow (the combination of almost full red and green but very little blue).

Prior to R2019b, the built-in colormaps had 64 colors. To use only 64 colors instead of 256, the colormap function can be called as follows:

```
>> colormap(parula(64))
```

Note

that this does not return the first 64 colors, rather, they are spread out over the full range.

The format of calling the **image** function is:

```
image(mat)
```

where the matrix *mat* represents the colors in an $m \times n$ image ($m \times n$ pixels in the image). If the matrix has the size $m \times n$, then each element is an index into the current colormap.

One way to display the colors in the default **parula** colormap (which has 256 colors) is to create a matrix that stores the values 1 through 256 and to pass that to the **image** function; the result is shown in Fig. 13.1. When the matrix is passed to the **image** function, the value in each element in the matrix is used as an index into the colormap.

For example, the value in imagemat(1,2) is 17 so the color displayed in location (1,2) in the image will be the color represented by the seventeenth row in the colormap. By using the numbers 1 through 256, we can see all colors in this colormap.

```
>> imagemat =reshape(1:256, 16, 16);
>> image(imagemat)
```

As with plots, the result of calling the **image** function can be stored in a variable; this allows the properties of the image to be inspected and/or modified.

```
>> im =image(imagemat);
```

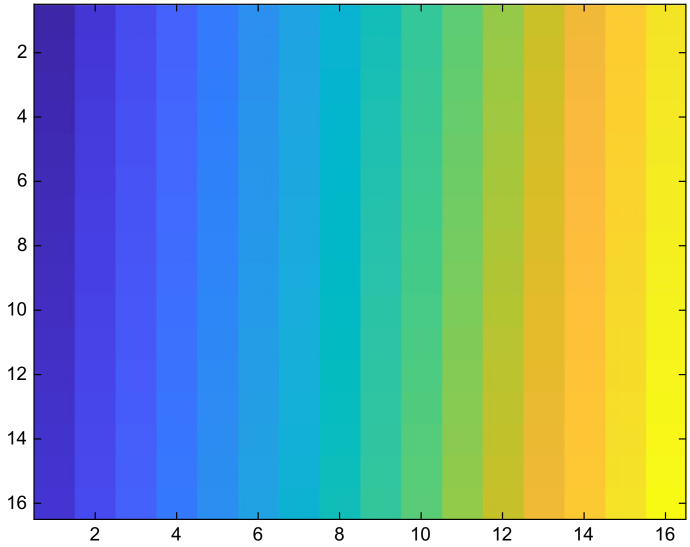


FIGURE 13.1

Columnwise display of the 256 colors in the **parula** colormap.

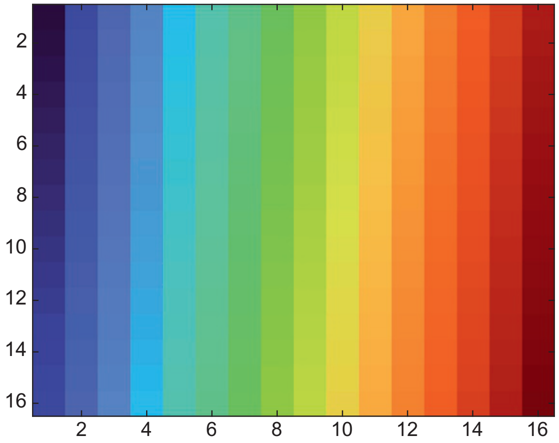


FIGURE 13.2
Columnwise display of the 256 colors in the **turbo** colormap.

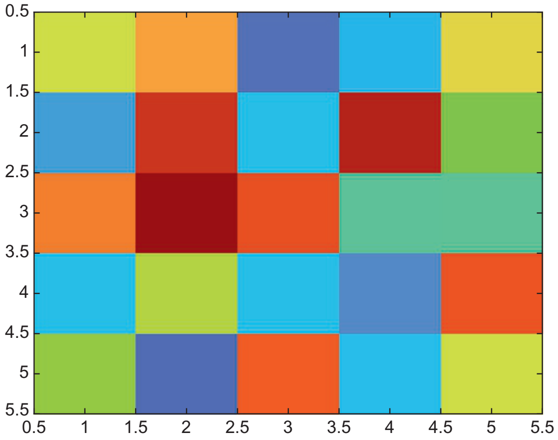


FIGURE 13.3
A 5×5 display of random colors from the **turbo** colormap.

To see the colors in the colormap **turbo** instead, we could make **turbo** the current colormap and re-display the image matrix, as seen in Fig. 13.2.

```
>> colormap(turbo)
>> image(imagemat)
```

Another example creates a 5×5 matrix of random integers in the range from 1 to the number of colors (stored in a variable *r*); the resulting image appears in Fig. 13.3 (assuming that the colormap is still **turbo** and that *r* is the number of rows, 256).

```
>> mat =randi(r,5);
>> image(mat)
```

Of course, these "images" are rather crude; the elements representing the pixel colors are quite large blocks. A larger matrix would result in something more closely resembling an image, as shown in Fig. 13.4.

```
>> mat =randi(r,500);
>> image(mat)
```

Although MATLAB has built-in colormaps, it is also possible to create others using any color combinations. For example, the following creates a customized colormap with just three colors: black, white, and red. This is then set to be the current colormap by passing the colormap matrix to the **colormap** function. Then, a 40×40 matrix of random integers, each in the range from 1 to 3 (as there are just three colors), is created, and that is passed to the **image** function; the results are shown in Fig. 13.5.

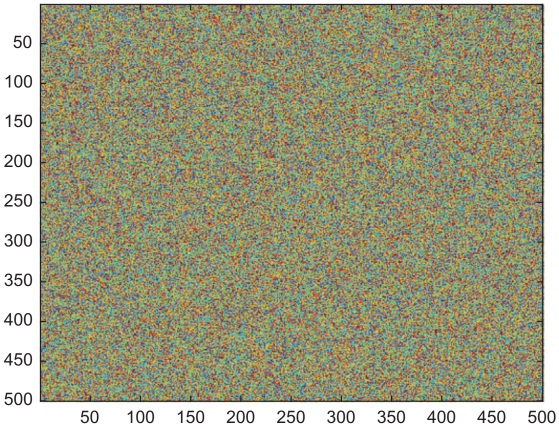


FIGURE 13.4
A *500* × *500* display of random colors.

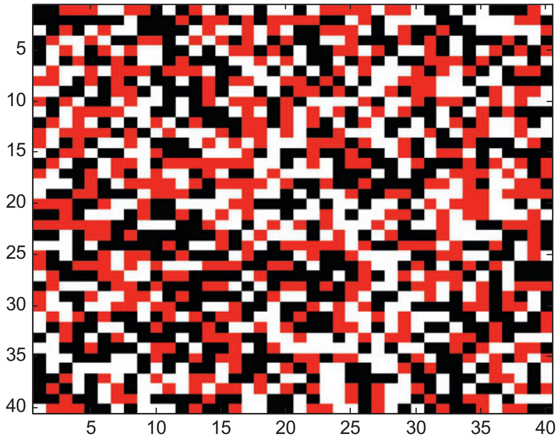


FIGURE 13.5
Random colors from a custom colormap.

```
>> mycolormap = [0 0 0; 1 1 1; 1 0 0];
>> colormap(mycolormap)
>> mat = randi(3,40);
>> image(mat)
```

The numbers in the colormap do not have to be integers; real numbers represent different shades as seen with the default colormap **parula**. For example, the following colormap gives us a way to visualize different shades of red, as shown in Fig. 13.6. All columns in the colormap matrix are initialized to zero, and then just the first column (red) is modified to vary from 0 to 1 in steps of 0.1.

```
>> colors = zeros(11,3);
>> colors(:,1) = [0:0.1:1]';
>> colormap(colors)
>> vec = 1:length(colors);
>> image(vec)
```

PRACTICE 13.1

Given the following colormap, "draw" the scene shown in Fig. 13.7. (Hint: Preallocate the image matrix. The fact that the first color in the colormap is white makes this easier.)

```
>> mycolors = [1 1 1; 0 1 0; 0 0.5 0; ...
               0 0 1; 0 0 0.5; 0.3 0 0];
```

Colormaps are used with many plot functions. Generally, the plots shown assume the default colormap **parula**, but the colormap can be modified. For

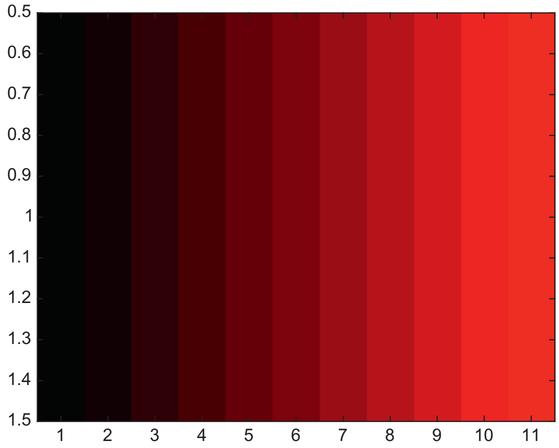


FIGURE 13.6
Shades of red.

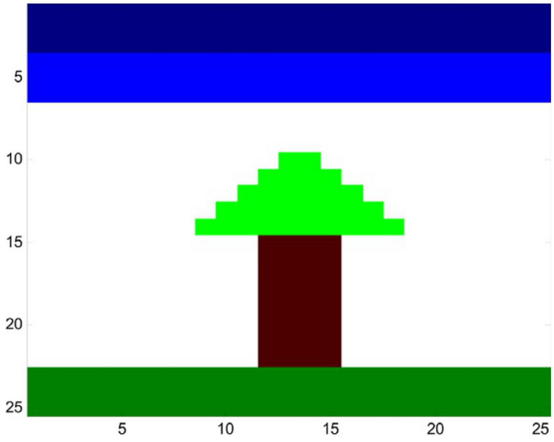


FIGURE 13.7
Draw this tree with grass and sky.

example, plotting a 3D object using **surf** or **sphere**, and displaying a **colorbar** would normally display the parula colors. The following is an example of modifying this to use the colormap **pink**, as shown in Fig. 13.8.

```
>> [x,y,z] = sphere(20);
>> colormap(pink)
>> surf(x,y,z)
>> title('Pink sphere')
>> colorbar
```

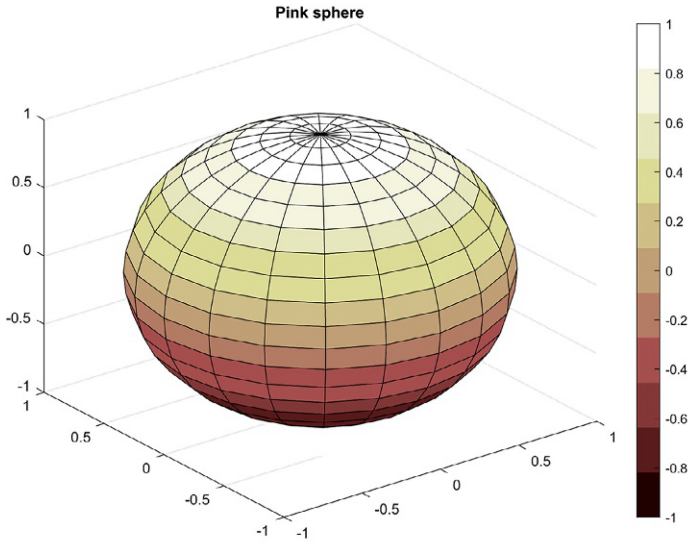


FIGURE 13.8
Pink colormap for sphere function.

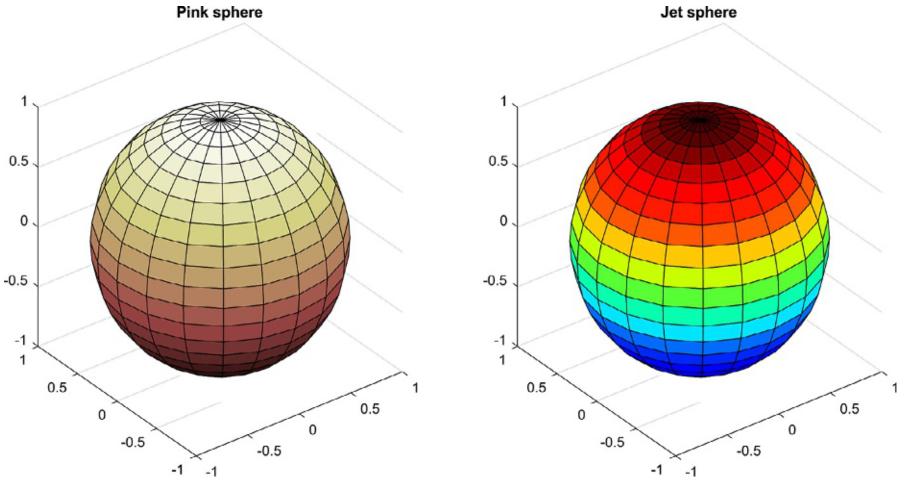


FIGURE 13.9
Subplot with multiple colormaps.

Multiple colormaps can be displayed in a single Figure Window by passing the axes handle to the **colormap** function, as shown in Fig. 13.9.

```
[x,y,z] = sphere(20);
ax1 = subplot(1,2,1)
surf(x,y,z);
colormap(ax1,pink)
title('Pink sphere')
ax2 = subplot(1,2,2)
surf(x,y,z);
colormap(ax2,jet)
title('Jet sphere')
```

13.1.2 True-Color Matrices

True-color matrices, or ***RGB matrices***, are another way to represent images. True color matrices are 3D matrices. The first two coordinates are the coordinates of the pixel. The third index is the color component; `(:,:,1)` is the red, `(:,:,2)` is the green, and `(:,:,3)` is the blue component.

In an 8-bit RGB image, each element in the matrix is of the type **uint8**, which is an unsigned integer type storing values in the range from 0 to 255. The minimum value, 0, represents the darkest hue available, so all 0s result in a black pixel. The maximum value, 255, represents the brightest hue. For example, if the values for a given pixel coordinates *px* and *py* are: (px,py,1) is 255, (px, py,2) is 0, and (px,py,3) is 0, then that pixel will be bright red. All 255s result in a white pixel.

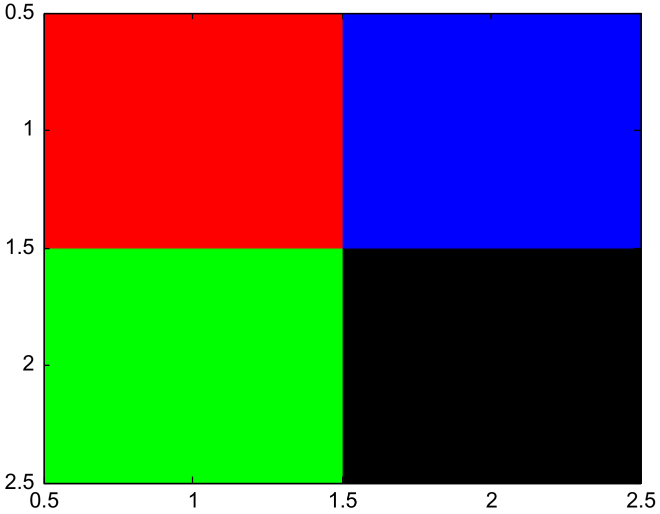


FIGURE 13.10

Image from a true-color matrix.

The **image** function displays the information in the 3D matrix as an image.

For example, the following creates a *2 × 2* image as shown in Fig. 13.10. The matrix is *2 × 2 × 3* where the third dimension is the color. The pixel in location (1,1) is red, the pixel in location (1,2) is blue, the pixel in location (2,1) is green, and the pixel in location (2,2) is black. To make the pixel in location (1,1) red, we could execute the following three statements, which would make the red layer the brightest possible, with no green or blue:

```
>> mat(1,1,1) = 255;
>> mat(1,1,2) = 0;
>> mat(1,1,3) = 0;
```

Similarly, we could execute three statements to set the color for each of the other pixels. However, it is much simpler to start by preallocating the entire image matrix to all zeros and then changing individual values to 255 as necessary.

```
>> mat = zeros(2,2,3);
>> mat(1,1,1) = 255;
>> mat(1,2,3) = 255;
>> mat(2,1,2) = 255;
>> image(mat)
```

The following shows how to separate the red, green, and blue components from an image matrix. In this case we are using the "image" matrix *mat*, and then use

Note

if a 2D image matrix is passed to **image**, it uses the current colormap to display the image, but if a 3D image matrix is passed to **image**, it ignores the colormap and instead uses the information from the 3D matrix to determine the color of each pixel.

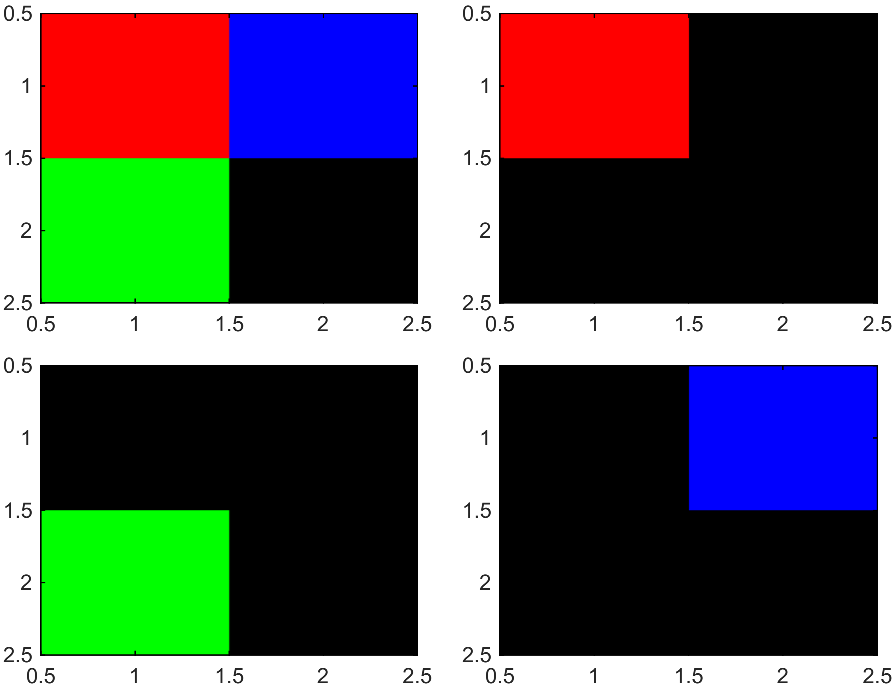


FIGURE 13.11

Separating red, green, and blue components.

subplot to display the original matrix and the red, green, and blue component matrices, as shown in Fig. 13.11.

```
matred = zeros(2,2,3);
matred(:,:,1) = mat(:,:,1);
matgreen = zeros(2,2,3);
matgreen(:,:,2) = mat(:,:,2);
matblue = zeros(2,2,3);
matblue(:,:,3) = mat(:,:,3);
subplot(2,2,1)
image(mat)
subplot(2,2,2)
image(matred)
subplot(2,2,3)
image(matgreen)
subplot(2,2,4)
image(matblue)
```

Superimposing the images from the three matrices *matred*, *matgreen*, and *matblue* would be achieved by simply adding the three arrays together. The following would result in the image from Fig. 13.10.

```
>> image(matred+matgreen+matblue)
```

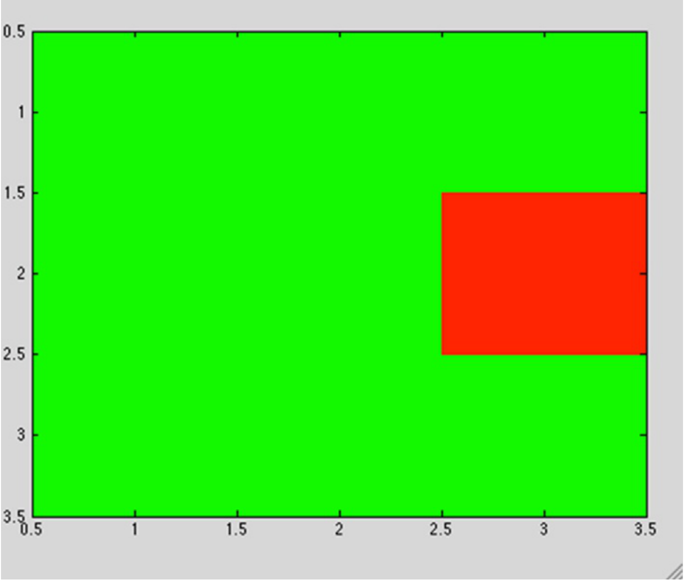


FIGURE 13.12
Create this true-color matrix.

PRACTICE 13.2

Create the 3 × 3 (× 3) true-color matrix shown in Fig. 13.12 (the axes are defaults).

13.1.3 Image Files

Images that are stored in various formats, such as JPEG, TIFF, PNG, GIF, and BMP, can be manipulated in MATLAB. Built-in functions, such as **imread** and **imwrite**, read from and write to various image file formats. Some images are stored as unsigned 8-bit data (**uint8**), some as unsigned 16-bit (**uint16**), and some are stored as **double**.

For example, the following reads a JPEG image into a 3D matrix; it can be seen from the **size** and **class** functions that this was stored as a **uint8** RGB matrix.

```
>> porchimage = imread('snowyporch.JPG');
>> size(porchimage)
ans =
        2848        4272          3
>> class(porchimage)
ans =
     'uint8'
```

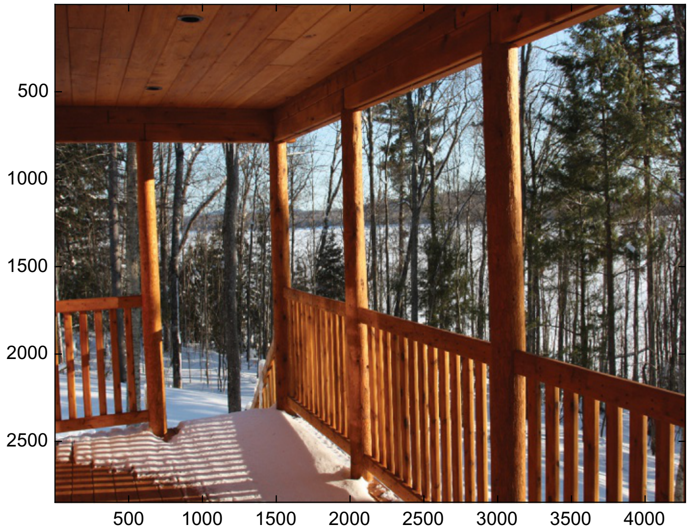


FIGURE 13.13

Image from a JPEG file displayed using **image**.

The image is stored as a true-color matrix and has *2848* × *4272* pixels. The image function displays the matrix as an image, as shown in Fig. 13.13.

```
>> image(porchimage)
```

The function **imshow** can also be used to display an image.

The image can be manipulated by modifying the numbers in the image matrix. For example, multiplying every number by 0.5 will result in a range of values from 0 to 128 instead of from 0 to 255. As the larger numbers represent brighter hues, this will have the effect of dimming the hues in the pixels, as shown in Fig. 13.14.

```
>> dimmer = 0.5*porchimage;
>> image(dimmer)
```

The function **imwrite** is used to write an image matrix to a file in a specified format:

```
>> imwrite(dimmer, 'dimporch.JPG')
```

Images can also be stored as an indexed image rather than RGB. In that case, the colormap is usually stored with the image and will be read in by the **imread** function.

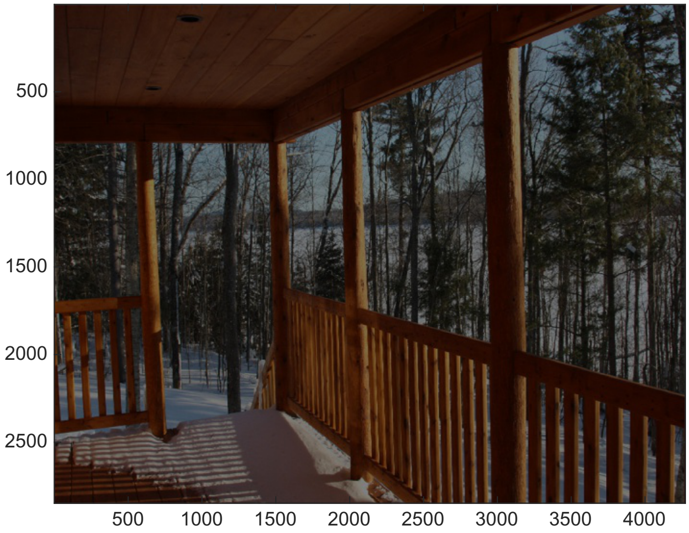


FIGURE 13.14
Image dimmed by manipulating the matrix values.

13.2 INTRODUCTION TO APPS AND GRAPHICAL USER INTERFACES

Apps in MATLAB are programs that allow users to have input using graphical interfaces, such as pushbuttons, sliders, radio buttons, toggle buttons, pop-up menus, and so forth. In MATLAB, there are apps that can be created within Figure Windows. These can be created programmatically from scratch, or (for now) using the built-in Graphical User Interface Development Environment (GUIDE), which allows the user to graphically lay out the GUI and MATLAB generates the code for it automatically. In the future, GUIDE will be removed. The newer App Designer creates apps in UI Figure Windows. Like GUIDE, App Designer allows the user to graphically lay out the app, and the code is generated automatically. The code that App Designer creates is based on objects.

In this section, the programming method of creating graphical objects and allowing the user to interact with them will be introduced. We use the term GUIs for these. In the next section, these concepts are reinforced using App Designer. GUIDE is not covered in this book.

13.2.1 GUI Basics

GUIs are an implementation of the handle classes that were introduced in Chapter 11, so there is a hierarchy. For example, the parent may be a

Figure Window and its children would be graphics objects, such as pushbuttons and text boxes.

The parent user interface object can be a **figure**, **uipanel**, or **uibuttongroup**. A **figure** is a Figure Window created by the **figure** function. A **uipanel** is a means of grouping together user interface objects (the "ui" stands for user interface). A **uibuttongroup** is a means of grouping together buttons (both radio buttons and toggle buttons).

A Figure Window is the parent of any GUI. Just calling the **figure** function will bring up a blank Figure Window; storing the handle in a variable allows us to manipulate its properties, as we have seen in Chapter 11.

```
>> f = figure;
>> f.Position
ans =
   616   598   560   420
```

The position vector specifies `[left bottom width height]`. The first two numbers, the left and bottom, are the distance that the lower left corner of the figure box is from the lower left of the monitor screen (first from the left and then from the bottom). The last two are the width and height of the figure box itself. All of these are in the default units of pixels.

```
>> f.Visible
ans =
    'on'
```

The 'Visible' property 'on' means that the Figure Window can be seen. When creating a GUI, however, the normal procedure is to create the parent Figure Window but make it invisible. Then, all user interface objects are added to it and properties are set. When everything has been completed the GUI is made visible.

If the figure is the only Figure Window that has been opened, then it is the current figure. Using **gcf** would be equivalent to *f* in that case. Recall that the parent of a figure window is the screen; this could be obtained with either *f.Parent* or **groot**.

Most user interface objects are created using the **uicontrol** function. Pairs of arguments are passed to the **uicontrol** function, consisting of the name of a property as a character vector and then its value. The default is that the object is created in the current figure; otherwise, a parent can be specified as in **uicontrol(parent,…)**. The 'Style' property defines the type of object, as a character vector. For example, 'text' is the Style of a static text box, which is normally used as a label for other objects in the GUI or for instructions.

The following example creates a GUI that just consists of a static text box in a Figure Window. The figure is first created, but made invisible. The color is white, and it is given a position. Storing the handle of this figure in a variable allows the function to refer to it later on, to set properties, for example.

The **uicontrol** function is used to create a text box, position it (the vector specifies the [left bottom width height] within the Figure Window itself), and put some text in it. Note that the position is within the Figure Window, not within the screen.

A name is put on the top of the figure. The **movegui** function moves the GUI (the figure) to the center of the screen. Finally, when everything has been completed, the GUI is made visible.

```
simpleGui.m
```

```
function simpleGui
% simpleGui creates a simple GUI with just a static text box
% Format: simpleGui or simpleGui()
% Create the GUI but make it invisible for now while
% it is being initialized
f = figure('Visible', 'off','Color','white','Position',...
 [300, 400, 450,250]);
htext = uicontrol('Style','text','Position', ...
 [200,50, 100, 25], 'String','My First GUI');
% Put a name on it and move to the center of the screen
f.Name = 'Simple GUI';
movegui(f,'center')
% Now the GUI is made visible
f.Visible = 'on';
end
```

The Figure Window shown in Fig. 13.15 will appear in the middle of the screen. The static text box requires no interaction with the user, so although this example shows some of the basics, it does not allow any graphical interface with the user.

Note that, as of R2021a, the new name=value syntax could be used in the **figure** and **uicontrol** functions, as in:

```
f = figure(Visible = 'off', Color = 'white', ...
  Position = [300, 400, 450,250]);
```

When the 'Units' property of objects is set to 'Normalized', this means that rather than specifying in pixels the position, it is done as a percentage. This allows the Figure Window to be resized without changing the way that the GUI appears. It also means that GUIs will look the same on different screen sizes. Normalized units for the figure means as a percentage of the screen, whereas Normalized units for a uicontrol object means as a percentage of the Figure Window. For example, the function *simpleGuiNormalized* is a version of the first GUI example that uses normalized units:

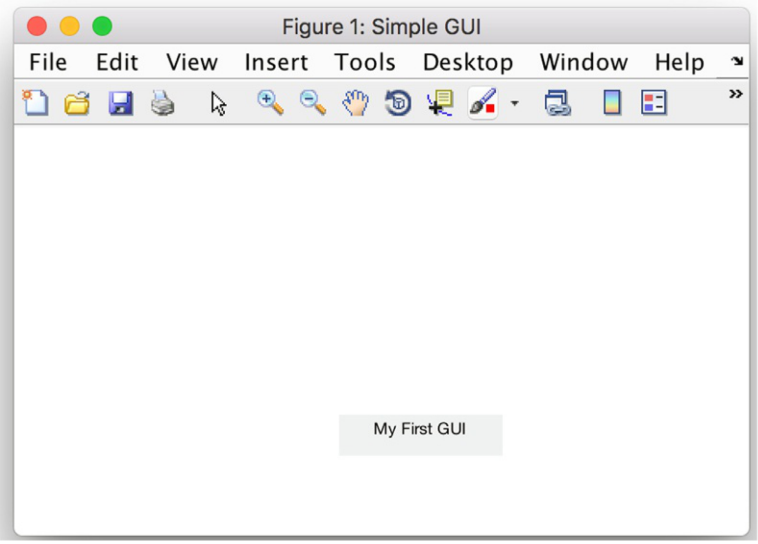


FIGURE 13.15
Simple GUI with a static text box.

simpleGuiNormalized.m

```
function simpleGuiNormalized
% simpleGuiNormalized creates a GUI with just a static text box
% Format: simpleGuiNormalized or simpleGuiNormalized()
% Create the GUI but make it invisible for now while
% it is being initialized
f = figure('Visible', 'off','Color','white','Units',...
 'Normalized', 'Position', [.25, .5, .35, .3]);
htext = uicontrol('Style','text','Units', 'Normalized', ...
 'Position', [.45, .2, .2, .1], ...
 'String','My First GUI');
% Put a name on it and move to the center of the screen
f.Name = 'Simple GUI Normalized';
movegui(f,'center')

% Now the GUI is made visible
f.Visible = 'on';
end
```

For example, the first two numbers in the position vector for the figure [.25 .5 .35 .3] specify that the lower left corner of the Figure Window is one-quarter of the way from the left and half-way from the bottom of the screen. Of course, the figure is then moved to the middle of the screen, but the Position vector is still useful in that it also specifies the width and height of the figure.

Because Normalized units are more general and more intuitive, for the most part they will be used for the remaining examples rather than pixels.

13.2.2 Text Boxes, Push Buttons, and Sliders

Now that we have seen the basic algorithm for a GUI, we will add user interaction.

In the next example, we will allow the user to enter text in an editable text box, and then the GUI will print the user's input in red. In this example, there will be user interaction. First, the user must type in the text and, once this happens, the user's entry in the editable text box will no longer be shown, but, instead, the text that the user typed will be displayed in a larger red font in a static text box. When the user's action (which is called an ***event***) causes a response, what happens is that a ***callback function*** is called or invoked. The callback function is the part of the code in which the text is read in and then printed in a larger red font. This is sometimes called ***event-driven programming***: the event triggers an action.

The callback function must be in the path; one way to do this is to make it a nested function within the GUI function. The algorithm for this example is as follows:

- Create the Figure Window, but make it invisible.
- Make the color of the figure white, put a title on it, and move it to the center.
- Create a static text box with an instruction to enter some text.
- Create an editable text box.
  - The Style of this is 'edit'.
  - The callback function must be specified as the user's entry of a text necessitates a response (the function handle of the nested function is used for this).
- Make the GUI visible so that the user can see the instruction and type in the text.
- When the text is entered, the callback function *callbackfn* is called. Note that in the function header, there are two input arguments, *hObject* and *eventdata*. The input argument *hObject* refers to the handle of the **uicontrol** object that called it; *eventdata* stores in a structure information about the event that triggered the call to the callback function (this varies depending on the type of object and is not always used).

- The algorithm for the nested function *callbackfn* is:
  - make the previous GUI objects invisible
  - get the text that the user typed (note that either *hObject* or the object handle name *huitext* can be used to refer to the object in which the text was entered)
  - create a static text box to print the text in red with a larger font
  - make this new object visible

guiWithEditbox.m

```
function guiWithEditbox
% guiWithEditbox has an editable text box
%  and a callback function that prints the user's
%  text in red
% Format: guiWithEditbox or guiWithEditbox()

% Create the GUI but make it invisible for now
f = figure('Visible', 'off','Color','white','Units',...
  'Normalized','Position', [.25 .5 .4 .2]);
% Put a name on it and move it to the center of the screen
f.Name = 'GUI with editable text';
movegui(f,'center')
% Create two objects: a box where the user can type and
% edit text and also a text title for the edit box
hsttext = uicontrol('Style','text',...
    'BackgroundColor','white','Units','Normalized',...
    'Position',[.2 .6 .6 .2],...
    'String','Enter your text here');
huitext = uicontrol('Style','edit', 'Units',...
    'Normalized','Position',[.3 .3 .4 .2], ...
    'Callback',@callbackfn);
% Now the GUI is made visible
f.Visible = 'on';

    % Call back function
    function callbackfn(hObject,eventdata)
        % callbackfn is called by the 'Callback' property
        % in the editable text box
        set([hsttext huitext],'Visible','off');
        % Get the text that the user entered and print
        % it in big red letters
        printstr = huitext.String;
        hstr = uicontrol('Style','text',...
            'BackgroundColor','white','Units',...
            'Normalized','Position',[.1 .3 .8 .4],...
            'String',printstr,...
            'ForegroundColor','Red','FontSize',30);
        hstr.Visible = 'on';
    end
end
```

When the Figure Window is first made visible, the static text and the editable text box are shown. In this case, the user entered 'Hello and how are you?' Note that to enter the text, the user must first click the mouse in the editable text box. The text that was entered by the user is shown in Fig. 13.16.

After the user enters this text and hits the Enter key, the callback function is executed; the results are shown in Fig. 13.17. The callback function sets the Visible property to off for both of the original objects by referring to their handles. As the callback function is a nested function, the handle variables can be used. It then gets the text and writes it in a new static text box in red.

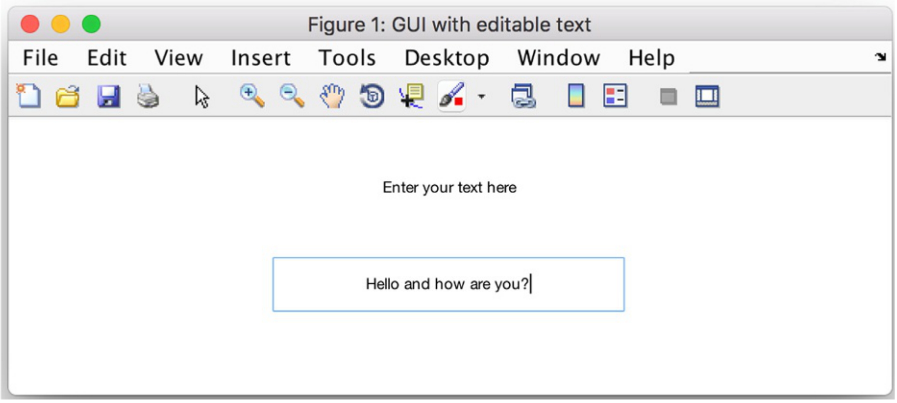


Figure 1: GUI with editable text
File Edit View Insert Tools Desktop Window Help

Enter your text here

Hello and how are you?

FIGURE 13.16
Text entered by user in editable text box.

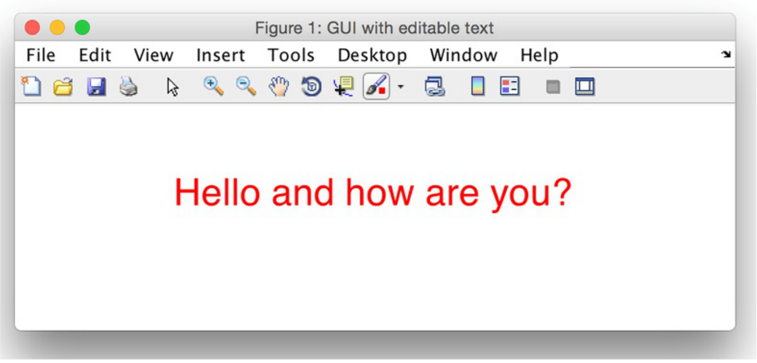


Figure 1: GUI with editable text
File Edit View Insert Tools Desktop Window Help

Hello and how are you?

FIGURE 13.17
The result from the callback function.

Now we will add a pushbutton to the GUI. This time, the user will enter text, but the callback function will be invoked when the pushbutton is pushed.

guiWithPushbutton.m

```
function guiWithPushbutton
% guiWithPushbutton has an editable text box and a pushbutton
% Format: guiWithPushbutton or guiWithPushbutton()

% Create the GUI but make it invisible for now while
%  it is being initialized
f = figure('Visible', 'off','Color','white','Units',...
    'Normalized', 'Position',[.25 .5 .5 .3]);
hsttext = ...
uicontrol('Style','text','BackgroundColor','white',...
    'Units','Normalized','Position',[.2 .7 .6 .2],...
    'String','Enter text here, then push the button');
huitext = uicontrol('Style','edit','Units','Normalized',...
    'Position',[.3 .5 .4 .2]);
f.Name = 'GUI with pushbutton';
movegui(f,'center')
% Create a pushbutton that says "Push me!!"
hbutton = uicontrol('Style','pushbutton','String',...
    'Push me!!', 'Units','Normalized','Position',...
    [.6 .1 .3 .2], 'Callback',@callbackfn);

% Now the GUI is made visible
f.Visible = 'on';

% Call back function
    function callbackfn(hObject,eventdata)
        % callbackfn is called by the 'Callback' property
        % in the pushbutton
        set([hsttext huitext hbutton],'Visible','off');
        printstr = huitext.String;
        if isempty(printstr)
            printstr = 'Enter something next time!';
        end
        hstr = uicontrol('Style','text','BackgroundColor',...
            'white', 'Units', 'Normalized','Position',...
            [.1 .3 .8 .4], 'String', printstr, ...
            'ForegroundColor','Red','FontSize',30);
        hstr.Visible = 'on';
    end
end
```

In this case, the user types the text into the edit box. Hitting Enter, however, does not cause the callback function to be called; instead, the user must push the button with the mouse. The callback function is associated with the pushbutton object. Therefore, pushing the button will bring up the text in a

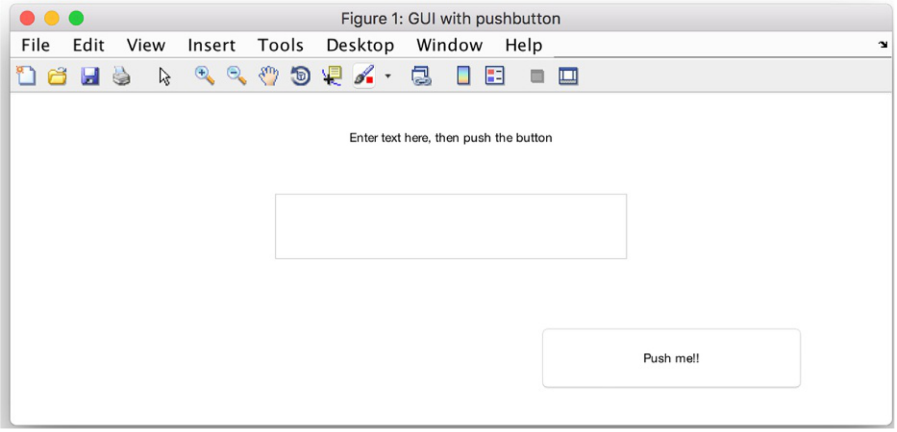


Figure 1: GUI with pushbutton
File Edit View Insert Tools Desktop Window Help
Enter text here, then push the button
Push me!!

FIGURE 13.18
GUI with a push button.

larger red font. The initial configuration with the pushbutton is shown in Fig. 13.18.

PRACTICE 13.3

Create a GUI that will convert a length from inches to centimeters. The GUI should have an editable text box in which the user enters a length in inches, and a pushbutton that says, "Convert me!" Pushing the button causes the GUI to calculate the length in centimeters and display that. The callback function that accomplishes this should leave all objects visible. That means that the user can continue converting lengths until the Figure Window is closed. The GUI should display a default length to begin with (e.g., 1 inch). Then, when the user enters a length and pushes the button, the Figure Window will show the new calculated length in centimeters.

Another GUI object that can be created is a slider. The slider object has a numerical value and can be controlled by either clicking on the arrows to move the value up or down, or by sliding the bar with the mouse. By default, the numerical value ranges from 0 to 1, but these values can be modified using the 'Min' and 'Max' properties.

The function *guiSlider* creates in a Figure Window a slider that has a minimum value of 0 and a maximum value of 5. It uses text boxes to show the minimum and maximum values, and also the current value of the slider.

guiSlider.m

```
function guiSlider
% guiSlider is a GUI with a slider
% Format: guiSlider or guiSlider()

f = figure('Visible', 'off','Color','white','Units',...
    'Normalized', 'Position', [.25 .5 .4 .2]);

% Minimum and maximum values for slider
minval = 0;
maxval = 5;
% Create the slider object
slhan = uicontrol('Style','slider', 'Units', 'Normalized', ...
    'Position',[.3 .5 .4 .2], 'Min', minval, 'Max', maxval,...
    'SliderStep', [0.5 0.5], 'Callback', @callbackfn);
% Text boxes to show the minimum and maximum values
hmintext = uicontrol('Style','text','BackgroundColor',...
    'white', 'Units', 'Normalized',...
    'Position', [.1 .5 .1 .1], 'String', num2str(minval));
hmaxtext = uicontrol('Style', 'text','BackgroundColor',...
    'white', 'Units', 'Normalized',...
    'Position', [.8 .5 .1 .1], 'String', num2str(maxval));
% Text box to show the current value (off for now)
hsttext = uicontrol('Style','text','BackgroundColor','white',...
    'Units', 'Normalized',...
    'Position',[.4 .3 .2 .1],'Visible', 'off');

movegui(f,'center')
f.Name = 'Slider Example';
f.Visible = 'on';

% Call back function displays the current slider value
   function callbackfn(hObject,eventdata)
       % callbackfn is called by the 'Callback' property
       % in the slider
       num = slhan.Value;
       set(hsttext,'Visible','on','String',num2str(num))
   end
end
```

Fig. 13.19 shows the configuration once the user has moved the slider.

PRACTICE 13.4

Use the Help browser to find the property that controls the increment value on the slider, and modify the *guiSlider* function to move in increments of 0.5 when the arrow is used.

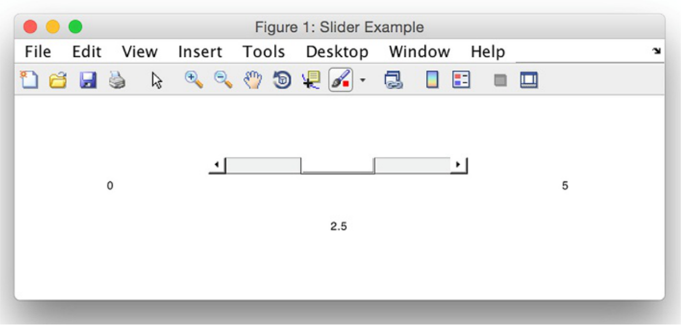


FIGURE 13.19
GUI with slider result shown.

GUI functions can have multiple callback functions. In the example *guiWithTwoPushbuttons*, there are two buttons that could be pushed (see Fig. 13.20). Each of them has a unique callback function associated with it. If the top button is pushed, its callback function prints red exclamation points (as shown in Fig. 13.21). If the bottom button is instead pushed, its callback function prints blue asterisks.

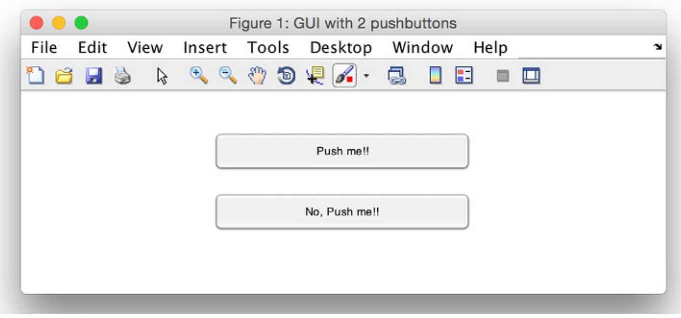


Figure 1: GUI with 2 pushbuttons
File Edit View Insert Tools Desktop Window Help
Push me!!
No, Push me!!

FIGURE 13.20
GUI with two pushbuttons and two callback functions.

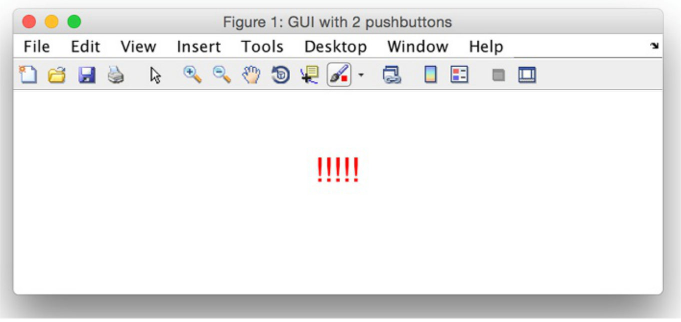


Figure 1: GUI with 2 pushbuttons
File Edit View Insert Tools Desktop Window Help
!!!!!

FIGURE 13.21
The result from the first callback function.

function guiWithTwoPushbuttons.m

```
function guiWithTwoPushbuttons
% guiWithTwoPushbuttons has two pushbuttons, each
%  of which has a separate callback function
% Format: guiWithTwoPushbuttons

% Create the GUI but make it invisible for now while
%  it is being initialized

f = figure('Visible', 'off','Color','white','Units',...
    'Normalized', 'Position', [.25 .5 .4 .2]);
f.Name = 'GUI with 2 pushbuttons';
movegui(f,'center')

% Create a pushbutton that says "Push me!!"
hbutton1 = uicontrol('Style','pushbutton','String',...
    'Push me!!', 'Units', 'Normalized',...
    'Position',[.3 .6 .4 .2], ...
    'Callback',@callbackfn1);

% Create a pushbutton that says "No, Push me!!"
hbutton2 = uicontrol('Style','pushbutton','String',...
    'No, Push me!!', 'Units', 'Normalized',...
    'Position',[.3 .3 .4 .2], ...
    'Callback',@callbackfn2);
% Now the GUI is made visible
f.Visible = 'on';

    % Call back function for first button
    function callbackfn1(hObject,eventdata)
       %  callbackfn is called by the 'Callback' property
       %  in the first pushbutton

       set([hbutton1 hbutton2],'Visible','off');
       hstr = uicontrol('Style','text',...
          'BackgroundColor', 'white', 'Units',...
          'Normalized','Position',[.4 .5 .2 .2],...
          'String','!!!!!', ...
          'ForegroundColor','Red','FontSize',30);
       hstr.Visible = 'on';
    end

  % Call back function for second button
  function callbackfn2(hObject,eventdata)
    %   callbackfn is called by the 'Callback' property
    %   in the second pushbutton

    set([hbutton1 hbutton2],'Visible','off');
    hstr = uicontrol('Style','text',...
        'BackgroundColor','white', 'Units', ...
        'Normalized', 'Position',[.4 .5 .2 .2],...
        'String','*****', ...
        'ForegroundColor','Blue','FontSize',30);
    hstr.Visible = 'on';
  end

end
```

If the first button is pushed, the first callback function is called, which would produce the result in Fig. 13.21.

It is also possible to have one callback function invoked, or called, by multiple objects. In the example with two pushbuttons, instead of having one callback function associated with each pushbutton, we could have just one callback function. In that case, the value of the input argument *hObject* would be checked to determine which object called it. A modified GUI to accomplish this is shown next.

```
function guiWithTwoPushbuttonsii.m
```

```
function guiWithTwoPushbuttonsii
% guiWithTwoPushbuttonsii has two pushbuttons
%   but just one callback function
% Format: guiWithTwoPushbuttonsii

% Create the GUI but make it invisible for now while
%  it is being initialized
f = figure('Visible', 'off','Color','white','Units',...
    'Normalized', 'Position', [.25 .5 .4 .2]);
f.Name = 'GUI with 2 pushbuttons';
movegui(f,'center')

% Create a pushbutton that says "Push me!!"
hbutton1 = uicontrol('Style','pushbutton','String',...
    'Push me!!', 'Units', 'Normalized',...
    'Position',[.3 .6 .4 .2], ...
    'Callback',@callbackfn);

% Create a pushbutton that says "No, Push me!!"
hbutton2 = uicontrol('Style','pushbutton','String',...
    'No, Push me!!', 'Units', 'Normalized',...
    'Position',[.3 .3 .4 .2], ...
    'Callback',@callbackfn);
% Now the GUI is made visible
f.Visible = 'on';

    % Call back function for both buttons
    function callbackfn(hObject,eventdata)
       % callbackfn is called by the 'Callback' property

       set([hbutton1 hbutton2],'Visible','off');
       hstr = uicontrol('Style','text',...
           'BackgroundColor', 'white', 'Units',...
           'Normalized','Position',[.4 .5 .2 .2],...
           'FontSize',30);
       if hObject == hbutton1
           hstr.String = '!!!!!';
           hstr.ForegroundColor = 'Red';
       else
           hstr.String = '*****';
           hstr.ForegroundColor = 'Blue';
       end
       hstr.Visible = 'on';
    end

end
```

In this example, the value of the input argument *hObject* was used by the callback function. The second input argument, *eventdata*, was not used, however. Whenever any callback function is called, both arguments are automatically passed to the callback function. If the callback function is not going to use one or both, the tilde can be put in the function header instead of the name of the input argument. In the previous example, the header could have been:

```
function callbackfn(hObject,~)
```

13.2.3 Plots and Images in GUIs

Plots and images can be imbedded in a GUI. The next example *guiSliderPlot* shows a plot of **sin(x)** from 0 to the value of a slider bar. The axes are positioned within the Figure Window using the **axes** function, and then when the slider is moved the callback function plots. Note that the default Units property for an **axes** object is Normalized.

function guiSliderPlot.m

```
function guiSliderPlot
% guiSliderPlot has a slider
% It plots sin(x) from 0 to the value of the slider
% Format: guiSliderPlot

f = figure('Visible', 'off', 'Units', 'Normalized',...
    'Position', [.2 .5 .4 .3], 'Color', 'white');

% Minimum and maximum values for slider
minval = 0;


maxval = 4*pi;

% Create the slider object
slhan = uicontrol('Style','slider','Units','Normalized',...
    'Position',[.3 .7 .4 .1], ...
    'Min', minval, 'Max', maxval,'Callback', @callbackfn);
% Text boxes to show the min and max values and slider value
hmintext = uicontrol('Style','text','BackgroundColor', 'white', ...
    'Units','Normalized','Position', [.1 .7 .1 .1],...
    'String', num2str(minval));
hmaxtext = uicontrol('Style','text', 'BackgroundColor', 'white',...
    'Units', 'Normalized','Position', [.8 .7 .1 .1], ...
    'String', num2str(maxval));
hsttext = uicontrol('Style','text','BackgroundColor', 'white',...
    'Units','Normalized', 'Position', [.45 .8 .1 .1],...
    'Visible','off');
% Create axes handle for plot
axhan = axes('Position', [.2 .1 .6 .5]);

f.Name = 'Slider Example with sin plot';
movegui(f,'center')
f.Visible = 'on';
```

```
% Call back function displays the current slider value & plots sin
  function callbackfn(~,~)
      % callbackfn is called by the 'Callback' property
      % in the slider
      num = slhan.Value;
      set(hsttext,'Visible','on','String',num2str(num))
      x = 0:num/50:num;
      y = sin(x);
      plot(x,y)
      xlabel('x')
      ylabel('sin(x)')
  end
end
```

After the slider bar is moved, the callback function plots **sin(x)** from 0 to the position of the slider bar. Figure 13.22 shows the configuration of the window, with the slider bar, static text boxes to the left and right showing the minimum and maximum values, and the axes positioned underneath with the plot.

Images can also be placed in GUIs, again using **axes** to locate the image. In a variation on the previous example, the next example displays an image and uses a slider to vary the brightness of the image. The result is shown in Fig. 13.23.

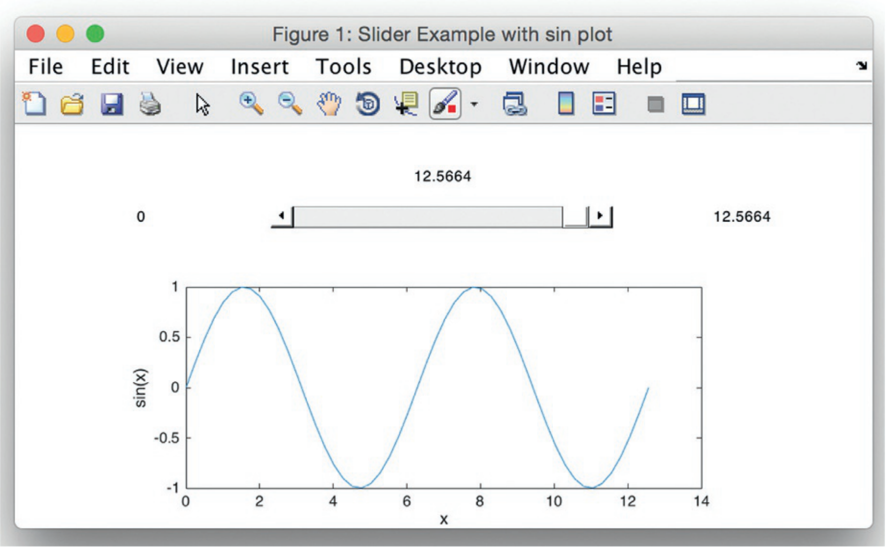


FIGURE 13.22
Plot shown in a GUI Figure Window.

guiSliderImage.m

```
function guiSliderImage
% guiSliderImage has a slider
% Displays an image; slider dims it
% Format: guiSliderImage

f = figure('Visible', 'off', 'Units', 'Normalized',...
    'Position', [.2 .5 .4 .3], 'Color', 'white');
% Minimum and maximum values for slider
minval = 0;

maxval = 1;
% Create the slider object
slhan = uicontrol('Style','slider','Units','Normalized',...
    'Position',[.3 .7 .4 .1], ...
    'Min', minval, 'Max', maxval,'Callback', @callbackfn);
% Text boxes to show the min and max values and slider value
hmintext = uicontrol('Style','text','BackgroundColor', 'white', ...
    'Units','Normalized','Position', [.1 .7 .1 .1],...
    'String', num2str(minval));
hmaxtext = uicontrol('Style','text', 'BackgroundColor', 'white',...
    'Units', 'Normalized','Position', [.8 .7 .1 .1], ...
    'String', num2str(maxval));
hsttext = uicontrol('Style','text','BackgroundColor', 'white',...
    'Units','Normalized', 'Position', [.45 .8 .1 .1],...
    'Visible','off');
% Create axes handle for plot
axhan = axes('Position', [.2 .1 .6 .5]);

f.Name = 'Slider Example with an image';
movegui(f,'center')
f.Visible = 'on';

% Call back function displays the current slider value & image
   function callbackfn(~,~)
       % callbackfn is called by the 'Callback' property
       % in the slider
       num = slhan.Value;

       set(hsttext,'Visible','on','String',num2str(num))
       myimage1 = imread('snowyporch.JPG');
       dimmer = num*myimage1;
       image(dimmer)

   end
end
```

13.2.4 Button Groups

This section illustrates radio buttons, and grouping objects together; in this case, in a button group.

The next GUI presents the user with a choice of colors using two radio buttons, only one of which can be chosen at any given time. The GUI prints text to the right of the radio buttons, in the chosen color.

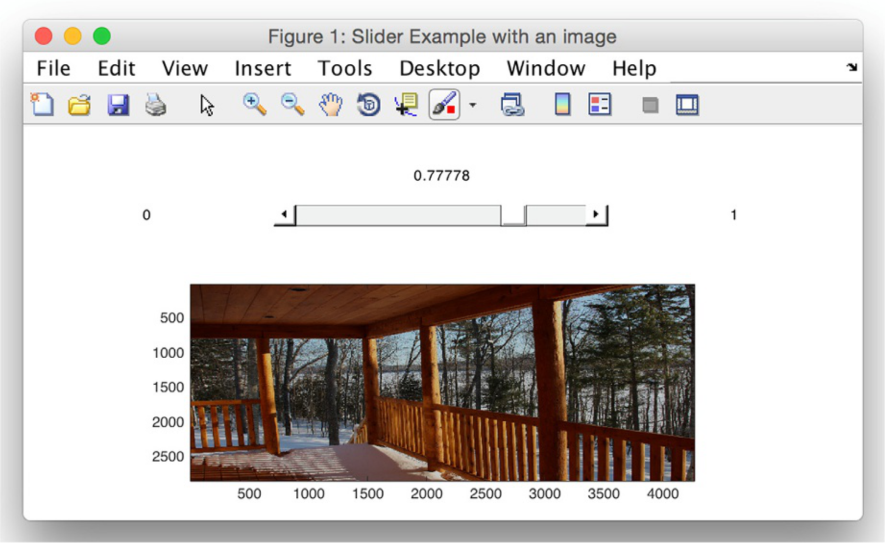


Figure 1: Slider Example with an image
File Edit View Insert Tools Desktop Window Help
0.77778
0
1
500
1000
1500
2000
2500
500
1000
1500
2000
2500
3000
3500
4000

FIGURE 13.23
GUI with an image and slider for brightness.

The function **uibuttongroup** creates a mechanism for grouping together the buttons. As only one button can be chosen at a time, there is a type of callback function called 'SelectionChangedFcn' that is called when a button is chosen (note: prior to R2014b, this was named 'SelectionChangeFcn').

This function gets from the button group which button is chosen with the 'SelectedObject' property. It then chooses the color based on this. This property is set initially to the empty vector, so that neither button is selected; the default is that the first button would be selected.

guiWithButtongroup.m

```
function guiWithButtongroup
% guiWithButtongroup has a button group with 2 radio buttons
% Format: guiWithButtongroup

% Create the GUI but make it invisible for now while
% it is being initialized
f = figure('Visible', 'off','Color','white','Units',...
    'Normalized', 'Position',[.2 .5 .4 .3]);

% Create a button group
group = uibuttongroup('Parent',f,'Units','Normalized',...
    'Position',[.2 .5 .4 .4], 'Title','Choose Color',...
    'SelectionChangedFcn',@whattodo);

% Put two radio buttons in the group
toph = uicontrol(group,'Style','radiobutton',...
    'String','Blue','Units','Normalized',...
    'Position', [.2 .7 .4 .2]);
```

```
both = uicontrol(grouph, 'Style','radiobutton',...
    'String','Green','Units','Normalized',...
    'Position',[.2 .4 .4 .2]);

% Put a static text box to the right
texth = uicontrol('Style','text','Units','Normalized',...
    'Position',[.6 .5 .3 .3],'String','Hello',...
    'Visible','off','BackgroundColor','white');

group.SelectedObject = []; % No button selected yet
f.Name = 'GUI with button group';
movegui(f,'center')

% Now the GUI is made visible
f.Visible = 'on';

    function whattodo(~, ~)
    % whattodo is called by the 'SelectionChangedFcn' property
    % in the button group

    which = get(grouph,'SelectedObject');

    if which == toph
        texth.ForegroundColor = 'blue';
    else
        texth.ForegroundColor = 'green';
    end

    texth.Visible = 'on';
    end

end
```

Figure 13.24 shows the initial configuration of the GUI: the button group is in place, as are the buttons (but neither is chosen).

Once a radio button has been chosen, the *whattodo* function chooses the color for the text, which is printed in a static text box on the right, as shown in Fig. 13.25.

13.3 APP DESIGNER

We have seen how to create GUI functions that include objects such as push buttons and sliders, and how to write callback functions that allow the user's actions to control what the code does. App Designer allows the user to graphically lay out similar objects, which are called ***components***. However, there are more types of components than what we had with GUIs, and the code that is generated is all object-based. Thus, the use of App Designer, which creates app classes derived from a superclass, will reinforce the OOP concepts covered in

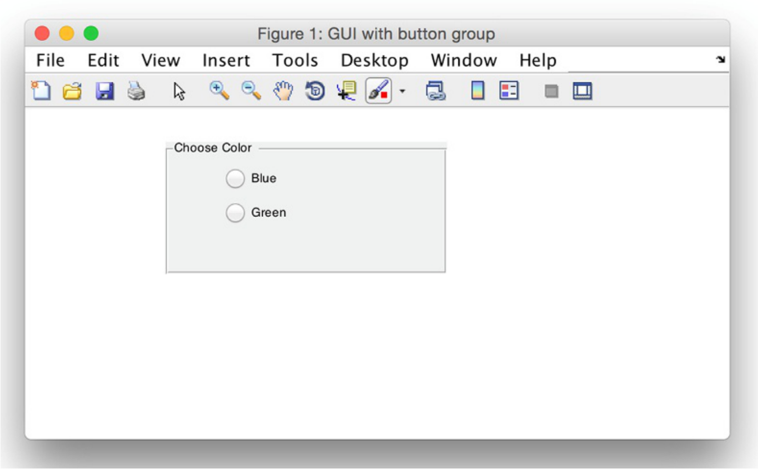


Figure 1: GUI with button group
File Edit View Insert Tools Desktop Window Help
Choose Color
○ Blue
○ Green

FIGURE 13.24
Button Group with Radio Buttons.

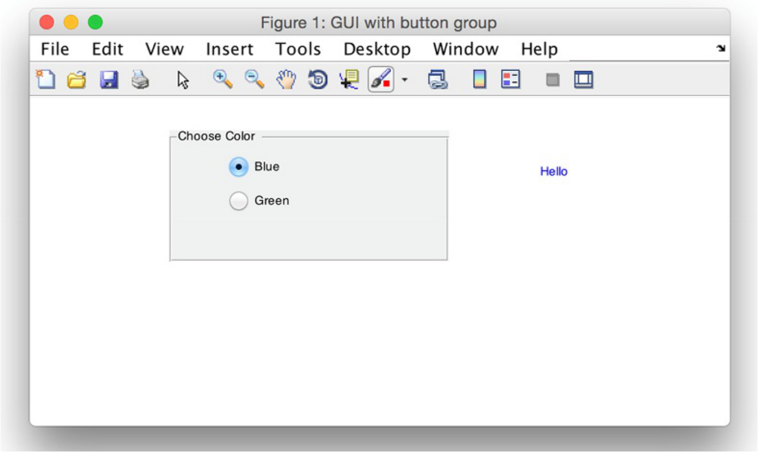


Figure 1: GUI with button group
File Edit View Insert Tools Desktop Window Help
Choose Color
● Blue
○ Green
Hello

FIGURE 13.25
Button Group: Choice of Color for Text.

Chapter 11. Also, App Designer creates UI Figure windows, whereas GUIs use Figure Windows.

13.3.1 Intro to App Designer

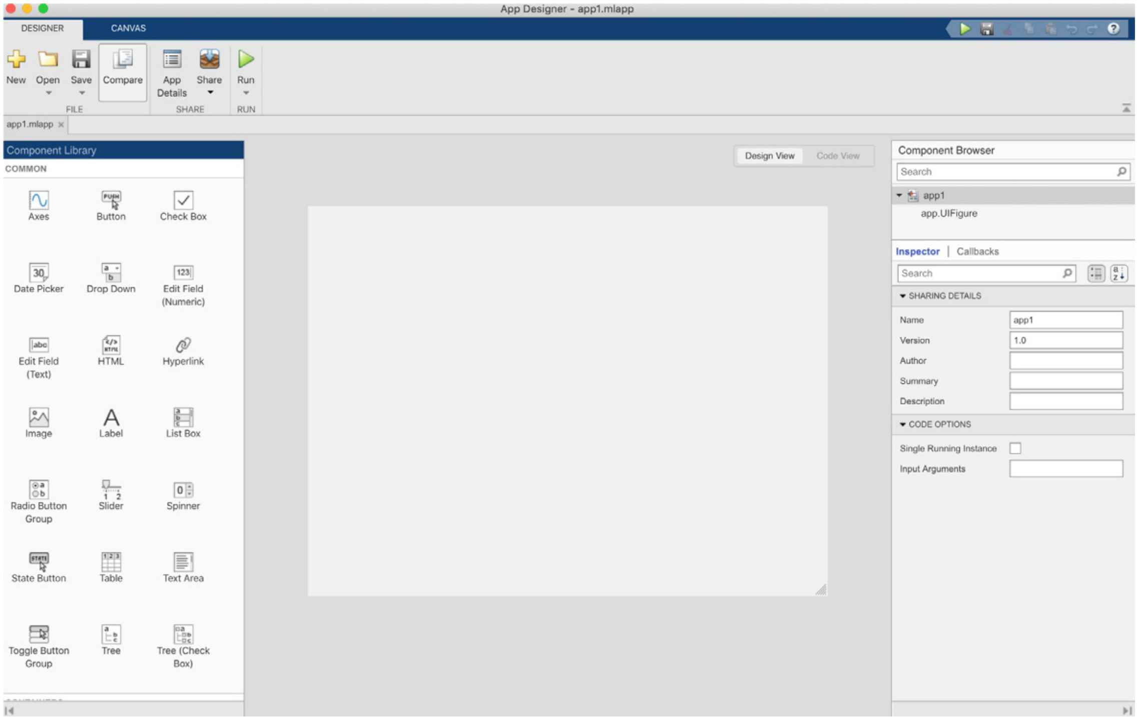
There are two ways to launch App Designer. You can click on Design Apps from the Apps tab. Typing the command **appdesigner** in the Command Window will also bring up App Designer.

```
>> appdesigner
```

The start page has tutorials, examples, and Recent Apps that you have created. To begin a new app, choose Blank App. Figure 13.26 shows the blank App Designer; in the middle is the blank layout under "Design View," which is called the ***canvas***. The Component Library on the left shows the icons of the components that can be created. On the right there is the Component Browser. In the Component Browser, the default name for the blank figure, *app.UIFigure*, can be seen.

On the top of the Component Library, the Common components can be seen (including axes, buttons, labels, sliders, and spinners). Scrolling down, one can see the remainder of the Component Library, including the Containers, Figure Tools, and Instrumentation components. The Containers include Grid Layout, Panel, and Tab Group. The Figure Tools include Context Menu, Menu Bar, and Toolbar. Finally, the Instrumentation Components include gauges, knobs, lamps, and switches.

Clicking on "Code View" instead of "Design View" shows the code that has been created for the blank app. App Designer creates a class named *app1* that is derived from a MATLAB apps superclass called **matlab.apps.AppBase**. The



Name app1
Version 1.0
Author
Summary
Description
Single Running Instance □
Input Arguments

FIGURE 13.26

App Designer layout.

properties will consist of all of the components; for now, there is just one property, which is the UI Figure Window. There is also a private methods block, and a public methods block.

```
classdef app1 < matlab.apps.AppBase
    % Properties that correspond to app components
    properties (Access = public)
        UIFigure matlab.ui.Figure
    end

    % Component initialization
    methods (Access = private)

        % Create UIFigure and components
        function createComponents(app)

    % Create UIFigure and hide until all components created
           app.UIFigure = uifigure('Visible', 'off');
           app.UIFigure.Position = [100 100 640 480];
           app.UIFigure.Name = 'MATLAB App';

           % Show the figure after all components are created
           app.UiFigure.Visible = 'on';
      end
    end

    %App creation and deletion
    methods (Access = public)

        % Construct app
        function app = app1()

            % Create UIFigure and components
            createComponents(app)

            % Register the app with App Designer
            registerApp(app, app.UIFigure)

            if nargout == 0
                clear app
            end
        end

        % Code that executes before app deletion
        function delete(app)

            % Delete UIFigure when app is deleted
            delete(app.UIFigure)
        end
    end
end
```

The methods are used for all of the app functions, including eventually callback functions. For now, with just a blank UI Figure Window, the public methods include the constructor function *app1*, and a function *delete* that deletes the figure when the app is deleted. The constructor calls a private function *createComponents*, which creates a UI Figure using the **uifigure** function. It then uses the dot notation to set properties for the *app.UIFigure*, including its *Name* and *Position*.

Note

that the dot notation is used twice here, as in *app.UIFigure.Name*.

Also, when Code View is in use, the Component Library no longer shows on the left. Instead, there is a Code Browser window on top, and an App Layout window on the bottom.

With just a blank canvas in Design View, none of the code in Code View is editable.

We have seen the code that is generated with just a blank canvas. In the Design View of the App Designer environment, components can be dragged from the Component Library onto the blank canvas. When this is done, the code will be updated to create a new property for each component, and to initialize some of its properties (for example, the Position property will be based on the location to which the component was dragged). Properties can then be modified in the Component Properties Window to the right of the layout.

For example, one can drag a Label (generically named 'Label'!) into the design area. Because clicking on the label in the Design View chooses the label, this brings up some of the label properties on the bottom right. Properties such as the text on the label, its justification, font name, font size, and so forth can then be modified. Each of these will modify the code that is created.

Assuming that no properties have been modified, and there is just a generic label in the canvas, most of the code remains the same as with just a blank UI Figure Window. Choosing Code View will show that the class *app1* now has a new property Label, and the *createComponents* method creates a Label using the **uilabel** function and gives it a Position. The added code is shown in bold here (not in App Designer itself).

```
classdef app1 < matlab.apps.AppBase
% Properties that correspond to app components
properties (Access = public)
    UIFigure matlab.ui.Figure
    Label    matlab.ui.control.Label
end

% Create UIFigure and components
    function createComponents(app)

        % Create Label
        app.Label = uilabel(app.UIFigure);
        app.Label.Position = [421 431 30 15];
    end
end
```

Modifying a property, such as changing the text of the label in the Label Properties window to be 'Hello' instead of 'Label' will modify the code in *createComponents* to:

```
% Create HelloLabel
app.HelloLabel = uilabel(app.UIFigure);
app.HelloLabel.Position = [421 431 30 15];
app.HelloLabel.Text = 'Hello';
```

Note
that the label object has been renamed.

To run the app, click on the green Run arrow. This brings up a dialog box that asks for the name of the file that will be created; the default name that shows is "app1.mlapp". Changing the name to "MyHelloLabel.mlapp" will create a file with this name and bring up a UI Figure Window.

App Designer creates one file with the extension '.mlapp'.

Although this example shows the basics of App Designer and the object-based code that it creates, it did not involve any callbacks.

13.3.2 UI Figure Functions

As we have seen in Section 13.2, traditional GUIs create different types of objects by specifying the Style property in the **uicontrol** function. For example, a slider is created with **uicontrol('Style', 'slider')**. By contrast, App Designer uses separate functions to create the different component types; for example, a slider is created with the **uislider** function. In the previous section, we saw two of these functions: **uifigure**, which creates the UI Figure Window, and **uilabel**, which creates a static text box.

Although typically these functions are only used within App Designer, all of these functions could actually be called directly from the Command Window or from any script or function. For example, the following code will bring up the UI Figure Window shown in Fig. 13.27.

```
>> uif = uifigure;
>> uif.Name = 'Simple UI Fig Slider';
>> uislid = uislider(uif);
```

By creating a UI Figure Window first, and then passing its handle to the **uislider** function, the slider is put inside of that UI Figure Window (otherwise, a new UI Figure Window would be created for the slider). The properties of the slider can be inspected, for example,

```
>> uislid
uislid =
  Slider (0) with properties:

               Value: 0
              Limits: [0 100]
          MajorTicks: [0 20 40 60 80 100]
     MajorTickLabels: {'0' '20' '40' '60' '80' '100'}
         Orientation: 'horizontal'
     ValueChangedFcn: ''
    ValueChangingFcn: ''
            Position: [100 100 150 3]

  Show all properties
```

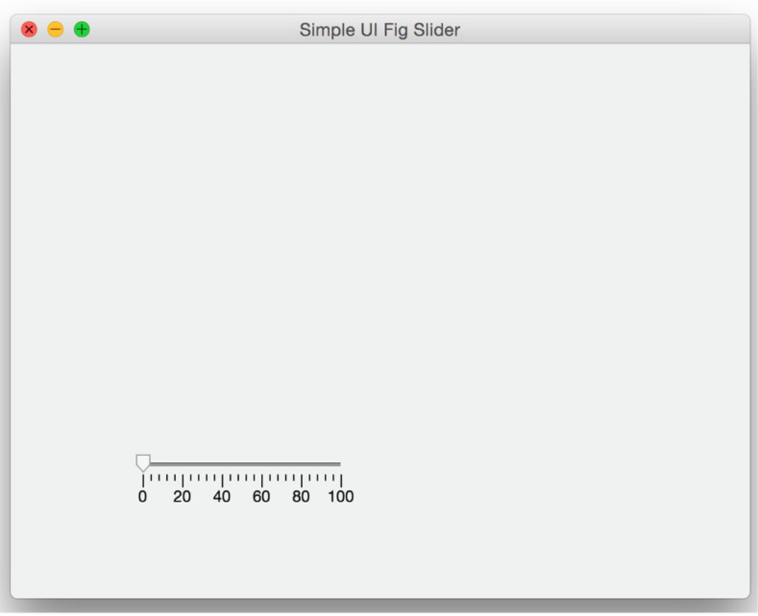


FIGURE 13.27
Simple slider in UI figure window.

For example, this shows that the value of the slider is 0. Of course, to do anything with the value of the slider would require more complicated code with callback functions. For sliders, there are two:

> 'ValueChangedFcn': executes when the slider value has been changed
> 'ValueChangingFcn': executes as the slider is being moved

For example, the function *uisliderulabel* creates a UI Figure Window with a slider and a label. When the slider has been moved, the 'ValueChangedFcn' callback is called, which puts the value of the slider in the label, as seen in Fig. 13.28. Many of the concepts here are similar to those used in GUI callbacks. The function *uisliderulabel* is a function that has a nested callback function, *whatslid*. Because the *whatslid* function is nested, the variable scope is such that the variables *uilab* and *uislid* can be used within the callback function without passing them. The callback function has two input arguments representing the source of the callback (in this case *uislid*) and the event, just like GUI callback functions.

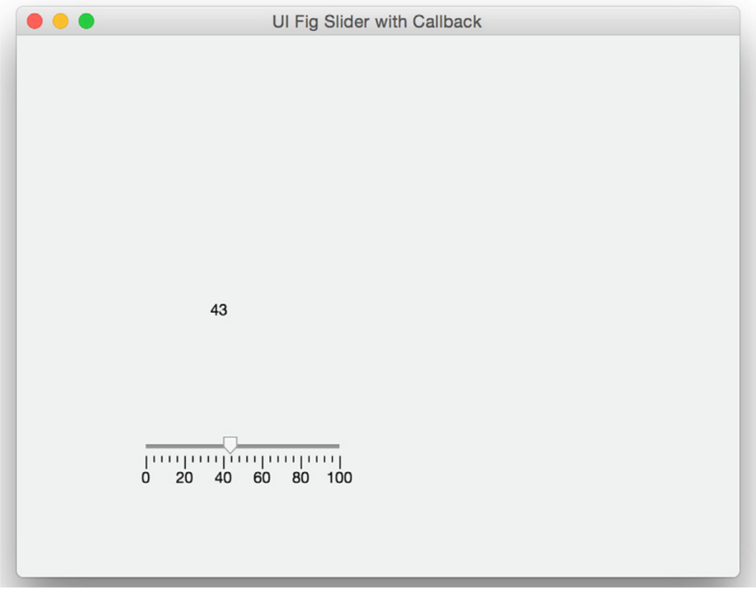


FIGURE 13.28
Slider with label example.

uisliderruilabel.m

```
function uisliderruilabel
uif = uifigure;
uif.Name = 'UI Fig Slider with Callback';
uislid = uislider(uif);
uilab = uilabel(uif,'Position',[150 200 30 15]);
uilab.Text = '0';

uislid.ValueChangedFcn = @whatslid;

function whatslid(source,event)
   uilab.Text = num2str(round(uislid.Value));
end
end
```

The list of UI functions that create object components can be found in the App Designer documentation. The documentation for each function describes the properties that can be used for each, including all of the possible callback functions. Of course, although these functions can be used programmatically as shown in this section, it is not at all common to do so; rather, these functions are used by App Designer.

13.3.3 App Designer Examples

An advantage of App Designer is that it will create much of the code automatically, and because it is based on objects, the private properties and methods protect the apps that are created.

As an example of an app that uses a callback, an app will be created that is similar to the previous example in which there is a slider and a label that shows the value of the slider. Therefore, in the Design view, a slider is dragged onto the canvas. Because it makes sense to label many components, such as sliders, App Designer automatically creates a label when the component is dragged into the design area. By default, the label is to the left of the slider. In Design View, because there is one component, the slider, the properties can be inspected and edited by clicking on the component (app.Slider) in the Component Browser.

The Code View shows that three properties have been created:

```
properties (Access = public)
    UIFigure matlab.ui.Figure
    Slider matlab.ui.control.Slider
    SliderLabel matlab.ui.control.Label
end
```

The constructor and other methods are similar to what was seen in a previous example. App Designer does not automatically create callback function stubs. Instead, on the top of the Component Browser, there is a choice of Inspector or Callbacks. Selecting the Callbacks tab brings up two possible callback functions. For example, enter the name "SliderValueChanged" for the *ValueChangedFcn*. This creates a new function, seen in Code View:

```
% Value changed function: Slider
function SliderValueChanged(app, event)
    value = app.Slider.Value;
end
```

In the function, an example is given that shows how to reference the Value property of the slider, but the function is editable. Most of the code has a gray background, but the white box in the *SliderValueChanged* function indicates that part of the function can be edited. Modifying the function body as follows will put the value of the slider in the label.

```
function SliderValueChanged(app, event)
    value = app.Slider.Value;
    app.SliderLabel.Text = num2str(round(value));
end
```

In Design View, clicking on either the slider or its label will change the Properties window. For example, clicking on the label and then Configuration under Label Properties allows one to change the initial label of "Slider" to "0", which is the initial value of the slider.

To change properties of any of the objects, one can click on the object name in the Component Browser. For example, clicking on "app.UIFigure" in the Component Browser shows the "UI Figure Properties". That allows us to change the title of the UI Figure Window, for example to "App with Slider". Do this by scrolling down to Identifiers, and change the Name Property.

When the app is executed, the app is saved. Name it "slidertest". After the slider has been moved, the UI Figure window seen in Fig. 13.29 is created.

Unless the slider label was modified, the generic label "Slider" will show up before the slider is moved. After that, the value of the slider will be shown in the label text box. One way to fix this is to create a particular type of callback function, a start-up function called *StartupFcn*, which can be used to specify what you want to happen when the app first runs. By clicking on *slidertest* in the Component Browser, and choosing Callbacks, a name can be given for the *StartupFcn*. For example, if it is named *StartMeUp*, this will appear in the Code View. It is editable, so a line can be added that initializes the slider label to an empty character vector.

```
% Code that executes after component creation
function StartMeUp(app)
    app.SliderLabel.Text = '';
end
```

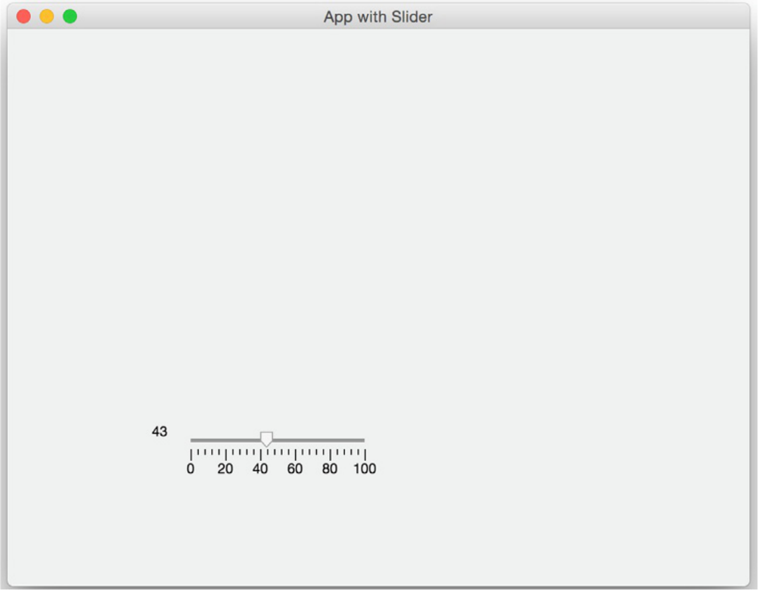


FIGURE 13.29
App with slider and label.

The *ValueChangedFcn* only executes when the slider has stopped moving. By contrast, another callback function, the *ValueChangingFcn*, can specify what to do while the slider is being changed. Notice that while the slider is changing, the Value property is obtained from the *event* input parameter.

```
% Value changing function: Slider
function SliderValueChanging(app, event)
    cv = event.Value;
    app.SliderLabel.Text = num2str(round(cv));
    app.SliderLabel.FontColor = [1 0 0];
end
```

Putting plots into apps uses a method that is very similar to GUIs: it is necessary to first drag axes into the design layout, and then any plot will be placed within the axes. For example, code was created by dragging axes into the canvas, and also a push button. The pushbutton was named Plot! A callback function was created for the push button, as follows:

```
% Button pushed function: PlotButton
function PlotButtonPushed(app, event)
    x = -pi:0.1:pi;
    y = sin(x);
    plot(app.UIAxes, x, y, '*')
end
```

Thus, when the push button is pushed, the sin plot shows in the axes. App Designer creates x, y, and z labels and a title by default.

In Code View, in between the line numbers and the code, there are boxes with dashes in them for all code blocks. Clicking on one will collapse that code display, and turn the dash into a plus (which allows the code to be expanded). App Designer code can get long, so this is a convenient way to display only the code that you are interested in seeing. This is new as of R2018b.

13.4 SOUND FILES

A ***sound wave*** is an example of a continuous signal that can be sampled to result in a discrete signal. In this case, sound waves traveling through the air are recorded as a set of measurements that can then be used to reconstruct the original sound signal, as closely as possible. The sampling rate, or ***sampling frequency***, is the number of samples taken per time unit, for example per second. Sound signals are usually measured in Hertz (Hz).

In MATLAB, the discrete sound signal is represented by a vector and the frequency is measured in Hertz. MATLAB has several MAT-files that store for various sounds the signal vector in a variable *y* and the frequency in a variable *Fs*. These MAT-files include **chirp**, **gong**, **laughter**, **splat**, **train**, and **handel**. There is a built-in function, **sound**, that will send a sound signal to an output device such as speakers.

The function call:

```
>> sound(y,Fs)
```

will play the sound represented by the vector *y* at the frequency *Fs*. For example, to hear a gong, load the variables from the MAT-file and then play the sound using the **sound** function:

```
>> load gong
>> sound(y,Fs)
```

Sound is a wave; the amplitudes are what are stored in the sound signal variable *y*. These are supposed to be in the range from −1 to 1. The **plot** function can be used to display the data. For example, the following script creates a **subplot** that displays the signals from **chirp** and from **train**, as shown in Fig. 13.30.

chirptrain.m

```
% Display the sound signals from chirp and train
subplot(2,1,1)
load chirp
plot(y)
ylabel('Amplitude')
title('Chirp')
subplot(2,1,2)
load train
plot(y)
ylabel('Amplitude')
title('Train')
```

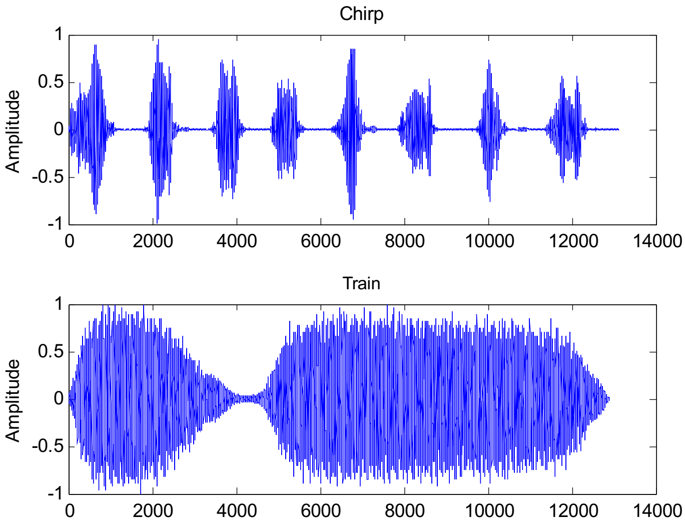


FIGURE 13.30

Amplitudes from **chirp** and **train**.

The first argument to the **sound** function can be an *n x 2* matrix for stereo sound. Also, the second argument can be omitted when calling the **sound** function, in which case the default sample frequency of 8192 Hz is used. This is the frequency stored in the built-in sound MAT-files.

```
>> load train
Fs
Fs =
   8192
```

For more control over playing sound files, an **audioplayer** object can be created using the **audioplayer** function, and then the sound can be played with the **play** function. For example:

```
>> load handel
>> pl = audioplayer(y,Fs)
>> play(pl)
```

If you have a microphone built in to your computer, or some other audio input device, you can record sound from it, and play it back using the **play** function. First, an **audiorecorder** object is created, and then the audio input is recorded for a specified block of time using the **recordblocking** method. For example, the following creates an **aurdiorecorder** object *myvoice*, and records from the microphone for 3 seconds, and then plays it back.

```
>> myvoice = audiorecorder;
>> recordblocking(myvoice, 3)
>> play(myvoice);
```

The **getaudiodata** function can be used to get the amplitude vector of the audio, so for example it could be plotted.

```
>> y = getaudiodata(myvoice);
```

PRACTICE 13.5

If you have speakers, try loading one of the sound MAT-files and use the **sound** function to play the sound. Then, change the frequency; for instance, multiply the variable *Fs* by 2 and by 0.5, and play these sounds again.

```
>> load train
>> sound(y, Fs)
>> sound(y, Fs*2)
>> sound(y, Fs*.5)
```

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Bias in Data Sets

If the training and testing sets are not representative of the entire population, then the data will be biased, and the model will not be adequately prepared to make predictions for the population. This can be a very serious problem. There are some rather infamous cases of this in image processing ML data sets (for facial recognition, for example). For example, if you are trying to build a model that will be able to distinguish between images of cats and dogs, and your training set has 1000 images of dogs but only 50 images of cats, the model will be much more adept at identifying dogs than cats. But, if most of the 1000 dog images are of beagles, the model will likely have trouble identifying other types of dogs. This is true not just for image processing. For all types of ML models, it is imperative that the data set represents the population as a whole.

Built-in Image Files

There are several built-in image files that can be used in MATLAB. Some are built in as .jpg files, e.g., 'street1.jpg'. Others are .mat files that store variables. For example, the file cape.mat stores three variables:

```
>> clear
>> load cape.mat
>> whos
  Name        Size          Bytes        Class       Attributes

  X           360x360       1036800      double
  caption     2x55          220          char
  map         192x3         4608         double
>> caption
caption =
  255 char array
    'NOAA altitude data for New England, including Cape Cod.'
    'Pseudocolor map uses blue for zero altitude.
```

The variable *X* is the image matrix, and *map* is a colormap with 192 colors. To view it, the function **imshow**(X, map) can be used, which does not show indices, unlike **image**.

Scrubbing Image Data

Image matrices are large, so it is very important when building a data set of images to cut down on the size wherever possible. Here is an image that uses the RGB method.

```
>> streetimage = imread('street1.jpg');
>> size(streetimage)
ans =
    480   640     3
>> image(streetimage)
```

The image shows a street with cars and trucks, and buildings on both sides of the street.

Cropping an image is one possibility. If, for example, we are only interested in the traffic on the street, we might crop out a lot of the image.

```
>> cropped = streetimage(150:250, 150:420, :);
>> image(cropped)
```

Now we have a much smaller image matrix, but we lose quality in the image by doing this!

If color is not important, another possibility is to convert the color image to grayscale, using the **rgb2gray** function:

```
>> gs = rgb2gray(cropped);
>> size(gs)
ans =
    101    271
```

The **rgb2gray** function takes the three-dimensional image matrix, which stores the Red, Green, and Blue components of each pixel, and converts it to a two-dimensional intensity image. The numbers stored for each pixel are a weighted combination of the numbers from the original RGB matrix. Therefore, the number of rows and columns of the matrix are not changed, but the dimensionality is reduced from three to two.

■ Explore Other Interesting Features

Several ***audio file formats*** are used in industry on different computer platforms. Audio files with the extension ".au" were developed by Sun Microsystems; typically, they are used with Java and Unix, whereas Windows PCs typically use ".wav" files that were developed by Microsoft. Investigate the MATLAB functions **audioread**, **audioinfo**, and **audiowrite**.

Investigate the **colorcube** function, which returns a colormap with regularly spaced R, G, and B colors.

Investigate the **imfinfo** function, which will return information about an image file in a structure variable.

Investigate how colormaps work with image matrices of types **uint8** and **uint16**.

In addition to true-color images and indexed images into a colormap, a third type of image is an intensity image, which is used frequently for grayscale images. Investigate how to use the image scale function **imagesc**.

The **uibuttongroup** function is used specifically to group together buttons; other objects can be grouped together similarly using the **uipanel** function. Investigate how this works.

When a GUI has a lot of objects, creating a structure to store the handles can be useful. Investigate the **guihandles** function, which accomplishes this.

Investigate the **uitable** function. Use it to create a GUI that demonstrates a matrix operation. ■

SUMMARY

COMMON PITFALLS

- Confusing true-color and colormap images
- Forgetting that **uicontrol** object positions are within the Figure Window, not within the screen

PROGRAMMING STYLE GUIDELINES

- Make a GUI invisible while it is being created, so that everything becomes visible at once.

MATLAB Functions and Commands		
colormap	imshow	uislider
parula	uipanel	sound
jet	uibuttongroup	audioplayer
turbo	uicontrol	play
image	movegui	audiorecorder
pink	appdesigner	recordblocking
imread	uifigure	getaudiodata
imwrite	uilabel	

MAT-Files		
chirp	laughter	train
gong	splat	handel

Exercises

1. Create a custom colormap for a sphere that consists of the first 150 colors in the colormap **turbo**. Display **sphere(150)** with a colorbar.
2. Write a function *numimage* that will receive two input arguments: a colormap matrix, and an integer *n*; the function will create an image that shows *n* "rings"

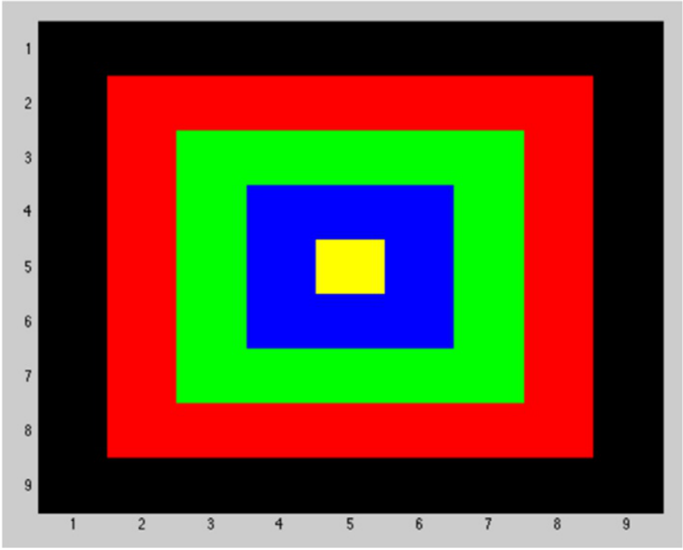

FIGURE 13.31
Color rings.

of color, using the first *n* colors from the colormap. For example, if the function is called as follows:

```
>> cm = [0 0 0; 1 0 0; 0 1 0; 0 0 1; ...
1 1 0; 1 0 1; 0 1 1];
>> numimage(cm,5)
```

the image as seen in Fig. 13.31 will be created.

Each "ring" has the thickness of one pixel. In this case, because n was 5, the image shows the first five colors from the colormap: the outermost ring is the first color, the next ring is the second color, and the innermost pixel is the fifth color. Note that, because n was 5, the image matrix is 9*9.

3. Write a script that would produce the 12 × 12 image seen in Fig. 13.32 using the RGB, or true-color method (NOT the colormap method), and using the type **uint8** for the pixels in the image. Note that the axes are the defaults. Do not use any loops; vectorize your code.
4. A script *rancolors* displays random colors in the Figure Window as shown in Fig. 13.33. It starts with a variable *nColors* which is the number of random colors to display (e.g., below this is 10). It then creates a colormap variable *mycolormap*, which has that many random colors, meaning that all three of the color components (red, green, and blue) are random real numbers in the range from 0 to 1. The script then displays these colors in an image in the Figure Window.

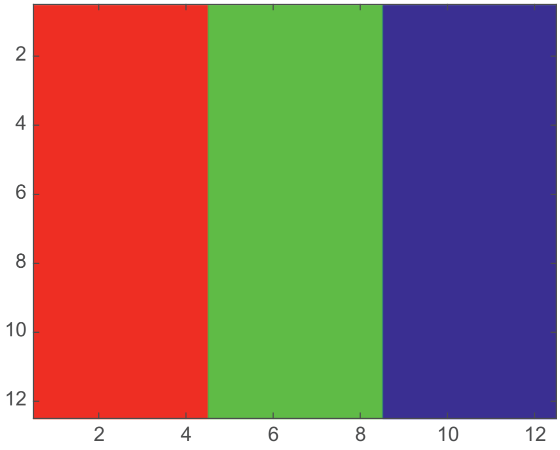

FIGURE 13.32
Red, green, blue stripes.

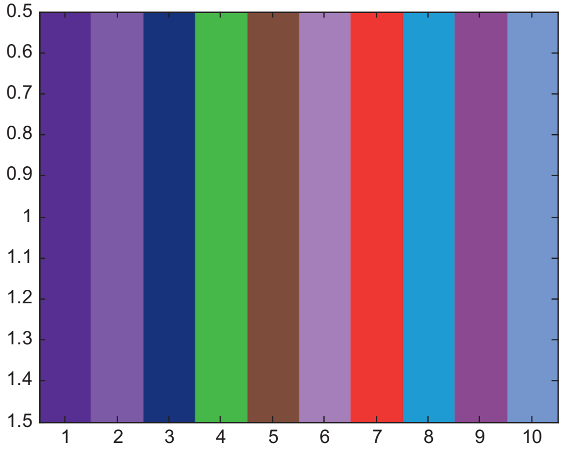

FIGURE 13.33
Rainbow of random colors.

5. It is sometimes difficult for the human eye to perceive the brightness of an object correctly. For example, in Fig. 13.34, the middle of both images is the same color, and yet, because of the surrounding colors, the one on the left looks lighter than the one on the right.

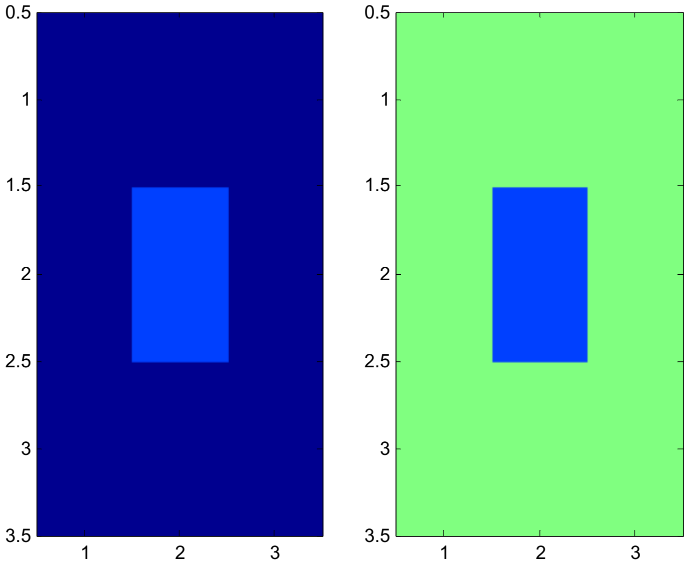

FIGURE 13.34
Depiction of brightness perception.

Write a script to generate a Figure Window similar to this one. Two *3* × *3* matrices were created. Use **subplot** to display both images side by side (the axes shown here are the defaults). Use the RGB method.

6. Put a JPEG file in your Current Folder and use **imread** to load it into a matrix. Calculate and print the **mean** separately of the red, green, and blue components in the matrix.
7. Some image acquisition systems are not very accurate, and the result is ***noisy*** images. To see this effect, put a JPEG file in your Current Folder and use **imread** to load it. Then, create a new image matrix by randomly adding or subtracting a value *n* to every element in this matrix. Experiment with different values of *n*. Create a script that will use **subplot** to display both images side by side.
8. Put a JPEG file into your Current Folder. Type in the following script, using your own JPEG file name.

```
I1 = imread('xxx.jpg');
[r c h] = size(I1);
Inew(:,:,:) = I1(:,c:-1:1,:);
figure(1)
subplot(2,1,1)
image(I1);
subplot(2,1,2)
image(Inew);
```

   Determine what the script does. Put comments into the script to explain it step-by-step.
9. Put a JPEG file into your Current Folder. Write a script that will read from this image file into a matrix, and create a new yellowed version of the image which consists of only the red and green parts of the original image. The script displays the images side-by-side in one Figure Window.
10. Load the built-in image stored in the file *earth.mat*. Which method is used, RGB or a colormap?
11. Load the built-in image stored in *mandrill.mat*. How many colors are used in its colormap?
12. Write a function that will create a GUI with one editable text box near the middle of the Figure Window. Put your name in the string. The GUI should have a callback function that prints the user's string twice, one under the other.
13. Write a function that creates a GUI to calculate the area of a rectangle. It should have edit text boxes for the length and width, and a push button that causes the area to be calculated and printed in a static text box.
14. Write a function that creates a simple calculator with a GUI. The GUI should have two editable text boxes in which the user enters numbers. There should be four pushbuttons to show the four operations (+, −, *, /). When one of the four pushbuttons is pressed, the type of operation should be shown in a static text box between the two editable text boxes and the result of the operation should

be displayed in a static text box. If the user tries to divide by zero, display an error message in a static text box.

15. Modify any example GUI to use the 'HorizontalAlignment' property to left-justify text within an edit text box.
16. The Wind Chill Factor (WCF) measures how cold it feels with a given air temperature T (in degrees Fahrenheit) and wind speed (V, in miles per hour). The formula is approximately

$$\mathrm{WCF} = 35.7 + 0.6\,\mathrm{T} - 35.7\left(\mathrm{V}^{0.16}\right) + 0.43\,\mathrm{T}\left(\mathrm{V}^{0.16}\right)$$

    Write a GUI function that will display sliders for the temperature and wind speed. The GUI will calculate the WCF for the given values, and display the result in a text box. Choose appropriate minimum and maximum values for the two sliders.
17. Write a GUI function that will graphically demonstrate the difference between a **for** loop and a **while** loop. The function will have two push buttons: one that says 'for', and the other says 'while'. There are two separate callback functions, one associated with each of the pushbuttons. The callback function associated with the 'for' button prints the integers 1 through 5, using **pause(1)** to pause for 1 second between each, and then prints 'Done.' The callback function associated with the 'while' button prints integers beginning with 1 and also pauses between each. This function, however, also has another pushbutton that says 'mystery' on it. This function continues printing integers until the 'mystery' button is pushed, and then it prints 'Finally!'.
18. Write a function that will create a GUI in which there is a plot of cos(x). There should be two editable text boxes in which the user can enter the range for x.
19. Write a GUI function that will create a rectangle object. The GUI should have two sliders to control the two numbers used in the Curvature of a rectangle (first the horizontal and then the vertical), and every time a slider is moved, it displays that rectangle (with all of the others still there).
20. Write a GUI that displays an image in which all of the elements are the same color. Put three sliders in that allow the user to specify the amount of red, green, and blue in the image. Use the RGB method.
21. Put two different JPEG files into your Current Folder. Read both into matrix variables. To superimpose the images, if the matrices are the same size, the elements can simply be added element-by-element. However, if they are not the same size, one method of handling this is to crop the larger matrix to be the same size as the smaller, and then add them. Write a script to do this.
22. Create an app that has a knob and a lamp. When the knob value goes past 50, the lamp color should change to red.
23. Create an app that has all three varieties of switches in it, and a label. The label should display the type of the switch that was most recently changed.

24. Use App Designer to create a text editor. Create an app that has a large text box. Under it there will be a slider that controls the font size of the text, and buttons to make the text bold and/or italic. Start by dragging a text box into the design area. Click on the box, and then in Design View look at the Edit Field (Text) Properties browser. By changing properties such as the style, Name, and Size, and then inspecting the code in Code View, you can see what to change in the callback functions.
25. Create a stoplight app. There are two pushbuttons labeled 'Stop' and 'Go', and three lamps. When the 'Go' button is pushed, the green lamp is lit. When the 'Stop' button is pushed, the yellow lamp is lit briefly, and then the red lamp is lit.
26. Load two of the built-in MAT-file sound files (e.g., **gong** and **chirp)**. Store the sound vectors in two separate variables. Determine how to concatenate these so that the **sound** function will play one immediately followed by the other; fill in the blank here:

```
sound(        , 8192)
```

27. The following function *playsound* below plays one of the built-in sounds. The function has a cell array that stores the names. When the function is called, an integer is passed, which is an index into this cell array indicating the sound to be played. The default is 'train', so if the user passes an invalid index, the default is used. The appropriate MAT-file is loaded. If the user passes a second argument, it is the frequency at which the sound should be played (otherwise, the default frequency is used). The function prints what sound is about to be played and at which frequency, and then actually plays this sound. You are to fill in the rest of the following function. Here are examples of calling it (you cannot hear it here, but the sound will be played!)

```
>> playsound(-4)
You are about to hear train at frequency 8192.0
>> playsound(2)
You are about to hear gong at frequency 8192.0
>> playsound(3,8000)
You are about to hear laughter at frequency 8000.0
playsound.m
function playsound(caind, varargin)
% This function plays a sound from a cell array
% of mat-file names
% Format playsound(index into cell array) or
% playsound(index into cell array, frequency)
% Does not return any values

soundarray = {'chirp','gong','laughter','splat','train'};
if caind < 1 || caind > length(soundarray)
    caind = length(soundarray);
end
mysound = soundarray{caind};
eval(['load ' mysound])

% Fill in the rest
```

28. Create a **bar** chart using the following:

    ```
    >> mat = randi(33, 2,3);
    >> bm = bar(mat);
    ```

    Try to duplicate the three colors. Check your answers by examining the properties bm(1).FaceColor, bm(2).FaceColor, and bm(3).FaceColor.
29. Create an audioplayer object using the built-in laughter MAT-file. Investigate some of the properties of the object.
30. If you have a built-in microphone, record your voice for 5 seconds and plot the resulting amplitude vector.
31. Load the sound file 'mtlb.mat', which stores the sound vector *y* and frequency *Fs* of a person saying the word "MATLAB". Plot this, and from the plot estimate the part that says "MAT" and the part that says "LAB". In a script, create two separate vectors for these. Using the **sound** function in a **for** loop, repeat the "MAT" sound four times, pausing for half a second after each one. Then, do the "LAB" sound once.

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32. Load the built-in image file *flujet.mat.* Make the *map* variable the current colormap, and show the image matrix *X* using the **image** function so that you can see the indices. There is a lot of dark blue background! Crop out as much of that as you can, creating a new image matrix *xnew*. Use **whos** to see the number of bytes of storage used by the original matrix and your cropped image matrix.
33. Read in the built-in image 'peppers.png' using **imread**. Use **rgb2gray** to convert the image to gray scale and display the new image.

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CHAPTER 14

Advanced Mathematics

KEY TERMS

symbolic mathematics
set operations
complex number
real part
imaginary part
purely imaginary
complex conjugate
magnitude
complex plane
linear algebraic equation
matrix inverse
matrix augmentation
coefficients
unknowns
determinant
Gauss-Jordan method
reduced row echelon form
integration
differentiation

CONTENTS

In this chapter, selected advanced mathematical concepts and related built-in functions in the MATLAB® software are introduced. This chapter begins with coverage of set operations that can be performed on data sets.

Other topics include complex numbers and a brief introduction to differentiation and integration in calculus. ***Symbolic mathematics*** means doing mathematics on symbols. Some of the symbolic math functions, all of which are in Symbolic Math Toolbox™ in MATLAB, are also introduced. (Note that this is a Toolbox and, as a result, may not be available universally.)

Solutions to sets of linear algebraic equations are important in many applications. To solve systems of equations using MATLAB, there are basically two methods, both of which are covered in this chapter: using a matrix representation and using the **solve** function (which is part of Symbolic Math Toolbox™).

Note: Two sections that were in this Chapter are now covered in the Machine Learning Supplements at the ends of chapters: Statistics in Chapters 2 and 10, and Curve Fitting in Chapter 12 and this chapter.

14.1 SET OPERATIONS

MATLAB has several built-in functions that perform ***set operations*** on vectors. These include **union**, **intersect**, **unique**, **setdiff**, and **setxor**. All of these

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00014-7

functions can be useful when working with data sets. By default, all returned vectors are sorted from lowest to highest (ascending order). These set functions also provide the option of having the results in sorted order or in the original order. Additionally, there are two "is" functions that work on sets: **ismember** and **issorted**.

For example, given the following vectors:

```
>> v1=6:-1:2
   6      5      4      3      2
>> v2=1:2:7
v2=
   1      3      5      7
```

The **union** function returns a vector that contains all of the values from the two input argument vectors, without repeating any.

```
>> union(v1,v2)
ans=
    1      2      3      4      5      6      7
```

By default, the result is in sorted order, so passing the arguments in the reverse order would not affect the result. This is the same as calling the function as:

```
>> union(v1,v2, 'sorted')
```

If, instead, the character vector 'stable' is passed to the function, the result would be in the original order; this means that the order of the arguments would affect the result.

```
>> union(v1,v2,'stable')
ans=
    6      5      4      3      2      1      7
>> union(v2,v1,'stable')
ans=
    1      3      5      7      6      4      2
```

The **intersect** function instead returns all of the values that can be found in both of the two input argument vectors.

```
>> intersect(v1,v2)
ans=
     3      5
```

The **setdiff** function receives two vectors as input arguments and returns a vector consisting of all of the values that are contained in the first vector argument but not the second. Therefore, the result that is returned (not just the order) will depend on the order of the two input arguments.

```
>> setdiff(v1,v2)
ans=
     2      4      6
>> setdiff(v2,v1)
ans=
     1      7
```

The function **setxor** receives two vectors as input arguments and returns a vector consisting of all of the values from the two vectors that are not in the intersection of these two vectors. In other words, it is the union of the two vectors obtained using **setdiff** when passing the vectors in different orders, as seen before.

```
>> setxor(v1,v2)
ans=
     1       2       4       6       7
>> union(setdiff(v1,v2), setdiff(v2,v1))
ans=
     1       2       4       6       7
```

The set function **unique** returns all of the unique values from a set argument:

```
>> v3=[1:5 3:6]
v3=
     1       2       3       4       5       3       4       5       6
>> unique(v3)
ans=
     1       2       3       4       5       6
```

All of these functions—**union**, **intersect**, **unique**, **setdiff**, and **setxor**—can be called with 'stable' to have the result returned in the order given by the original vector(s).

Many of the set functions return vectors that can be used to index into the original vectors as optional output arguments. For example, the two vectors *v1* and *v2* were defined previously as:

```
>> v1
v1=
     6       5       4       3       2
>> v2
v2=
     1       3       5       7
```

The **intersect** function returns, in addition to the vector containing the values in the intersection of *v1* and *v2*, an index vector into *v1*, and an index vector into *v2* such that *outvec* is the same as *v1(index1)* and also *v2(index2)*.

```
>> [outvec, index1, index2]=intersect(v1,v2)
outvec=
     3       5
index1=
     4
     2
index2=
     2
     3
```

Using these vectors to index into *v1* and *v2* will return the values from the intersection. For example, this expression returns the second and fourth elements of *v1* (it puts them in ascending order):

```
>> v1(index1)
ans =
     3     5
```

This returns the second and third elements of *v2*:

```
>> v2(index2)
ans =
     3     5
```

The function **ismember** receives two vectors as input arguments and returns a **logical** vector that is the same length as the first argument, containing **logical** 1 for **true** if the element in the first vector is also in the second, or **logical** 0 for **false** if not. The order of the arguments matters for this function.

```
>> v1
v1=
     6     5     4     3     2
>> v2
v2=
     1     3     5     7
>> ismember(v1,v2)
ans=
     0     1     0     1     0
>> ismember(v2,v1)
ans=
     0     1     1     0
```

Using the result from the **ismember** function as an index into the first vector argument will return the same values as the **intersect** function (although not necessarily sorted).

```
>> logv=ismember(v1,v2)
logv=
    0     1     0     1     0
>> v1(logv)
ans=
    5     3

>> logv=ismember(v2,v1)
logv=
    0     1     1     0
>> v2(logv)
ans=
    3     5
```

The **issorted** function will return **logical** 1 for **true** if the argument is sorted in ascending order, or **logical** 0 for **false** if not.

```
>> v3=[1:5 3:6]
v3=
     1     2     3     4     5     3     4     5     6
```

```
>> issorted(v3)
ans=
     0

>> issorted(v2)
ans=
     1
```

PRACTICE 14.1

Create two vector variables *vec1* and *vec2* that contain five random integers, each in the range from 1 to 20. Do each of the following operations by hand first and then check in MATLAB (if you have one of the latest versions, do this with both 'stable' and 'sorted'):

- union
- intersection
- setdiff
- setxor
- unique (for each)

14.2 COMPLEX NUMBERS

A ***complex number*** is generally written in the form

```
z=a+bi
```

where a is called the ***real part*** of the number z, b is the ***imaginary part*** of z, and i is $\sqrt{-1}$.

Note that this is the way mathematicians usually write a complex number; in engineering it is often written as a + bj, where j is $\sqrt{-1}$.

A complex number is ***purely imaginary*** if it is of the form z = bi (in other words if *a* is 0).

We have seen that in MATLAB both **i** and **j** are built-in functions that return $\sqrt{-1}$ (therefore, they can be thought of as built-in constants). Complex numbers can be created using **i** or **j**, such as "5 + 2i" or "3 – 4j". The multiplication operator is not required between the value of the imaginary part and the constant **i** or **j**.

QUICK QUESTION!

Is the value of the expression "3i" the same as "3*i"?

Answer: It depends on whether *i* has been used as a variable name or not. If *i* has been used as a variable (e.g., an iterator variable in a **for** loop), then the expression "3*i" will use the defined value for the variable and the result will not be a complex number. The expression "3i" will always be complex. Therefore, it is a good idea when working with complex numbers to use 1**i** or 1**j** rather than just **i** or **j**. The expressions 1**i** and 1**j** always result in a complex number, regardless of whether *i* and *j* have been used as variables. Therefore, use "3*1i" or "3i".

```
>> i=5;

>> i
i=
   5
>> 1i
ans=
        0+1.0000i
```

MATLAB also has a function **complex** that will return a complex number. It receives two numbers, the real and imaginary parts in that order, or just one number, which is the real part (in which case the imaginary part would be 0). Here are some examples of creating complex numbers in MATLAB:

```
>> z1=4+2i
z1=
  4.0000+2.0000i

>> z2=sqrt(-5)
z2=
      0+2.2361i

>> z3=complex(3,-3)
z3=
  3.0000-3.0000i

>> z4=2+3j
z4=
  2.0000+3.0000i

>> z5=(-4) ^ (1/2)
ans=
  0.0000+2.0000i

>> myz=input('Enter a complex number: ')
Enter a complex number: 3+4i
myz=
  3.0000+4.0000i
```

Note that even when **j** is used in an expression, **i** is used in the result. MATLAB shows the type of the variables created here in the Workspace Window as **double (complex)**, or by using **whos** as **double** with the attribute complex. MATLAB has functions **real** and **imag** that return the real and imaginary parts of complex numbers.

```
>> real(z1)
ans=
    4

>> imag(z3)
ans=
   -3
```

To print an imaginary number, the **disp** function will display both parts automatically:

```
>> disp(z1)
   4.0000+2.0000i
```

The **fprintf** function will print only the real part unless both parts are printed separately:

```
>> fprintf('%f\n', z1)
4.000000

>> fprintf('%f+%fi\n', real(z1), imag(z1))
4.000000+2.000000i
```

The function **isreal** returns **logical** 1 for **true** if there is no imaginary part of the argument or **logical** 0 for **false** if the argument does have an imaginary part (even if it is 0). For example,

```
>> isreal(z1)
ans=
     0

>> z6=complex(3)
z5=
     3

>> isreal(z6)
ans=
     0

>> isreal(3.3)
ans=
     1
```

For the preceding variable *z6*, even though it shows the answer as 3, it is really stored as 3 + 0i, and that is how it is displayed in the Workspace Window. Therefore, **isreal** returns **logical false** as it is stored as a complex number.

14.2.1 Equality for Complex Numbers

Two complex numbers are equal to each other if both their real parts and imaginary parts are equal. In MATLAB, the equality operator can be used.

```
>> z1 == z2
ans=
     0

>> complex(0,4) == sqrt(-16)
ans=
     1
```

14.2.2 Adding and Subtracting Complex Numbers

For two complex numbers z1 = a + bi and z2 = c + di,

```
z1 + z2 = (a + c) + (b + d)i

z1 - z2 = (a - c) + (b - d)i
```

As an example, we will write a function in MATLAB to add two complex numbers together and return the resulting complex number.

THE TRADITIONAL METHOD

In most cases, to add two complex numbers together, you would have to separate the real and imaginary parts and add them to return your result.

```
addcomp.m
```

```
function outc=addcomp(z1, z2)
% addcomp adds two complex numbers z1 and z2 &
%   returns the result
% Adds the real and imaginary parts separately
% Format: addcomp(z1,z2)

realpart=real(z1)+real(z2);
imagpart=imag(z1)+imag(z2);
outc=realpart+imagpart*1i;
end
```

```
>> addcomp(3+4i, 2-3i)
ans=
   5.0000+1.0000i
```

THE EFFICIENT METHOD

MATLAB does this automatically to add two complex numbers together (or subtract).

```
>> z1=3+4i;
>> z2=2-3i;
>> z1+z2
ans=
   5.0000+1.0000i
```

14.2.3 Multiplying Complex Numbers

For two complex numbers z1 = a + bi and z2 = c + di,

```
z1*z2=(a+bi)*(c+di)
     =a*c+a*di+c*bi+bi*di
     =a*c+a*di+c*bi - b*d
     =(a*c - b*d)+(a*d+c*b)i
```

For example, for the complex numbers

```
z1=3+4i
z2=1-2i
```

the result of the multiplication would be defined mathematically as

```
z1*z2=(3*1--8)+(3*-2+4*1)i=11-2i
```

This is, of course, automatic in MATLAB:

```
>> z1*z2
ans=
  11.0000-2.0000i
```

14.2.4 Complex Conjugate and Absolute Value

The ***complex conjugate*** of a complex number $z = a + bi$ is $\bar{z} = a - bi$. The ***magnitude*** or absolute value of a complex number z is $|z| = \sqrt{a^2 + b^2}$. In MATLAB, there is a built-in function **conj** for the complex conjugate, and the **abs** function returns the absolute value.

```
>> z1=3+4i
z1=
  3.0000+4.0000i

>> conj(z1)
ans=
  3.0000-4.0000i

>> abs(z1)
ans=
     5
```

14.2.5 Complex Equations Represented as Polynomials

MATLAB represents a polynomial as a row vector of coefficients; this can be used when the expressions or equations involve complex numbers, also. For example, the polynomial $z^2 + z - 3+2i$ would be represented by the vector `[1 1 -3+2i]`. The **roots** function in MATLAB can be used to find the roots of an equation represented by a polynomial. For example, to solve the equation $z^2 + z - 3+2i = 0$:

```
>> roots([1 1-3+2i])
ans=
  -2.3796+0.5320i
  1.3796-0.5320i
```

The **polyval** function can be used with this polynomial, for example

```
>> cp=[1 1-3+2i]
cp=
  1.0000         1.0000         -3.0000+2.0000i

>> polyval(cp,3)
ans=
  9.0000+2.0000i
```

14.2.6 Polar Form

Any complex number z = a + bi can be thought of as a point (a,b) or vector in a ***complex plane*** in which the horizontal axis is the real part of z, and the vertical axis is the imaginary part of z. Therefore, *a* and *b* are the Cartesian or rectangular coordinates. As a vector can be represented by either its rectangular or polar coordinates, a complex number can also be given by its polar coordinates *r* and θ, where *r* is the magnitude of the vector and θ is an angle.

To convert from the polar coordinates to the rectangular coordinates:

```
a=r cos θ
b=r sin θ
```

To convert from the rectangular to polar coordinates:

$$r = |z| = \sqrt{a^2 + b^2}$$

$$\theta = \arctan\left(\frac{b}{a}\right)$$

Note
that the function is **atan** in MATLAB.

Therefore, a complex number z = a + bi can be written as `r cos θ+(r sin θ)i` or

```
z=r cos θ+(i sin θ)
```

As $e^{i\theta} = \cos\,\theta + i\,\sin\,\theta$, a complex number can also be written as $z = re^{i\theta}$. In MATLAB, r can be found using the **abs** function, while there is a built-in function called **angle** to find θ.

```
>> z1=3+4i;
r=abs(z1)
r=
    5
>> theta=angle(z1)
theta=
     0.9273
>> r*exp(i*theta)
ans=
   3.0000+4.0000i
```

14.2.7 Plotting

Several methods are used commonly for plotting complex data:

- plot the real parts versus the imaginary parts using **plot**
- plot only the real parts using **plot**
- plot the real and the imaginary parts in one figure with a legend, using **plot**
- plot the magnitude and angle using **polarplot** (or, prior to R2016a, **polar**)

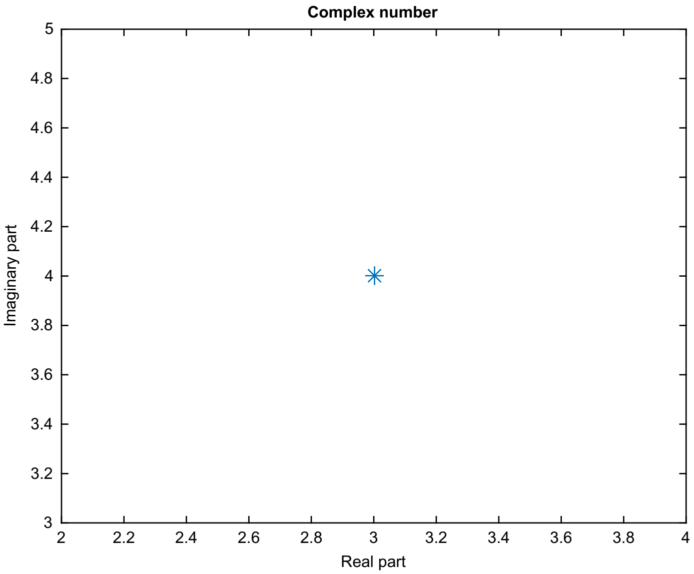

FIGURE 14.1
Plot of complex number.

Using the **plot** function with a single complex number or a vector of complex numbers will result in plotting the real parts versus the imaginary parts, for example **plot(z)** is the same as **plot(real(z), imag(z))**. Thus, for the complex number `z1=3+4i`, this will plot the point (3,4) (using a large asterisk so we can see it!), as shown in Fig. 14.1.

```
>> z1=3+4i;
>> plot(z1,'*', 'MarkerSize', 12)
>> xlabel('Real part')
>> ylabel('Imaginary part')
>> title('Complex number')
```

PRACTICE 14.2

Create the following complex variables

```
c1=complex(0,2);
c2=3+2i;
c3=sqrt(-4);
```

Then, carry out the following:

- Get the real and imaginary parts of *c2*.
- Print the value of *c1* using **disp**.
- Print the value of *c2* in the form 'a+bi'.

- Determine whether any of the variables are equal to each other.
- Subtract *c2* from *c1*.
- Multiply *c2* by *c3*.
- Get the complex conjugate and magnitude of *c2*.
- Put *c1* in polar form.
- Plot the real part versus the imaginary part for *c2*.

14.3 MATRIX SOLUTIONS TO SYSTEMS OF LINEAR ALGEBRAIC EQUATIONS

A ***linear algebraic equation*** is an equation of the form

$$a_1x_1 + a_2x_2 + a_3x_3 + \ldots. + a_nx_n = b$$

Solutions to sets of equations in this form are important in many applications. In MATLAB, to solve systems of equations, there are basically two methods:

- using a matrix representation
- using the **solve** function (which is part of Symbolic Math Toolbox™)

In this section, we will first investigate some relevant matrix properties and then use these to solve linear algebraic equations. The use of ***symbolic mathematics*** including the **solve** function will be covered in the next section.

14.3.1 Matrix Operations

There are several common operations on matrices, some of which we have seen already. These include matrix transpose, matrix augmentation, and matrix inverse.

A matrix transpose interchanges the rows and columns of a matrix. For a matrix A, its transpose is written A^T in mathematics. For example, if

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

then

$$A^T = \begin{bmatrix} 1 & 4 \\ 2 & 5 \\ 3 & 6 \end{bmatrix}.$$

In MATLAB, as we have seen, there is a built-in transpose operator, the apostrophe.

If the result of multiplying a matrix A by another matrix is the identity matrix I, then the second matrix is the ***inverse*** of matrix A. The inverse of a matrix A is written as A^{-1}, so

$$AA^{-1} = I$$

How to actually compute the inverse A^{-1} of a matrix by hand is not so easy. MATLAB, however, has a function **inv** to compute a matrix inverse. For example, here a matrix is created, its inverse is found, and then multiplied by the original matrix to verify that the product is in fact the identity matrix:

```
>> a=[1 2; 2 2]
a=
    1    2
    2    2
>> ainv=inv(a)
ainv=
  -1.0000    1.0000
   1.0000   -0.5000
>> a*ainv
ans=
     1     0
     0     1
```

Matrix augmentation means adding column(s) to the original matrix. In MATLAB, matrix augmentation can be accomplished using square brackets to concatenate the two matrices. The square matrix *A* is concatenated with an identity matrix which has the same size as the matrix *A*:

```
>> A=[1 3 7; 2 5 4; 9 8 6]
A=
    1      3      7
    2      5      4
    9      8      6

>> [A eye(size(A))]
ans=
    1      3      7      1      0      0
    2      5      4      0      1      0
    9      8      6      0      0      1
```

14.3.2 Linear Algebraic Equations

A ***linear algebraic equation*** is an equation of the form

$$a_1x_1 + a_2x_2 + a_3x_3 + \ldots. + a_nx_n = b$$

where the *a*s are constant ***coefficients***, the *x*s are the ***unknowns***, and *b* is a constant. A solution is a sequence of numbers that satisfy the equation. For example,

$$4x_1 + 5x_2 - 2x_3 = 16$$

is such an equation in which there are three unknowns: x_1, x_2, and x_3. One solution to this equation is $x_1 = 3$, $x_2 = 4$, and $x_3 = 8$, as $4*3+5*4 - 2*8$ is equal to 16.

A system of linear algebraic equations is a set of equations of the form:

$$\begin{array}{l}
a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \ldots. + a_{1n}x_n = b_1 \\
a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \ldots. + a_{2n}x_n = b_2 \\
a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \ldots. + a_{3n}x_n = b_3 \\
\vdots \qquad \vdots \qquad \vdots \qquad\qquad \vdots \qquad \vdots \\
a_{m1}x_1 + a_{m2}x_2 + a_{m3}x_3 + \ldots. + a_{mn}x_n = b_m
\end{array}$$

This is called an *m x n* system of equations; there are m equations and n unknowns.

Because of the way that matrix multiplication works, these equations can be represented in matrix form as $A\,x = b$, where A is a matrix of the coefficients, x is a column vector of the unknowns, and b is a column vector of the constants from the right side of the equations:

$$\begin{array}{cccc}
A & x & = & b \\
\begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn} \end{bmatrix} & \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{bmatrix} & = & \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_m \end{bmatrix}
\end{array}$$

Once the system of equations has been written in matrix form, what we want is to solve the equation `Ax=b` for the unknowns x. To do this, we need to isolate x on one side of the equation. If we were working with scalars, we would divide both sides of the equation by A. In fact, with MATLAB we can use the **divided into** operator to do this. However, most languages cannot do this with matrices, so instead, we multiply both sides of the equation by the inverse of the coefficient matrix A:

$$A^{-1}\ A\ x = A^{-1}\ b$$

Then, because multiplying a matrix by its inverse results in the identity matrix I, and because multiplying any matrix by I results in the original matrix, we have:

$$I\ x = A^{-1}\ b$$

or

$$x = A^{-1}\ b$$

For example, consider the following three equations with three unknowns x_1, x_2, and x_3:

$$\begin{aligned} 4x_1 - 2x_2 + 1x_3 &= 7 \\ 1x_1 + 1x_2 + 5x_3 &= 10 \\ -2x_1 + 3x_2 - 1x_3 &= 2 \end{aligned}$$

We write this in the form Ax=b, where A is a matrix of the coefficients, x is a column vector of the unknowns x_i, and b is a column vector of the values on the right side of the equations:

$$\begin{array}{cccc} \text{A} & \text{x} & & \text{b} \\ \begin{bmatrix} 4 & -2 & 1 \\ 1 & 1 & 5 \\ -2 & 3 & -1 \end{bmatrix} & \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} & = & \begin{bmatrix} 7 \\ 10 \\ 2 \end{bmatrix} \end{array}$$

The solution is then $x=A^{-1}b$. In MATLAB, there are two simple ways to solve this. The built-in function **inv** can be used to get the inverse of A and then we multiply this by b, or we can use the divided into operator.

```
>> A=[4-2 1; 1 1 5;-2 3-1];
>> b=[7;10;2];
>> x=inv(A)*b
x=
    3.0244
    2.9512
    0.8049

>> x=A\b
x=
    3.0244
    2.9512
    0.8049
```

14.3.2.1 Solving 2 × 2 Systems of Equations

Although this may seem easy in MATLAB, in general finding solutions to systems of equations is not. However, *2 × 2* systems are fairly straightforward, and there are several methods of solution for these systems for which MATLAB has built-in functions.

Consider the following *2 × 2* system of equations:

$$\begin{aligned} x_1 + 2x_2 &= 2 \\ 2x_1 + 2x_2 &= 6 \end{aligned}$$

This system of equations in matrix form is:

$$\begin{array}{cccc} \text{A} & \text{x} & & \text{b} \\ \begin{bmatrix} 1 & 2 \\ 2 & 2 \end{bmatrix} & \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} & = & \begin{bmatrix} 2 \\ 6 \end{bmatrix} \end{array}$$

We have already seen that the solution is `x=A`$^{-1}$ `b`, so we can solve this if we can find the inverse of A. One method of finding the inverse for a *2* × *2* matrix involves calculating the ***determinant*** D.

For a *2* × *2* matrix

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

the determinant D is defined as:

$$D = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = \mathrm{a}_{11}\mathrm{a}_{22} - \mathrm{a}_{12}\mathrm{a}_{21}$$

It is written using vertical lines around the coefficients of the matrix and is defined as the product of the values on the diagonal minus the product of the other two numbers.

For a *2* × *2* matrix, the matrix inverse is defined in terms of D as

$$A^{-1} = \frac{1}{D}\begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}$$

The inverse is therefore the result of multiplying the scalar 1/D by every element in the matrix shown here. Note that this is not the matrix A, but is determined using the elements from A in the following manner: the values on the diagonal are reversed and the negation operator is used on the other two values.

Notice that if the determinant D is 0, it will not be possible to find the inverse of the matrix A.

For our coefficient matrix $A = \begin{bmatrix} 1 & 2 \\ 2 & 2 \end{bmatrix}$, $D = \begin{vmatrix} 1 & 2 \\ 2 & 2 \end{vmatrix} = 1{*}2 - 2{*}2$ or -2 so

$$A^{-1} = \frac{1}{1{*}2 - 2{*}2}\begin{bmatrix} 2 & -2 \\ -2 & 1 \end{bmatrix} = \frac{1}{-2}\begin{bmatrix} 2 & -2 \\ -2 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 1 \\ 1 & -\frac{1}{2} \end{bmatrix}$$

and

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} -1 & 1 \\ 1 & -\frac{1}{2} \end{bmatrix}\begin{bmatrix} 2 \\ 6 \end{bmatrix}$$

The unknowns are found by performing this matrix multiplication. Consequently,

```
x1 =-1*2+1*6=4

x2 =1*2+(-1/2)*6=-1
```

To do this in MATLAB, we would first create the coefficient matrix variable *A* and column vector *b*.

```
>> A=[1 2; 2 2];
>> b=[2;6];
```

We have already seen that MATLAB has a built-in function, **inv**, to find a matrix inverse. It also has a built-in function **det** to find a determinant:

```
>> det(A)
ans=
   -2

>> inv(A)
ans=
  -1.0000     1.0000
   1.0000    -0.5000
```

And then, the unknowns x are found:

```
>> x=inv(A)*b
x=
    4
   -1
```

PRACTICE 14.3

For the following *2* × *2* system of equations:

$$\begin{aligned} x_1 + 2x_2 &= 4 \\ -x_1 \quad\quad &= 3 \end{aligned}$$

Do the following on paper:

- Write the equations in matrix form Ax=b.
- Solve by finding the inverse A^{-1} and then $x=A^{-1}$ b.

Next, get into MATLAB and check your answers.

14.3.2.2 Reduced Row Echelon Form

For *2* × *2* systems of equations, there are solving methods that are well-defined and simple. However, for larger systems of equations, finding solutions is frequently not as straightforward.

Several methods of solving are based on the observation that systems of equations are equivalent if they have the same solution set. Performing some simple operations on rows of the matrix form of a set of equations results in equivalent systems. The ***Gauss-Jordan method*** starts by augmenting the coefficient matrix A with the column vector b and performing operations until the square part of the matrix becomes diagonal.

Reduced Row Echelon Form takes this one step further to result in all 1s on the diagonal, or in other words until the square part is the identity matrix. In this case, the column of b's is the solution. For example, for a 3×3 matrix.

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & 0 & b_1' \\ 0 & 1 & 0 & b_2' \\ 0 & 0 & 1 & b_3' \end{bmatrix}$$

In other words, we are reducing [A|b] to [I | b′]. Note that the prime in b′ indicates that the numbers may have changed, but the systems are equivalent. MATLAB has a built-in function to do this, called **rref**. For example:

```
>> a=[1 3 0; 2 1 3; 4 2 3];
>> b=[1 6 3]';
>> ab=[a b];
>> rref(ab)
ans=
     1     0     0    -2
     0     1     0     1
     0     0     1     3
```

The solution is found from the last column, so x_1 = -2, x_2 = 1, and x_3 = 3. To get this in a column vector in MATLAB:

```
>> x=ans(:,end)
x=
   -2
    1
    3
```

14.3.2.3 Finding a Matrix Inverse by Reducing an Augmented Matrix

For a system of equations larger than a *2 x 2* system, one method of finding the inverse of a matrix A mathematically involves augmenting the matrix with an identity matrix of the same size, and then reducing it. The algorithm is:

- Augment the matrix with I: [A | I].
- Reduce it to the form [I | X]; X will be A^{-1}.

For example, in MATLAB we can start with a matrix, augment it with an identity matrix, and then use the **rref** function to reduce it.

```
>> a=[1 3 0; 2 1 3; 4 2 3];
>> rref([a eye(size(a))])
ans=
   1.0000          0          0    -0.2000    -0.6000     0.6000
        0     1.0000          0     0.4000     0.2000    -0.2000
        0          0     1.0000          0     0.6667    -0.3333
```

In MATLAB, the **inv** function can be used to verify the result.

```
>> inv(a)
ans=
  -0.2000    -0.6000     0.6000
   0.4000     0.2000    -0.2000
        0     0.6667    -0.3333
```

14.4 SYMBOLIC MATHEMATICS

Symbolic mathematics means doing mathematics on symbols (not numbers!). For example, a+a is 2a. The symbolic math functions are in Symbolic Math Toolbox™ in MATLAB. Toolboxes contain related functions and are add-ons to MATLAB. (Therefore, this may or may not be part of your own system.) Symbolic Math Toolbox™ includes an alternative method for solving equations and is therefore covered in this chapter.

14.4.1 Symbolic Variables and Expressions

MATLAB has a type called **sym** for symbolic variables and expressions; these work with character vectors. For example, to create a symbolic variable *a* and perform the addition just described, a symbolic variable would first be created by passing the character vector 'a' to the **sym** function:

```
>> a=sym('a');
>> a+a
ans=
2*a
```

Symbolic variables can also store expressions. For example, the variables *b* and *c* store symbolic expressions:

```
>> b=a^2
b=
a^2
>> c=a^4;
>> class(b)
ans=
    'sym'
```

All basic mathematical operations can be performed on symbolic variables and expressions (e.g., add, subtract, multiply, divide, raise to a power, etc.). The following are examples:

```
>> c/b
ans=
a^2
>> b^3
ans=
a^6
>> c*b
ans=
a^6
>> b+4*a^2
ans=
5*a^2
```

It can be seen from the last example that MATLAB will collect like terms in these expressions, adding the a^2 and $4a^2$ to result in $5a^2$.

If using multiple variables as symbolic variable names is desired, the **syms** function is a shortcut instead of using **sym** repeatedly. For example,

```
>> syms x y z
```

is equivalent to

```
>> x=sym('x');
>> y=sym('y');
>> z=sym('z');
```

The built-in functions **sym2poly** and **poly2sym** convert from symbolic expressions to polynomial vectors and vice versa. For example:

```
>> myp=[1 2-4 3];
>> poly2sym(myp)
ans=
x^3+2*x^2-4*x+3
>> mypoly=[2 0-1 0 5];
>> poly2sym(mypoly)
ans=
2*x^4-x^2+5

>> sym2poly(ans)
ans=
    2     0    -1     0     5
```

14.4.2 Simplification Functions

There are several functions that work with symbolic expressions and simplify the terms. Not all expressions can be simplified, but the **simplify** function does whatever it can to simplify expressions, including gathering like terms. For example:

```
>> x=sym('x');
>> myexpr=cos(x)^2+sin(x)^2
myexpr=
cos(x)^2+sin(x)^2

>> simplify(myexpr)
ans=
1
```

The functions **collect**, **expand**, and **factor** work with polynomial expressions. The **collect** function collects coefficients, such as the following:

```
>> x=sym('x');
>> collect(x^2+4*x^3+3*x^2)
ans=
4*x^3+4*x^2
```

The **expand** function will multiply out terms, and **factor** will do the reverse:

```
>> ea=expand((x+2)*(x-1))
ea=
x^2+x-2
>> f=factor(ea)
f=
[ x+2, x-1]
>> expand(f(1)*f(2))
ans=
x^2+x - 2
```

If the argument is not factorable, the original input argument will be returned unmodified.

The **subs** function will substitute a value for a symbolic variable in an expression. For example,

```
>> myexp=x^3+3*x^2-2
myexp=
x^3+3*x^2-2
>> subs(myexp,3)
ans=
52
```

If there are multiple variables in the expression, one will be chosen by default for the substitution (in this case, *x*), or the variable for which the substitution is to be made can be specified:

```
>> syms a b x
>> varexp=a*x^2+b*x;
>> subs(varexp,3)
ans=
9*a+3*b
>> subs(varexp,'a',3)
ans=
3*x^2+b*x
```

With symbolic math, MATLAB works by default with rational numbers, meaning that results are kept in fractional forms. For example, performing the addition 1/3 + 1/2 would normally result in a **double** value:

```
>> 1/3+1/2
ans=
   0.8333
```

However, by making the expression symbolic, the result is symbolic also. Any numeric function (e.g., **double)** could change that:

```
>> sym(1/3+1/2)
ans=
5/6
>> double(ans)
ans=
    0.8333
```

The **numden** function will return separately the numerator and denominator of a symbolic expression:

```
>> frac=sym(1/3+1/2)
frac=
5/6
>> [n, d]=numden(frac)
n=
5
d=
6
```

14.4.3 Displaying Expressions

The **pretty** function will display symbolic expressions using exponents. For example:

```
>> syms x b
>> b=x^2
b=
x^2
>> pretty(b)
 2
x
```

The function **fplot** will draw a two-dimensional plot in the default x-range from −5 to 5. The following code produces the figure that is shown in Fig. 14.2. The DisplayName property of the plot is used for the title of the plot.

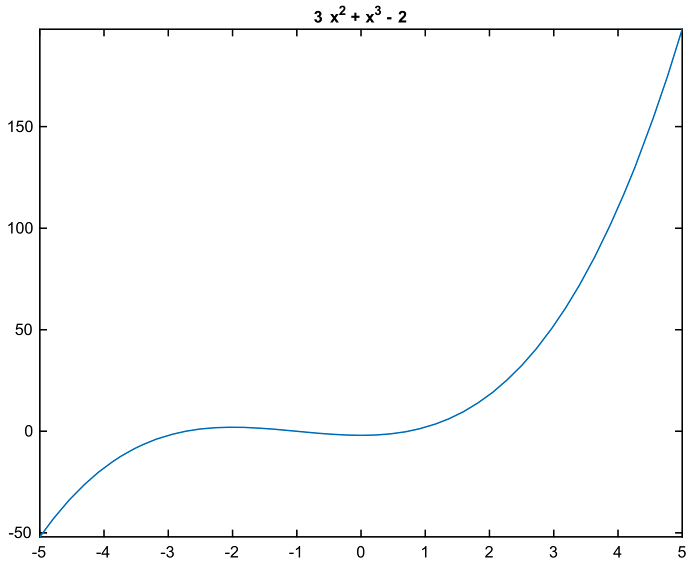

FIGURE 14.2
Plot produced using **fplot**.

```
>> expr=x^3+3*x^2-2;
>> fpe=fplot(expr);
>> title(fpe.DisplayName)
```

14.4.4 Solving Equations

We have already seen several methods for solving simultaneous linear equations using a matrix representation. MATLAB can also solve sets of equations using symbolic math.

The function **solve** solves an equation and returns the solution(s) as symbolic expressions. The solution can be converted to numbers using any numeric function, such as **double**:

```
>> syms a b x
>> solve(2*x^2+x== 6)
ans=
   -2
  3/2
>> double(ans)
ans=
   -2.0000
    1.5000
```

If an expression is passed to the **solve** function rather than an equation, the **solve** function will set the expression equal to 0 and solve the resulting equation. For example, the following will solve $3x^2+x=0$:

```
>> solve(3*x^2+x)
ans=
-1/3
   0
```

If there is more than one variable, MATLAB chooses which to solve for. In the following example, the equation $ax^2+bx=0$ is solved. There are three variables. As can be seen from the result, which is given in terms of *a* and *b*, the equation was solved for *x*. MATLAB has rules built in that specify how to choose which variable to solve for. For example, *x* will always be the first choice if it is in the equation or expression.

```
>> solve(a*x^2+b*x)
ans=
   0
-b/a
```

However, it is possible to specify which variable to solve for:

```
>> solve(a*x^2+b*x, b)
ans=
-a*x
```

MATLAB can also solve sets of equations. In this example, the solutions for x, y, and z are returned as a structure consisting of fields for *x*, *y*, and *z*. The individual solutions are symbolic expressions stored in fields of the structure.

```
>> syms x y z
>> solve(4*x-2*y+z==7, x+y+5*z==10,-2*x+3*y-z==2)
ans=
  struct with fields:

    x: [11 sym]
    y: [11 sym]
    z: [11 sym]
```

To refer to the individual solutions, which are in the structure fields, the dot operator is used.

```
>> x=ans.x
x=
124/41
>> y=ans.y
y=
121/41
>> z=ans.z
z=
33/41
```

The **double** function can then be used to convert the symbolic expressions to numbers and store the results from the three unknowns in a vector.

```
>> double([x y z])
ans=
   3.0244     2.9512     0.8049
```

PRACTICE 14.4

For each of the following expressions, show what the MATLAB result would be. Assume that all expressions are typed SEQUENTIALLY.

```
x=sym('x');
a=x^3-2*x^2+1;
b=x^3+x^2;
res=a+b

p=sym2poly(res)

polyval(p,2)

sym(1/2+1/4)

solve(x^2-16)
```

14.5 CALCULUS: INTEGRATION AND DIFFERENTIATION

MATLAB has functions that perform common calculus operations on a mathematical function f(x), such as ***integration*** and ***differentiation***.

14.5.1 Integration and the Trapezoidal Rule

The integral of a function f(x) between the limits given by x = a and x = b is written as

$$\int_a^b f(x)dx$$

and is defined as the area under the curve f(x) from a to b, as long as the function is above the x-axis. Numerical integration techniques involve approximating this.

One simple method of approximating the area under a curve is to draw a straight line from f(a) to f(b) and calculate the area of the resulting trapezoid as

$$(b-a)\frac{f(a)+f(b)}{2}$$

In MATLAB, this could be implemented as a function.

THE TRADITIONAL METHOD

Here is a function to which the function handle and limits a and b are passed:

trapint.m

```
function int=trapint(fnh, a, b)
% trapint approximates area under a curve f(x)
% from a to b using a trapezoid
% Format: trapint(handle of f, a, b)
int=(b-a)*(fnh(a)+fnh(b))/2;
end
```

To call it, for example, for the function $f(x) = 3x^2 - 1$, an anonymous function is defined, and its handle is passed to the *trapint* function.

```
>> f=@ (x) 3*x .^ 2-1;
approxint=trapint(f, 2, 4)
approxint=

     58
```

THE EFFICIENT METHOD

MATLAB has a built-in function **trapz** that will implement the trapezoidal rule. Vectors with the values of x and y=f(x) are passed to it. For example, using the anonymous function defined previously:

```
>> x=[2 4];
>> y=f(x);
>> trapz(x,y)
 ans=
     58
```

An improvement on this is to divide the range from a to b into n intervals, apply the trapezoidal rule to each interval, and sum them. For example, for the preceding if there are two intervals, you would draw a straight line from f(a) to f((a+b)/2) and then from f((a+b)/2) to f(b).

THE TRADITIONAL METHOD

The following is a modification of the previous function to which the function handle, limits, and the number of intervals are passed:

trapintn.m

```
function intsum=trapintn(fnh, lowrange,highrange, n)
% trapintn approximates area under a curve f(x) from
%  a to b using trapezoids with n intervals
% Format: trapintn(handle of f, a, b, n)
intsum=0;
increm=(highrange-lowrange)/n;
for a=lowrange: increm : highrange-increm
    b=a+increm;
    intsum=intsum+(b-a)*(fnh(a)+fnh(b))/2;
end
end
```

For example, this approximates the integral of the previous function f with two intervals:

```
>> trapintn(f,2,4,2)
ans=
    55
```

THE EFFICIENT METHOD

To use the built-in function **trapz** to accomplish the same thing, the *x* vector is created with the values 2, 3, and 4:

```
>> x=2:4;
>> y=f(x)
>> trapz(x,y)
ans=
    55
```

In these examples, straight lines, which are first-order polynomials, were used. Other methods involve higher-order polynomials. The built-in function **quad** uses Simpson's method. Three arguments are normally passed to it: the handle of the function, and the limits a and b. For example, for the previous function:

```
>> quad(f,2,4)
ans=
    54
```

MATLAB has a function **polyint**, which will find the integral of a polynomial. For example, for the polynomial $3x^2 + 4x - 4$, which would be represented by the vector `[3 4-4]`, the integral is found by:

```
>> origp=[3 4-4];
>> intp=polyint(origp)
intp=
     1      2      -4      0
```

which shows that the integral is the polynomial $x^3 + 2x^2 - 4x$.

14.5.2 Differentiation

The derivative of a function y = f(x) is written as $\frac{dy}{dx}f(x)$ or `f'(x)` and is defined as the rate of change of the dependent variable y with respect to x. The derivative is the slope of the line tangent to the function at a given point.

MATLAB has a function **polyder**, which will find the derivative of a polynomial. For example, for the polynomial $x^3 + 2x^2 - 4x+3$, which would be represented by the vector `[1 2-4 3]`, the derivative is found by:

```
>> origp=[1 2-4 3];
>> diffp=polyder(origp)
diffp=

      3      4      -4
```

which shows that the derivative is the polynomial $3x^2 + 4x - 4$. The function **polyval** can then be used to find the derivative for certain values of x, such as for x = 1, 2, and 3:

```
>> polyval(diffp, 1:3)
ans=
     3      16      35
```

The derivative can be written as the limit

$$f'(x) = \lim_{h\to 0}\frac{f(x+h)-f(x)}{h}$$

and can be approximated by a difference equation.

Recall that MATLAB has a built-in function, **diff**, which returns the differences between consecutive elements in a vector. For a function `y=f(x)` where x is a vector, the values of `f'(x)` can be approximated as **diff(y)** divided by **diff(x)**. For example, the equation $x^3 + 2x^2 - 4x+3$ can be written as an anonymous function. It can be seen that the approximate derivative is close to the values found using **polyder** and **polyval**.

```
>> f=@ (x) x .^ 3+2*x .^ 2-4*x+3;
>> x=0.5 : 3.5
x=
   0.5000      1.5000      2.5000      3.5000
>> y=f(x)
y=
   1.6250      4.8750     21.1250     56.3750
>> diff(y)
ans=
   3.2500     16.2500     35.2500
>> diff(x)
ans=
   1     1     1
>> diff(y) ./ diff(x)
ans=
   3.2500     16.2500     35.2500
```

14.5.3 Calculus in Symbolic Math Toolbox™

There are several functions in Symbolic Math Toolbox™ to perform calculus operations symbolically (e.g., **diff** to differentiate and **int** to integrate). To learn about the **int** function, for example, from the Command Window:

```
>> help sym/int
```

For instance, to find the indefinite integral of the function $f(x)=3x^2 - 1$:

```
>> syms x
>> int(3*x^2-1)
ans=
x^3-x
```

To instead find the definite integral of this function from $x=2$ to $x=4$:

```
>> int(3*x^2-1, 2, 4)
ans=
54
```

Limits can be found using the **limit** function. For example, for the difference equation described previously:

```
>> syms x h
>> f=@ (x) x .^ 3+2*x .^ 2-4*x+3;
>> limit((f(x+h)-f(x))/h,h,0)
ans=
3*x^2+4*x - 4
```

To differentiate, instead of the anonymous function we write it symbolically:

```
>> syms x f
>> f=x^3+2*x^2-4*x+3
f=
x^3+2*x^2-4*x+3

>> diff(f)
ans=
3*x^2+4*x - 4
```

PRACTICE 14.5

For the function $3x^2 - 4x+2$:

- Find the indefinite integral of the function.
- Find the definite integral of the function from x=2 to x=5.
- Approximate the area under the curve from x=2 to x=5.
- Find its derivative.
- Approximate the derivative for x=2.

Data Science and Machine Learning Supplement

Fitting Polynomial Curves, Underfitting/Overfitting

We have seen in Chapter 12 how to use the functions **polyfit** and **polyval** to fit a straight line through data points. In this section, we will see how to use the same functions to fit polynomial curves of greater degrees to data points.

As an example, let us say the temperature was recorded every hour one afternoon from 2:00 PM to 6:00 PM; the vectors might be:

```
>> x=2:6;
>> y=[65 67 72 71 63];
```

For example, to fit a straight line (degree 1) through the points representing temperatures, the call to the **polyfit** function would be

```
>> polyfit(x,y,1)
ans=
    0.0000    67.6000
```

which says that the best straight line is of the form `0x+67.6`. However, we can see that the temperatures rise and then fall, so it seems like a quadratic would be a much better fit. The following would create the vectors and then fit a polynomial of degree 2 through the data points, storing the values in a vector called *coefs*.

```
>> x=2:6;
>> y=[65 67 72 71 63];
>> coefs=polyfit(x,y,2)
coefs=
   -1.8571   14.8571   41.6000
```

This says that the **polyfit** function has determined that the best quadratic that fits these data points is $-1.8571x^2 + 14.8571x+41.6$. Therefore, the variable *coefs* now stores a coefficient vector that represents this polynomial.

The function **polyval** can then be used to evaluate the polynomial at specified values. For example, we could evaluate at every value in the *x* vector.

```
>> curve=polyval(coefs,x)
```

This results in *y* values for each point in the *x* vector and stores them in a vector called *curve*. We could then plot both the points and the curve on the same figure as seen in Fig. 14.3. The curve does not look very smooth on this plot, but that is because there are only five points in the *x* vector.

```
plot(x,y,'ro',x,curve)
xlabel('Time')
ylabel('Temperatures')
title('Temperatures one afternoon')
axis([1 7 60 75])
```

Using the **subplot** function, we can loop to show the difference between fitting curves of degrees 1, 2, and 3 to the temperature data. (Note that the variable *morex* stores 100 points so the graph will be smooth.)

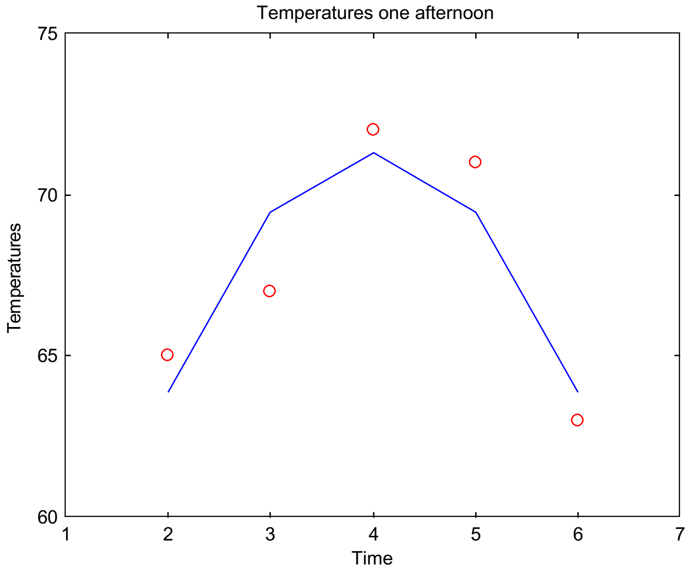

FIGURE 14.3

Quadratic fit to points.

```
morex=linspace(min(x),max(x));
for pd=1:3
   coefs=polyfit(x,y,pd);
   curve=polyval(coefs,morex);
   subplot(1,3,pd)
   plot(x,y,'ko',morex,curve,'k', LineWidth=2)
   xlabel('Time')
   ylabel('Temperatures')
   title(sprintf('Degree %d',pd))
   axis([1 7 60 75])
end
```

This will create the Figure Window shown in Fig. 14.4.

In ML, we use the terms ***underfitting*** to describe a fit that does not describe the data very well, and ***overfitting*** to describe a fit that perhaps fits the data too well. For example, the straight line above underfits the data. Using this line to interpolate or extrapolate would not produce very good results! If we had a 4th degree polynomial that exactly fits all of our data points, that would be overfitting. If the data points are the training set, it might perfectly describe the training set, for example, but would likely not work for the test set because the fit was too specific to the training set.

If you have Curve Fitting Toolbox™, there is a Curve Fitting App that can be used to explore fitting various types of curves to data points.

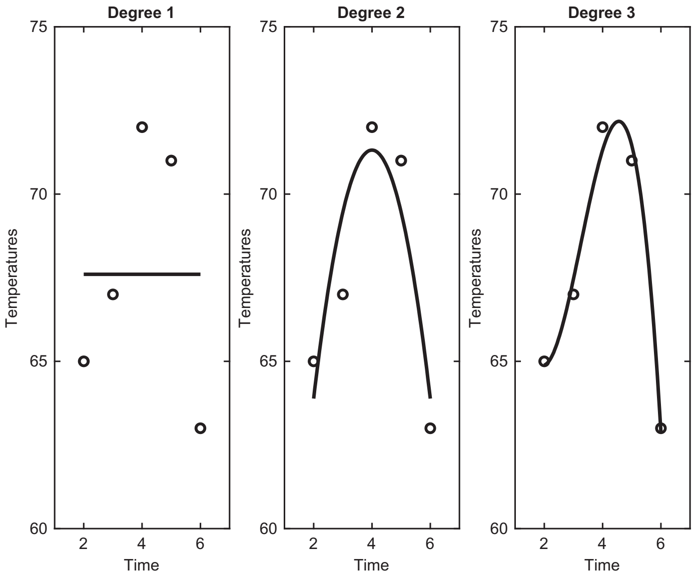

FIGURE 14.4

Possible overfitting.

■ Explore Other Interesting Features

Investigate the index vectors returned by the set functions.

Investigate passing matrices to the set functions, using the 'rows' specifier.

Investigate the **fzero** function, which attempts to find a zero of a function near a specified x value.

Investigate linear algebra functions, such as **rank** for the rank of a matrix, or **null**, which returns the null space of a matrix.

Investigate the functions that return eigenvalues and eigenvectors, such as **eig** and **eigs**.

Investigate the **norm** function to find a vector or matrix norm.

Investigate the Ordinary Differential Equation (ODE) solve functions, such as **ode23** and **ode45**, which use the Runge-Kutta integration methods.

In the Command Window, type "odeexamples" to see some ODE example codes.

Investigate some of the other numerical integration functions, such as **integral**, **integral2** for double integrals, and **integral3** for triple integrals.

Investigate the **poly** function, which finds the characteristic equation for a matrix, and the **polyeig** function, which solves a polynomial eigenvalue problem of a specified degree. ■

SUMMARY

COMMON PITFALLS

- Forgetting that the **fprintf** function by default prints only the real part of a complex number
- Forgetting that to augment one matrix with another, the number of rows must be the same in each

PROGRAMMING STYLE GUIDELINES

- When working with symbolic expressions, it is generally easier to make all variables symbolic variables to begin with.

MATLAB Functions and Commands

union
intersect
unique
setdiff
setxor
ismember
issorted
complex
real
imag
isreal
conj
angle
polarplot
inv
det
rref
sym
syms
sym2poly
poly2sym
simplify
collect
expand
factor
subs
numden
pretty
ezplot
solve
trapz
quad
polyint
polyder
int
limit

Exercises

1. Create a vector that has 10 elements. Use the mink function to determine the two smallest, and use a set function to create a new vector that does not include those two values.
2. Investigate the use of the bounds function to find the smallest and largest values in a vector.
3. The set functions can be used with cell arrays of character vectors. Create two cell arrays to store course numbers taken by two students. For example,

```
s1={'EC 101', 'CH 100', 'MA 115'};
s2={'CH 100', 'MA 112', 'BI 101'};
```

   Use a set function to determine which courses the students have in common.
4. Redo problem 3 using a string array.
5. A vector *v* is supposed to store unique random numbers. Use set functions to determine whether or not this is true.
6. Find the roots of the equation f(x) = 0 for the following function. Also, create *x* and *y* vectors and plot this function in the range from −3 to 3 to visualize the solution.

$$f(x)=3x^2 - 2x-4$$

7. Store the following complex numbers in variables, and print them in the form a+bi.

$$3-2i$$

$$\sqrt{-3}$$

8. Create the following complex variables

```
c1=1-3i;
c2=5+2i;
```

Perform the following operations on them:

- add them
- multiply them
- get the complex conjugate and magnitude of each
- put them in polar form

9. Represent the expression $z^3 - 2z^2 + 3 - 5i$ as a row vector of coefficients, and store this in a variable *compoly*. Use the **roots** function to solve $z^3 - 2z^2 + 3 - 5i = 0$. Also, find the value of *compoly* when z=2 using **polyval**.
10. Analyzing electric circuits can be accomplished by solving sets of equations. For a particular circuit, the voltages V_1, V_2, and V_3 are found through the system:

    $V_1 = 5$
    $-6V_1 + 10V_2 - 3V_3 = 0$
    $-V_2 + 51V_3 = 0$

    Put these equations in matrix form and solve in MATLAB.
11. Re-write the following system of equations in matrix form:

    $4x_1 - x_2 + 3x_4 = 10$
    $-2x_1 + 3x_2 + x_3 - 5x_4 = -3$
    $x_1 + x_2 - x_3 + 2x_4 = 2$
    $3x_1 + 2x_2 - 4x_3 = 4$

    Set it up in MATLAB and use any method to solve.
12. Solve the simultaneous equations $x - y = 2$ and $x^2 + y = 0$ using **solve**. Plot the corresponding functions, $y = x - 2$ and $y = -x^2$, on the same graph with an x range from −5 to 5.
13. For the following set of equations,

    $2x_1 + 2x_2 + x_3 = 2$
    $x_2 + 2x_3 = 1$
    $x_1 + x_2 + 3x_3 = 3$

    write it in symbolic form and solve using the **solve** function. From the symbolic solution, create a vector of the numerical (**double**) equivalents.
14. The reproduction of cells in a bacterial colony is important for many environmental engineering applications such as wastewater treatments. The formula

    $\log(N) = \log(N_0) + t/T \log(2)$

    can be used to simulate this, where N_0 is the original population, N is the population at time t, and T is the time it takes for the population to double. Use the **solve** function to determine the following: if $N_0 = 10^2$, $N = 10^8$, and t=8 hours, what will be the doubling time T? Use **double** to get your result in hours.
15. Using the symbolic function **int**, find the indefinite integral of the function $4x^2 + 3$, and the definite integral of this function from x=-1 to x=3. Also, approximate this using the **trapz** function.

16. Use the **quad** function to approximate the area under the curve $4x^2+3$ from -1 to 3. First, create an anonymous function and pass its handle to the **quad** function.
17. Use the **polyder** function to find the derivative of $2x^3 - x^2 + 4x - 5$.
18. Examine the motion, or *trajectory*, of a *projectile* moving through the air. Assume that it has an initial height of 0, and neglect the air resistance for simplicity. The projectile has an initial velocity v_0, an angle of departure θ_0, and is subject to the gravity constant $g = 9.81 m/s^2$. The position of the projectile is given by x and y coordinates, where the origin is the initial position of the projectile at time $t = 0$. The total horizontal distance that the projectile travels is called its *range* (the point at which it hits the ground), and the highest peak (or vertical distance) is called its *apex*. Equations for the trajectory can be given in terms of the time t or in terms of x and y. The position of the projectile at any time t is given by:

$$x = v_0 \cos(\theta_0)\, t$$
$$y = v_0 \sin(\theta_0)\, t - ½\, g\, t^2$$

For a given initial velocity v_0, and angle of departure θ_0, describe the motion of the projectile by writing a script to answer the following:

- What is the range?
- Plot the position of the projectile at suitable x values
- Plot the height versus time
- How long does it take to reach its apex?

Data Science and Machine Learning

19. How well does a quadratic curve fit a sin curve in the x range from 0 to pi? Write a script that will create an x vector that has 100 points in the range from 0 to pi, and a y vector that is sin(x). Fit a quadratic to these points. Plot the sin curve as a black line, and the quadratic as individual red stars. Verify the difference at $x = 1.5$ using **polyval** on your quadratic curve and sin(1.5).

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CHAPTER 15

Basic Machine Learning Algorithms and Concepts

KEY TERMS

Silhouette coefficients	k-means clustering	centroid

CONTENTS

With Machine Learning (ML), large data sets are inputs into computer programs, which then find patterns in the data in order to aid in making predictions. Machine Learning is a very complex field. Two of the basic foundations are computer coding, and probability and statistics. This text serves as an introduction to the necessary computer programming constructs. However, it is way beyond the scope of this book to introduce all of the mathematics necessary to understand how ML algorithms work.

This chapter is intended to serve as a basic introduction to some of the ML concepts, algorithms, and workflows. It is meant to be a bridge between the programming concepts covered in this book and the fields of data science and ML. There are so many concepts and so many technical terms that some of the background information has already been spread throughout the book. At the end of every chapter in this text, there is a roughly two-page section on data science and ML. Therefore, the first 30 pages of this chapter are to be found at the ends of the other chapters! It is strongly recommended that before continuing with this chapter, readers go back and review all of that material. When the concepts that were covered in these sections are referenced in this chapter, the chapter in which the concepts appeared will be given in parentheses.

The rest of this chapter synthesizes some of the material already covered and introduces some of the algorithms used in both supervised and unsupervised learning. The last section briefly introduces Statistics and Machine Learning Toolbox™.

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.00015-9

15.1 PREPROCESSING DATA, BASIC WORKFLOW

The workflow will be slightly different with the different types of ML algorithms, but the basics will remain the same:

- Get the data set
- Iterate through these steps until accurate model is found:
  - Preprocess/scrub the data
  - Choose an algorithm
  - Fit a model to the data
  - Assess the model performance
- Use model to make predictions
  - Get new data
  - Preprocess/scrub the data using the same methods as for the training/testing data
  - Use the fitted model
  - Make predictions

Because the same methods are used to preprocess/scrub the new data as the original training/testing data, it is generally useful to write a function to do this preprocessing.

Built-in Data Sets

To demonstrate some of these steps, we use some data files that are built-in to MATLAB®. We have already seen some built-in files, including the following:

- outages.csv: stores information on some power outages. Use **readtable** to read it into a table.
- census.mat: stores census data in the US every 10 years from 1790 to 1990, in two variables *cdate* and *pop*. Use **load** to read them in and then put them into a matrix or table.
- cape.mat: Stores an image of Cape Cod in a variable *X* and a colormap in the variable *map*.
- street1.jpg: image of a street; read it using **imread**.

Other built-in .mat files include “accidents.mat,” which stores accident data from the 50 United States and Washington, D.C.; “patients.mat,” which stores 10 features for 100 hypothetical medical patients; and “wind.mat,” which stores position and velocity components of air currents.

MATLAB also has some built-in labeled data sets, which are in Statistics and Machine Learning Toolbox™. These include the following:

Fisher Iris: This labeled data set contains 50 rows for each of three different iris species. For every flower, the Petal Length and Width, the Sepal Length and Width, and the species were recorded. This is a very famous data set and can be found in many forms. In MATLAB, it is available as a .csv file ('fisheriris.csv') and also as a .mat file ('fisheriris.mat') that stores two variables: *meas*, which is a 150 × 4 matrix storing the data, and *species*, which is a cell array that stores the iris species labels. If you do not have access to this data set through MATLAB, you can do a search on the web for "Fisher Iris Data Set" to find and download it.

Cars: These labeled data sets contain information on cars. There are two: carsmall.mat (stores 100 rows) and carbig.mat (stores 406 rows). The .mat files have 10 column vectors, "Acceleration", "Cylinders", "Displacement", "Horsepower", "Mfg", "Model", "Model_Year", "MPG", "Origin", and "Weight". The "Origin" vector stores the country of origin; this vector can be used as labels. The "Mfg" column vector stores the names of the manufacturers, and the "Model" column vector stores the names of the car models.

Ovarian Cancer: This labeled data set stores information on 216 patients. There are 4000 factors, and two labels, either 'Cancer' or 'Normal'. There is a .mat file ('ovariancancer.mat') that stores two variables: *obs* which is a matrix storing the factor data, and *grp* which is a cell array storing the character vectors 'Cancer' or 'Normal'.

Arrhythmia: This labeled data set stores information on 452 patients. There are 279 factors that are predictors, and 16 different classifications indicating varying degrees of arrhythmia in the patients. There is a .mat file ('arrhythmia.mat') that stores four variables: "Description", "VarNames", "X", and "Y". "Description" is a brief description of the data set and its origin. "VarNames" is a cell array that stores the names of the variables. "X" is a 452 × 279 matrix that stores the data. "Y" is the response variable, which stores integers from 1 to 16 representing the degrees of arrhythmia.

There are others, many of which are used in examples in the MATLAB documentation.

Preprocessing Data

Data sets are usually represented in MATLAB as either matrices or tables. For labeled data, generally the predictor features are called X, and the response vector is called Y. It is common for the response vector to be the last column in either the matrix or table. The first step in working with any ML algorithm is to preprocess the data to get it into a format that can be used by the algorithm. This includes both cleaning the data if it is messy (and, almost always this will be true!), as well as feature engineering to reduce the number of features or to create new features, and to make sure that the feature types can be used by the chosen algorithm.

Messy data includes data that are missing or incorrect. Missing data is represented in different ways, depending on the type of the feature. For example, missing numbers, as we have seen (Chapter 4), are frequently represented by

NaN in data sets (sometimes also by 0). Other representations of missing data include the following:

- datetime: NaT
- character vectors: ‘ ’
- strings: <missing>
- categorical: <undefined>

The function **ismissing** returns 1 for true for every element that stores a missing value, and 0 for false for all other elements. To simulate a data set with missing values, the function **missing** can be used to create missing values in a data set.

Missing data can either be deleted (deleting the entire row), or it can be replaced by a specified value. Because it is usually best to keep a data set as large as possible, replacing the missing value is preferred. Missing values are sometimes replaced by the mean, median, or mode of the feature vector. Missing values can also be replaced by a specified constant, or perhaps by the previous value in the feature vector. In MATLAB, the function **fillmissing** can be used to replace missing values of all types.

For example, a string array is created with one missing element, and then the missing value(s) are modified to store a constant value:

```
>> strarr=["hello" "hi" missing "ciao"]
strarr=
  1×4 string array
   "hello"    "hi"    <missing>    "ciao"
>> strarr=fillmissing(strarr, 'constant', "xyz")
strarr=
  1×4 string array
   "hello"    "hi"    "xyz"    "ciao"
```

In another example, a categorical array is created, one of the elements is modified to be missing, and then the missing value(s) are modified to store the previous value in the array:

```
>> cat=categorical({'north', 'east', 'north', ...
     'south', 'west'});
>> cat(2)=missing
cat=
  1×5 categorical array
    north      <undefined>      north      south      west
>> fillmissing(cat, 'previous')
ans=
  1×5 categorical array
    north      north      north      south      west
```

Of course, the **missing** function is just used here to simulate missing data. Normally these missing values would occur automatically when importing the data set.

Incorrect data might be in the form of outliers, but keep in mind that not all outliers are errors and in fact may represent vital information. However, if outliers are deemed to be errors, those observations should be removed. The **rmoutliers** function, new in R2018b, can be used to do this.

Once the missing and incorrect values have been dealt with, the next task is to examine the feature vectors to see whether it makes sense to leave them, delete them, or transform them in some way. Some features may be completely irrelevant, and some may be redundant, so these can be deleted. This generally involves some domain knowledge, knowing what makes sense for a particular application.

Doing statistical analyses (Chapters 2, 3, and 10) and visualizing the data (Chapter 5) can be very helpful at this stage. Looking at correlations (Chapter 5), for example, can help determine whether some features are irrelevant or not.

If it is determined that a numerical feature vector stores information that is too detailed, it may be wise to put the real numbers into bins, or categories (Chapter 4). This, of course, only works if the algorithm accepts data of the type **categorical**. If **categorical** data are not possible, one-hot encoding (Chapter 8) can be used to transform this data into 1/0 numbers. Sometimes new features are also created from other features, or combinations of features.

Once the feature analysis and engineering are complete, it may be necessary to normalize the numerical feature vectors so that larger numbers do not dominate in importance in the ML algorithm (Chapter 3). The **normalize** function, new as of R2018a, can be used to normalize feature columns in matrices or tables.

If the algorithm involves creating training and test sets, the data set should first be randomized (Chapter 5).

The Live Editor has some Tasks that can be used to help preprocess the data. These include Clean Missing Data, Clean Outlier Data, and Smooth Data. In future releases, more Tasks will be added, and more data types will be supported for these Tasks.

15.2 ALGORITHMS AND MODEL PERFORMANCE

15.2.1 Supervised Learning

With supervised learning algorithms, the data set is labeled. A validation method must be chosen (Chapter 5). As we have seen, for large data sets holdout validation can be used, which means splitting the data into training and validation (holdout) sets. Otherwise, for smaller data sets, it may be better to use the k-folds cross-validation method.

Supervised algorithms include Classification algorithms that can be used to predict categories (e.g., spam/not spam for email) or Regression algorithms that can be used to predict continuous data (real numbers). For both of these types of algorithms, the basic workflow is as follows:

- Get the data set
- Preprocess/scrub the data
- Iterate through these steps:
  - Feature engineering/feature selection/principal component analysis
  - Choose a validation method and split the data if necessary (first randomizing)
  - Choose an algorithm
  - Fit a model to the data
  - Train the model
  - Assess the model performance (e.g., accuracy for classification algorithms)
  - Tune hyperparameters
  - Visualize the results
  - Validate the model if holdout validation used
- Test the model
- Use model to make predictions

Classification Algorithms

Some basic classification algorithms include the following:

- Nearest Neighbor
- Linear Discriminant
- Decision Trees
- Support Vector Machines
- Neural Networks

Some of these algorithms are conceptually easy to grasp. For example, Nearest Neighbors algorithms use a distance metric (Chapter 6) to calculate how close data points are to each other and classify based on that distance. Decision trees (Chapter 4) create branches based on yes/no questions; an example will be given in the next section. Other algorithms, however, are very complex mathematically and are virtually impossible to explain to the novice. These algorithms must be used as a "black box". A black box means that you send input into it, you get output, but you really have no idea how the output was obtained. Neural Networks definitely fall into this category!

Once a model has been trained using one of these algorithms, it is necessary to assess the performance of the model. We have seen some of the assessment mechanisms already such as accuracy (Chapter 1) and confusion matrices (Chapter 8). Visualizing the categories using a scatter plot is also very helpful.

Regression Algorithms

Some basic algorithms include the following:

- Linear Regression
- Regression Trees
- Support Vector Machines

As with classification algorithms, some regression algorithms are easier for the novice to understand than others. Linear regression creates a linear function of predictor variables. Linear regression commonly uses a least squares algorithm, as we have seen in Chapter 12.

Because regression algorithms are used to predict real numbers, assessing the model performance is typically accomplished by measuring the differences between the actual and predicted values. The most common validation metric is Root Mean Squared Error (RMSE), which is the square root of the average squared error. The smaller the RMSE is, the better the fit. Visualizing the fit by plotting (as in Chapter 12) is also helpful.

15.2.2 Unsupervised Learning

With unsupervised learning, the data is not labeled. An algorithm, typically a Clustering algorithm, is used to discover patterns and group data into clusters. Some basic algorithms include the following:

- K-Means
- K-Nearest Neighbors
- Hierarchical
- Neural Networks

The K-Nearest Neighbors clustering algorithm is similar to the Nearest Neighbors classification algorithm in that it uses a distance metric to determine how closely spaced points are, and uses that to create the clusters. This particular algorithm puts the data points into mutually exclusive clusters. With some other algorithms, however, points can be members of more than one cluster.

One method of assessing how well the clusters have been established is by calculating ***silhouette coefficients***, which measure how similar individual points are to the other points in that particular cluster.

15.3 STATISTICS AND MACHINE LEARNING TOOLBOX™

Statistics and Machine Learning Toolbox™ has many built-in functions to perform ML tasks, and it also has some built-in labeled data sets that can be used as examples. It also has Apps built in for supervised learning (both classification and regression) but currently no App for unsupervised learning (clustering). The Apps are tools that allow you to train, validate, and test data using a variety of algorithms without writing code yourself. The Apps can also be used to learn how to write the code programmatically. Once a model has been created, the code can be autogenerated and inspected.

It is easiest to prepare the data set first, and then open up the appropriate App.

Most of the functions that fit models to data follow the naming convention: fit c/r algorithm (the word 'fit' followed by 'c' for classification or 'r' for regression, followed by a word representing the algorithm). For example, **fitctree** uses a decision tree for classification, and **fitrtree** uses a tree for regression.

There are many ML functions and options in the Apps. Most of this is beyond the scope of this book. Rather than exhaustive explanations, one example will be used for each type of algorithm (classification, regression, and clustering) to illustrate the basic ideas.

15.3.1 Classification

There are several types of classification algorithms, for which there are functions and also options within the Classification Learner App. These include the following:

- Decision Trees
- Discriminant Analysis
- Logistic Regression
- Naïve Bayes
- Support Vector Machines
- Nearest Neighbors
- Ensemble

There are several variations for most of these.

The classification algorithms have requirements for the types of data that are allowed. All of the algorithms accept data sets consisting of all numbers. Most of the algorithms accept data sets consisting of all categorical data (except for Discriminant Analysis, and Nearest Neighbors if using Hamming distance metric only). Most of the algorithms accept data sets consisting of some numerical features and some categorical (except for Discriminant Analysis and Nearest Neighbors).

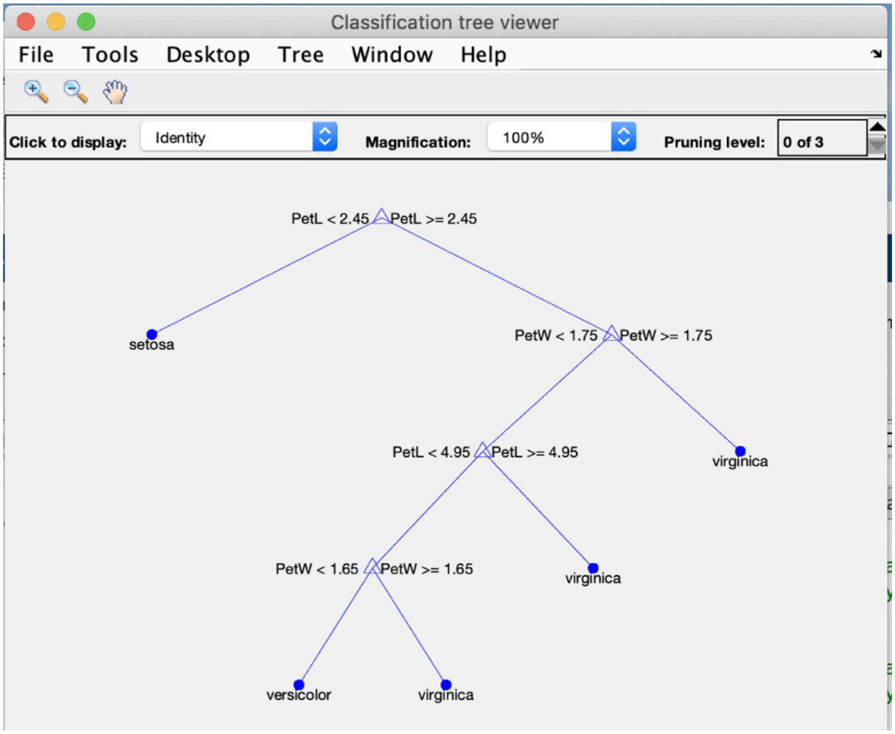
Classification Functions

Here is an example of fitting a decision tree to the Fisher Iris data. The function to do this is called **fitctree**. The PredictorNames property gives names for the Sepal Length, Sepal Width, Petal Length, and Petal Width. The cross-validation method is used for training, which by default uses 10 folds.

```
>> load fisheriris
>> irismodel=fitctree(meas, species, 'CrossVal', 'on', ...
'PredictorNames', {'SepL', 'SepW', 'PetL', 'PetW'})

irismodel=

  ClassificationPartitionedModel
    CrossValidatedModel: 'Tree'
         PredictorNames: {'SepL'  'SepW'  'PetL'  'PetW'}
           ResponseName: 'Y'
        NumObservations: 150
                  KFold: 10
              Partition: [1×1 cvpartition]
             ClassNames: {'setosa'  'versicolor'  'virginica'}
         ScoreTransform: 'none'

  Properties, Methods
```

One of the properties of the model is called Trained. This is a 10 × 1 cell array that stores the models used in each of the 10 folds. For example, irismodel.Trained{1} is the model that was created using the first tenth of the data as validation data, and the rest as the training data. The resulting decision tree can be displayed as follows, as shown in Fig. 15.1.

```
>> view(irismodel.Trained{1},'Mode', 'graph')
```



Click to display: Identity Magnification: 100% Pruning level: 0 of 3

FIGURE 15.1

Decision tree.

Notice that the branches of the decision tree are all based on the Petal Length and Petal Width. You can similarly view the other nine models (e.g., irismodel. Trained{2}, etc.).

Classification Learner App

The Classification Learner App allows you to graphically set parameters and to see the results from training and testing models. The first task is to split your cleaned data into training and testing sets. Then, from the MATLAB Home page, choose APPS and then Classification Learner. Choose "New Session" on the left, and then where the data is (workspace or a file). From the workspace, choose predictor and response variables on the left from your training variable(s), and on the right choose a validation method. For the validation method, you can choose cross validation and for that you choose the desired number of folds (the default is 5), or you can choose holdout validation and then the percentage of the training data set to use for validation (the default is 25%).

Then, click on "Start Session". One or more algorithms will be chosen by default. Under Model Type, click on the down arrow next to the chosen algorithms to see all of the possible algorithms. If your data is not of the correct type(s) for a particular algorithm, it will be grayed out and cannot be used. The best way to get started is to click on "All Quick to Train", and then click on the "Train" button. This will go through all of the available algorithms, and on the left will show the different algorithms with the results from each. The accuracy of each algorithm is important. You can choose a particular algorithm, and then you can view such diagnostics as a scatter plot and the confusion matrix. Once an accurate model is chosen, the model can then be tested using the test data. The Export button allows you to generate a function that would duplicate the results from the App, and also to export a model to a variable that can be used in the Command Window. Examining the code in the function is a good way to learn how to create models programmatically.

15.3.2 Regression

There are several types of regression algorithms, for which there are functions and also options within the Regression Learner App. These include the following:

- Linear Regression
- Regression Trees
- Support Vector Machines
- Gaussian
- Ensemble of Trees
- Neural Networks

There are several variations for most of these.

The regression algorithms have requirements for the types of data that are allowed.

Regression Functions

One function for regression is **fitlm**, which fits a linear regression model. The predictors can be numerical, logical, categorical, character, or string. The response can be numeric or logical. If the data set has not been cleaned, the **fitlm** function will exclude observations that include <missing>, <undefined>, or NaN values.

For example, we will load the carsmall.mat file and put some of the variables together in a table. Because the model year of each car is really a category, and so that later models (with higher numbers) will not adversely impact the result, that predictor feature is modified to be the type **categorical**. Passing this table to the **fitlm** function creates a model. There are many properties of the model, which can be seen with properties(mdl). By default, the Formula and Coefficients properties and some statistical results, including the RMSE, are displayed.

```
   >> load carsmall
   >> cartable=table(Cylinders, Horsepower, Weight, Model_Year, MPG);
   >> cartable.Model_Year=categorical(cartable.Model_Year);
   >> mdl=fitlm(cartable)
   mdl=

   Linear regression model:
       MPG ~ 1+Cylinders+Horsepower+Weight+Model_Year

   Estimated Coefficients:
                  Estimate        SE         tStat        pValue
                  ________    _________    ________    __________

(Intercept)          40.042       1.5901       25.182    1.0068e-41
Cylinders          -0.18671      0.42858     -0.43565       0.66417
Horsepower        -0.016474     0.017297     -0.95239       0.34354
Weight            -0.005531    0.0010132      -5.4588    4.4654e-07
Model_Year_76        1.2804      0.93786       1.3653       0.17569
Model_Year_82        7.5479       0.9923       7.6064    3.0992e-11

   Number of observations: 93, Error degrees of freedom: 87
   Root Mean Squared Error: 2.89
   R-squared: 0.879, Adjusted R-Squared: 0.872
   F-statistic vs. constant model: 126, p-value=2.68e-38
```

The properties can also be queried separately (e.g., the Formula), which show the linear combination of the predictors that was used:

```
>> mdl.Formula
ans=
MPG ~ 1+Cylinders+Horsepower+Weight+Model_Year
```

Regression Learner App

The Regression Learner App allows you to graphically set parameters and to see the results from training and testing models. From the MATLAB Home page, choose APPS and then Regression Learner. Choose "New Session" on the left, and then where the training data is (workspace or a file). From the workspace, choose predictor and response variables on the left, and on the right choose a validation method. Then, click on "Start Session". One or more algorithms will be chosen by default. Under Model Type, click on the down arrow next to the chosen algorithms, to see all of the possible algorithms. If your data is not of the correct type(s) for a particular algorithm, it will be grayed out and cannot be used. The best way to get started is to click on "All Quick to Train", and then click on the "Train" button. This will go through all of the available algorithms, and on the left will show the different algorithms with the results from each. The training results, including the RMSE, are shown. The model can then be tested using the test data. Once an accurate model has been chosen, the Export button allows you to generate a function that would duplicate the results from the App, and also to export a model to a variable that can be used in the Command Window.

15.3.3 Clustering

Clustering algorithms are unsupervised algorithms, used when the data is not labeled. These algorithms attempt to put the data into clusters, or groups. As of R2021b, there is no App, although there will be one in a future version.

Perhaps the simplest algorithm to understand is the ***k-means clustering*** algorithm. This algorithm creates k clusters (where k is a positive integer). Each cluster has a ***centroid***, which is the center of the cluster. The basic idea is that the distance between the data points and the mean of the cluster is minimized. With this algorithm, the clusters are all mutually exclusive. The function **kmeans** is used for this. This function returns several values, but one of the basic ways to call it is:

```
[idx, cent]=kmeans(X, k)
```

where *X* is the data set, *k* is the desired number of clusters, *idx* is a vector storing, for every observation, the index or the cluster number to which that observation was assigned, and *cent* is the centroid locations.

To illustrate this function, we will use the Fisher Iris data set (without the labels). We know that this data set stores 150 observations, 50 for each of the three types of irises. Loading the .mat file:

```
load fisheriris
```

creates the matrix variable *meas*, which stores the predictors. We will cheat a little here, knowing that the Petal length (column 3) and Petal width (column 4) are good predictors, so we will create our matrix with just those columns. We will also specify that we want three clusters:

```
fishX=meas(:, 3:4);
[idx, cent]=kmeans(fishX, 3);
```

The **gscatter** function can be used to visualize the clustering of the data. The **gscatter** function creates a scatter plot showing groups in different colors, as seen in Fig. 15.2.

```
gscatter(fishX(:,1),fishX(:,2), idx, 'rgb')
```

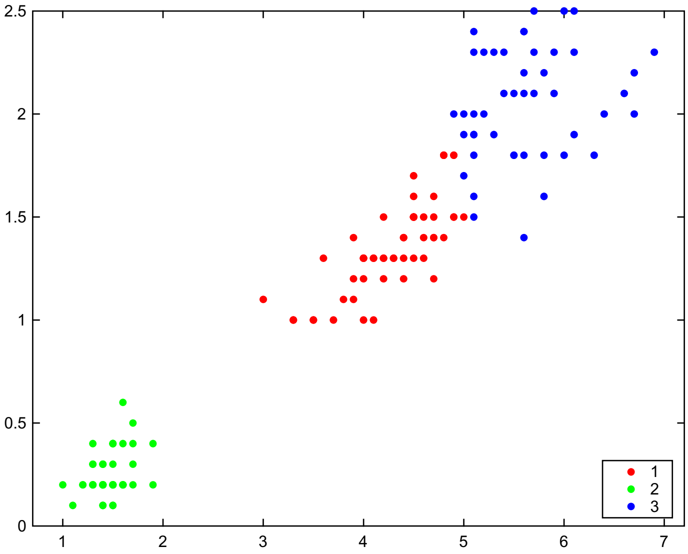


FIGURE 15.2
Gscatter plot.

We could also plot the centroids. We can see that the second category is well separated from the other two, but some of the points in Categories 1 and 3 are very close to each other. In fact, the **kmeans** function did not do a perfect job of finding the three classifications, but it came close. One piece of information is the number in each of the categories found by **kmeans** (knowing that in the original data set there were 50 in each category):

```
>> catlen=sum(idx == 1:3)
catlen=
     48     50     52
```

Of course, just because there were 50 observations categorized as 2, that does not mean that they were all correctly categorized, but it is an indication. Another way of visualizing the categories and how well separated they are from each other is with a **silhouette** plot, as seen in Fig. 15.3.

```
silhouette(fishX, idx)
```

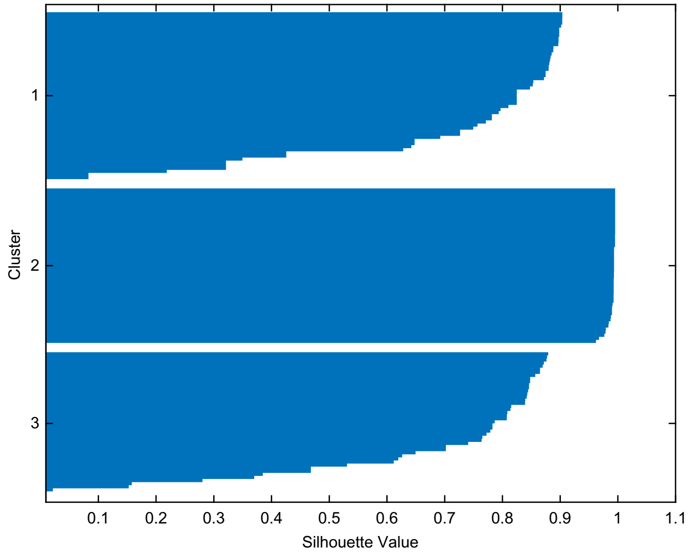


FIGURE 15.3
Silhouette plot.

Silhouette values measure how "similar" individual points are to the other points in the assigned cluster. A high value, close to 1, indicates that the points in the cluster have been assigned well. The silhouette values in Cluster 2 are all 1 or close to 1. The silhouette values for Clusters 1 and 3 are not as close to 1, which means that there is more uncertainty in assigning data points to those clusters.

■ Explore Other Interesting Features

Investigate how to add a least squares line to a scatter plot using the **lsline** function. ■

SUMMARY

COMMON PITFALLS

- Not cleaning data properly
- Not realizing that some algorithms require certain types of data
- Not splitting the data into training and testing sets

MATLAB Functions and Commands

ismissing
missing
fillmissing
rmoutliers
normalize
fitctree
fitrtree
fitlm
kmeans
gscatter
silhouette

Exercises

1. Load the census.mat data file, create a table with the *cdate* and *pop* variables, and then randomize the rows of the table.
2. Read the data from the outages.csv file into a table. Write code that will determine, for each feature, how many values are missing.
3. Load the accidents.mat file. Convert the *hwydata* matrix to a table using the **array2table** function. Modify the Properties.VariableNames property of your table to use the labels from the *hwyheaders* variable. Add the state labels to the beginning of the table using the **addvars** function.
4. Read the data from the outages.csv file into a table. Use the **fillmissing** function to replace the NaN values for the *Loss* and *Customers* features with the mean of the remaining values for that particular feature.
5. Read the data from the fisheriris.csv file into a table. Randomize the data and create a testing data set and a holdout data set. Use the **fitcknn** function to fit a K-Nearest Neighbors model to the test data. Use the **predict** function on the holdout data to predict the categories. Display a confustion matrix using the **confusionmat** function, passing the Species vector for the holdout set and the result from the prediction.
6. Read the data from the fisheriris.csv file into a table. Launch the Classification Learner App, and accept the defaults for the data and the validation method. Choose All Quick to Train, and then Train. Find the model with the greatest accuracy. Examine the confusion matrix for this model. Look at a scatter plot with the Petal Length on the x-axis, and the Petal Width on the y-axis. Does enabling PCA improve the accuracy? Click on Export to export the function that has been auto-generated.
7. Load the carbig.mat file, and create a table using Cylinders, Horsepower, Weight, Model_Year, and MPG. Make the Model_Year categorical. Launch the Regression Learner app and choose your table (MPG should be the response). Choose All Quick to Train, and then Train. Find the model with the lowest RMSE. Click on Export Model to export the model to the Command Window.
8. Load the carbig.mat file, and create a matrix using the Horsepower and Weight columns. Clean the missing data by removing any rows in which there are missing values. Use the **kmeans** function to put the data into seven categories. Use the **gscatter** function to display the clusters (make sure to specify seven different colors). Examine the **silhouette** plot. Try different values for k.

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APPENDIX I

MATLAB® Functions (Not Including Those Listed in the "Explore Other Interesting Features" Sections or in the "Data Science and Machine Learning Supplement" Sections)

abs	absolute value
addvars	adds variables to a table
all	true if all elements in the input argument are true
angle	angle of a complex number
any	true if any element in the input argument is true
append	concatenates text and does note remove blanks
area	filled two-dimensional area plot
array2table	converts an array to a table
asin	arcsine in radians
asind	arcsine in degrees
asinh	inverse hyperbolic sine in radians
audioplayer	creates an audioplayer object
audiorecorder	creates an audiorecorder object
axis	sets limits on axes for a plot
bar	two-dimensional bar chart
bar3	three-dimensional bar chart
bar3h	three-dimensional horizontal bar chart
barh	two-dimensional horizontal bar chart
blanks	creates a character vector of all blank spaces
cast	casts a variable to a specified type
categorical	converts cell array to categorical array
categories	lists categories from a categorical array
ceil	rounds toward infinity
cell	creates a cell array
celldisp	displays contents of a cell array
cellplot	displays contents of a cell array in boxes

MATLAB. https://doi.org/10.1016/B978-0-323-91750-6.09999-6

cellstr	converts from a character matrix to a cell array of character vectors
char	creates a character matrix
checkcode	displays Code Analyzer results for code files
class	returns the type or class of the input argument
clear	clears variable(s) and functions from the workspace
clearvars	clears variable(s) from the workspace
clf	clears the figure window
clock	stores the current date and time in a vector
collect	collects like terms in a symbolic math expression
colorbar	displays a color scale in a plot
colormap	returns the current colormap, or sets a matrix to be the current colormap
comet	animated two-dimensional plot
comet3	three-dimensional animated plot
complex	creates a complex number
conj	complex conjugate
connector	connects mobile device to MATLAB
contains	returns true if a substring is found in text
count	counts the number of occurrences of a substring in text
cross	cross product
csvread	reads from a file filename.csv (no longer recommended)
csvwrite	writes to a file filename.csv (no longer recommended)
cummax	cumulative, or running, maximum of a vector or columns of a matrix
cummin	cumulative, or running, minimum of a vector or columns of a matrix
cumprod	cumulative, or running, product of a vector or columns of a matrix
cumsum	cumulative, or running, sum of a vector or columns of a matrix
cylinder	returns three-dimensional data vectors to create a cylinder
date	stores the current date as a character vector
dbcont	continue executing code in debug mode
dbquit	quit debug mode
dbstep	step through code in debug mode
dbstop	set a breakpoint in debug mode

deblank	gets rid of trailing blanks in text
deg2rad	converts from degrees to radians
demo	shows MATLAB Examples in the Help Browser
det	finds the determinant of a matrix
diag	returns the diagonal of a matrix, or creates a diagonal matrix
diff	finds differences between consecutive elements; used to approximate derivatives
disp	simple display (output)
doc	brings up a documentation page
dot	dot product
double	converts to the type double
echo	toggle; displays all statements as they are executed
end	ends control statements and functions; refers to last element
endsWith	returns true if text ends with a given pattern
eq	functional equivalent of the equality operator
erase	removes occurrences of a substring in text
error	displays an error message
eval	evaluates text as a function or command
exit	quits out of MATLAB
exp	exponential function
expand	expands a symbolic math expression
eye	creates an identity matrix
ezplot	simple plot function that plots a function without need for data vectors
factor	factors a symbolic math expression
factorial	factorial of an integer n, is 1*2*3*…*n
false	equivalent to logical(0); creates an array of false values
fclose	closes an open file
feof	true if the specified file is at the end-of-file
feval	evaluates a function handle on text as a function call
fgetl	low-level input function reads one line from a file as a character vector
fgets	same as fgetl but does not remove newline characters
fieldnames	returns the names of fields in a structure as a cell array of character vectors
figure	create or refer to Figure Windows
fillmissing	fills missing values in data structures such as tables

find	returns indices of an array for which a logical expression is true
fitctree	fits a model to data using a decision tree for classification
fitlm	fits a linear regression model
fitrtree	fits a model to data using a decision tree for regression
fix	rounds toward zero
flip	flips an array, either left to right or up to down
fliplr	flips columns of a matrix from left to right
flipud	flips rows of a matrix up to down
floor	rounds toward negative infinity
fopen	low-level file function; opens a file for a specified operation
format	many options for formatting displays
fplot	plots a function passed as a function handle
fprintf	formatted display (output); writes either to a file or to the screen (the default)
fscanf	low-level file input function; reads from a file into a matrix
func2str	converts from a function handle to a character vector
fzero	attempts to find a zero of a function, given the function handle
gca	handle to the current axes
gcf	handle to the current figure
get	gets properties of a plot object
getaudiodata	gets amplitude form an audiorecorder object
getframe	gets a movie frame, which is a snapshot of the current plot
ginput	gets graphical coordinates from a mouse click
grid	plot toggle; turns grid lines on or off
gscatter	creates a scatter plot using different colors to display groups
gtext	allows the user to place text on a plot in location of a mouse click
head	displays the first eight rows from a table
height	the number of rows in a matrix
help	displays help information for built-in or user-defined functions, or scripts
histogram	plot function: plots a histogram
hold	plot toggle; freezes plot in Figure Window so the next will be superimposed

i	constant for the square root of negative one
im2double	converts an image matrix to type double
imag	imaginary part of a complex number
image	displays an image matrix
imread	reads in an image matrix
imshow	displays an image
imwrite	writes a matrix in an image format
inf	constant for infinity
input	prompts the user and reads user's input
int	symbolic math integration
int16	converts a number to a 16-bit signed integer
int2str	converts from an integer to a character vector storing the integer
int32	converts a number to a 32-bit signed integer
int64	converts a number to a 64-bit signed integer
int8	converts a number to an 8-bit signed integer
intersect	set intersection
intmax	largest value possible in a specified integer type
intmin	smallest value possible in a specified integer type
inv	inverse of a matrix
isa	true if the input argument is the specified class
iscellstr	true if the input argument is a cell array storing only character vectors
ischar	true if the input argument is a string, or character vector
isdiag	true if the input matrix is a diagonal matrix
isempty	true if the input argument is an empty vector or empty string
isequal	true if two array arguments are equal element-by-element
isfield	true if a string or character vector is the name of a field within a structure
iskeyword	true if the text input argument is the name of a keyword
isletter	true if the input argument is a letter of the alphabet
ismember	set function receives two sets; true for every member of first set also in second
ismethod	true if a string or character vector is a method of an object
ismissing	true for missing entries in a data structure
isnumeric	true if the argument is any numeric type
isreal	true if input argument is a real number (not complex)

issorted	true if the input vector is sorted in ascending order
issortedrows	true if the rows in a matrix are sorted
isspace	true if the input argument is a white space character
isstring	true if the input argument is a string array
isStringScalar	true if the input argument is a string scalar
isstrprop	true if the string argument is a specified property
isstruct	true if the input argument is a structure
issymmetric	true if the input matrix is symmetric
j	constant for the square root of negative one
jet	returns all or part of the 256 colors in the jet colormap
join	appends strings in string arrays together
jsondecode	decodes from JSON format, e.g., to a structure
jsonencode	encodes a MATLAB type (e.g., a struct) into JSON format
kmeans	performs k-means clustering
legend	displays a legend on a plot
length	length, or number of elements, in a vector; largest dimension for a matrix
limit	computes limit of a symbolic math expression
line	graphics primitive object that creates a line
linspace	creates a vector of linearly spaced values
load	inputs a file into a matrix or reads variables from a .mat file (the default)
log	natural logarithm
log10	base 10 logarithm
log2	base 2 logarithm
logical	converts numbers to the type logical
loglog	plot function that uses logarithmic scales for x and y axes
logspace	creates a vector of logarithmically spaced values
lookfor	looks for text in the H1 comment line in files
lower	converts letters to lower-case in a string or character vector
listdlg	creates a dialog box that allows the user to make a choice
max	the maximum value in a vector, or for every column in a matrix
maxk	the maximum k values in a vector, or for every column in a matrix
mean	the mean (average) of values in a vector, or every column in a matrix

median	the median (middle) value in a sorted vector, or for every column in a matrix
menu	displays a menu of push buttons and returns number of choice (not recommended)
mesh	three-dimensional mesh surface plot
meshgrid	creates x and y vectors to be used in images or as function arguments
methods	displays methods of a class
min	the minimum value in a vector, or for every column in a matrix
mink	the minimum k values in a vector, or for every column in a matrix
missing	creates missing value(s) in a data structure
mobiledev	creates an object to enable reading sensor data from a mobile device
mod	modulus after division
mode	the maximum value in a vector, or for every column in a matrix
movegui	moves a Figure Window within the screen
movie	plays a movie, or sequence of screen shots
movevars	moves the locations of variables in a table
mustBeGreaterThan	validates that one value is greater than another
mustBeInteger	validates that an argument is of any integer type
mustBeNumeric	validates that an argument is of any numeric type
mustBePositive	validates that an argument is a positive number
mustBeText	validates that an argument is text
mustBeVector	validates that an argument is a vector
namelengthmax	the maximum length of identifier names
NaN	mathematics constant for "Not a Number"
nargin	number of input arguments passed to a function
nargout	number of output arguments expected to be returned by a function
ne	functional equivalent of the inequality operator
newline	returns a newline character
normalize	normalizes data in a table or matrix
nthroot	nth root of a number
num2str	converts a real number to a character vector containing the number
numden	symbolic math function, separates the numerator and denominator of a fraction
numel	total number of elements in a vector or matrix
ones	creates a matrix of all ones

parula	returns all or part of the 256 colors in the parula colormap
pause	pauses the code a specified number of seconds
patch	graphics primitive object that creates a filled in two-dimensional polygon
pi	constant for π
pie	creates a two-dimensional pie chart
pie3	creates a three-dimensional pie chart
pink	returns all or part of the 256 colors in the pink colormap
play	plays an audio signal
plot	simple plot function, plots 2D points; markers, color, etc. can be specified
plot3	simple three-dimensional plot function, plots three-dimensional points
plus	the functional form of the addition operator; also concatenates strings
polarplot	plot function for complex numbers, plots the magnitude and angle
poly2sym	converts a vector of coefficients of a polynomial to a symbolic expression
polyder	derivative of a polynomial
polyfit	fits a polynomial curve of a specified degree to data points
polyint	integral of a polynomial
polyval	evaluates a polynomial at specified value(s)
pretty	displays a symbolic expression using exponents
preview	previews the first eight rows of a file without opening and reading it in
print	prints or saves a figure or image
prod	the product of all values in a vector, or of every column in a matrix
profile	toggle; the Profiler generates reports on execution time of code
properties	displays properties of a class
quad	integration using Simpson's method
quit	quits MATLAB
rad2deg	converts from radians to degrees
rand	generates uniformly distributed random real number(s) in the open interval (0,1)
randi	generates random integer(s) in the specified range
randn	generates normally distributed random real numbers

readmatrix	reads a spreadsheet or .csv file into a matrix
readtable	reads a spreadsheet or .csv file into a table
real	real part of a complex number
recordblocking	records audio from a microphone
rectangle	graphics primitive to create a rectangle; curvature can vary
rem	remainder after division
removevars	removes variables in a table
renamevars	renames variables in a table
repelem	replicates elements in a matrix; creates $m \times n$ copies of each
repmat	replicates a matrix; creates $m \times n$ copies of the matrix
reshape	changes dimensions of a matrix to any matrix with the same number of elements
rgb2gray	converts an RGB image matrix to grayscale
rmfield	remove a field from a structure
rmoutliers	removes outliers from a data structure
rng	random number generator, sets the seed for random functions and gets the state
roots	roots of a polynomial equation
rot90	rotates a matrix 90 degrees counterclockwise
round	rounds a real number toward the nearest integer
rref	puts an augmented matrix in reduced row echelon form
save	writes a matrix to a file or saves variables to a .mat file
scatter	creates a scatter plot
semilogx	plot function, uses a scale for logarithmic x and a linear scale for y
semilogy	plot function, uses a linear scale for x and a logarithmic scale for y
set	sets properties of a plot object
setdiff	set function, returns elements that are in one vector, but not in another
setxor	set exclusive or, returns the elements that are not in the intersection of two sets
sgtitle	puts a title on a set of subplots
sign	signum, returns −1, 0, or 1
silhouette	creates a silhouette plot to show categories for a clustering algorithm
simplify	simplifies a symbolic math expression

sin	sine in radians
sind	sine in degrees
single	converts a number to the type single
sinh	hyperbolic sine in radians
size	returns the dimensions of a matrix
solve	symbolic math function to solve an equation or simultaneous equations
sort	sorts the elements of a vector (default is ascending order)
sortrows	sorts the rows of a matrix; for text results in an alphabetical sort
sound	sends a sound signal (vector of amplitudes) to an output device
sphere	returns three-dimensional data vectors to create a sphere
sprintf	creates a formatted string or character vector
sqrt	square root
startsWith	true if input text starts with a given pattern
std	standard deviation
stem	two-dimensional stem plot
stem3	three-dimensional stem plot
str2double	converts from text containing a number to a double number
str2func	converts text to a function handle
str2num	converts from text containing number(s) to a number array
strcat	horizontal text concatenation
strcmp	string compare, used instead of equality operator for text
strcmpi	string compare, ignoring case
strfind	find a substring within a longer string or character vector
string	creates a string
strings	preallocates a string array
strip	removes leading and trailing whitespace characters from text
strjoin	concatenates text in a cell array or string array into a long string
strlength	determines the length of a string
strncmp	string compare the first n characters of text
strncmpi	string compare the first n characters, ignoring case
strrep	replace all occurrences of one substring with another within longer text

strsplit	splits a string or character vector into elements in a cell array
strtok	breaks one longer string into two shorter strings, with all characters retained
strtrim	deletes both leading and trailing blanks from a string or character vector
struct	create a structure by passing pairs of field names and values
subplot	creates a matrix of plots in the Figure Window
subs	substitutes a value into a symbolic math expression
subtitle	puts a subtitle on a plot
sum	the sum of the values in a vector or of every column in a matrix
summary	shows variables and statistics for a table
surf	three-dimensional surface plot
sym	creates a symbolic variable or expression
sym2poly	converts a symbolic expression to a vector of coefficients for a polynomial
syms	creates multiple symbolic variables
table	creates a table data structure
tail	displays the last eight rows from a table
text	graphics primitive object to put text on a plot
textscan	file input function, reads from a file into a cell array of column vectors
tic / toc	used to time code
timeit	times a function execution
title	writes text as a title on a plot
trace	the trace (sum of values on the diagonal) of a matrix
trapz	trapezoidal rule to approximate the area under a curve
true	equivalent to logical(1), creates a matrix of all true values
type	display the contents of a file in the Command Window
uibuttongroup	groups together button objects
uicontrol	basic function to create graphical user interface objects of different styles
uifigure	creates a UI Figure Window
uilabel	creates a UI label
uislider	creates a UI slider

uint16	converts a number to a 16-bit unsigned integer
uint32	converts a number to a 32-bit unsigned integer
uint64	converts a number to a 64-bit unsigned integer
uint8	converts a number to an 8-bit unsigned integer
uipanel	groups together graphical user interface objects
union	set function, the union of two sets
unique	returns all of the unique values within a set (vector)
upper	converts all letters to upper-case
var	variance
varargin	built-in cell array to store input arguments
varargout	built-in cell array to store output arguments
weboptions	creates options as Key Value pairs for web service requests
webread	reads information from a RESTful web service
webwrite	reads information from a web service using a POST request
who	displays variables in the base workspace
whos	displays more information on the variables in the base workspace
width	returns the number of columns in a matrix
writematrix	writes from a matrix to a spreadsheet or .csv file
writetable	writes from a table to a spreadsheet or .csv file
xlabel	puts text as a label on the x-axis of a plot
xline	plots a vertical line
xlsread	reads from a spreadsheet with filename.xls (no longer recommended)
xlswrite	writes to a spreadsheet with filename.xls (no longer recommended)
xticklabels	specifies labels for the tick marks on the x-axis of a plot
xor	exclusive or, true if only one argument is true
ylabel	puts text as a label on the y-axis of a plot
yline	plots a horizontal line
zeros	creates a matrix of all zero values
zlabel	puts text as a label on the z-axis of a three-dimensional plot

MATLAB® and Simulink Toolboxes

In addition to the many functions included in MATLAB, there are additional Toolboxes that can be added. These toolboxes have groups of related functions that can be used for more advanced computations and data processing. The MathWorks, Inc. also has a family of simulation software called Simulink; it, too, can be augmented with additional Toolboxes. For more detailed information, see the website www.mathworks.com.

Here is a list of some of these Toolboxes:

Statistics and Machine Learning Toolbox™ (some used in this text)
Deep Learning Toolbox™
Reinforcement Learning Toolbox™
Text Analytics Toolbox™ (mentioned in this text)
Curve Fitting Toolbox™ (mentioned in this text)
Symbolic Math Toolbox™ (some used in this text)
Partial Differential Equation Toolbox™
Optimization Toolbox™
Mapping Toolbox™
Image Processing Toolbox™
Data Acquisition Toolbox™
Signal Processing Toolbox™
Control System Toolbox™
Parallel Computing Toolbox™
Robotics Toolbox™
Automated Driving Toolbox™
Aerospace Toolbox™
Bioinformatics Toolbox™

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MATLAB®

A PRACTICAL INTRODUCTION TO PROGRAMMING AND PROBLEM SOLVING

SIXTH EDITION

STORMY ATTAWAY

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MATLAB: A Practical Introduction to Programming and Problem Solving, winner of TAA's 2017 Textbook Excellence Award ("Texty"), guides the reader through both programming and built-in functions to easily exploit MATLAB's extensive capabilities for tackling engineering and scientific problems. Assuming no knowledge of programming, this book starts with programming concepts, such as variables, assignments, and selection statements, moves on to loops, modular code and data structures and then solves problems using both the traditional programming method and the power of MATLAB. Advanced applications include data transfer, graphics, object-oriented programming, event-driven programming, and image processing. The sixth edition has been updated to reflect the functionality of the current version of MATLAB (R2021b) and includes the introduction of basic data science and machine learning concepts for context.

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- Presents programming concepts and MATLAB built-in functions side by side, giving students the ability to program efficiently and exploit the power of MATLAB to solve technical problems
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NEW TO THE SIXTH EDITION:

- Use of MATLAB version R2021b
- New sections introducing concepts relevant to data science and machine learning at the end of every chapter along with a new Basic Machine Learning Algorithms and Concepts chapter
- New section introducing controls and tasks in the Live Editor
- New section on validating function arguments
- Earlier coverage of matrix operations and matrix properties
- Earlier coverage of live scripts
- Earlier coverage of .mat files
- Usage of built-in files, including .mat files, .csv files, and .jpg files
- More coverage of data structures including tables

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