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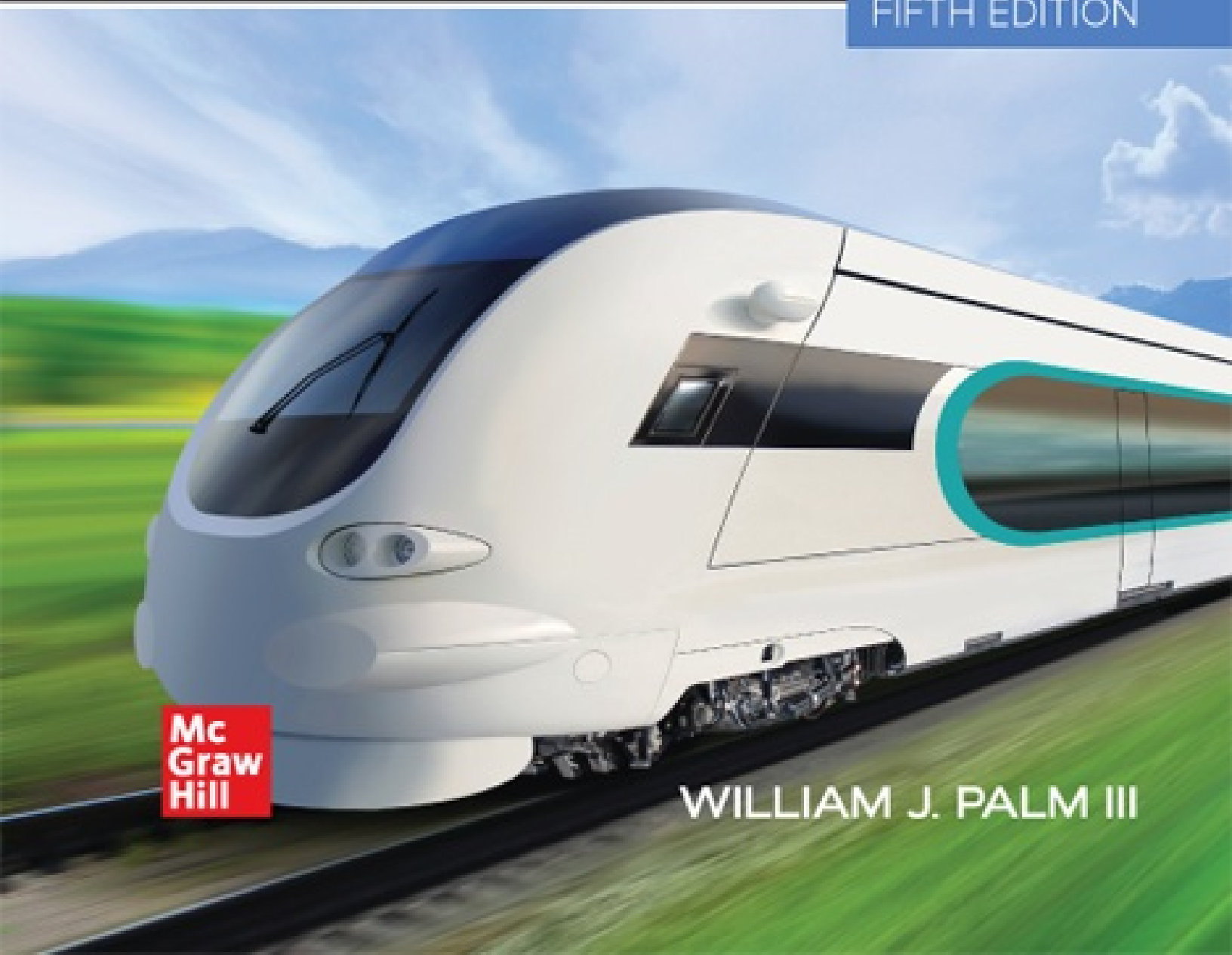
MATLAB®

for

ENGINEERING APPLICATIONS

FIFTH EDITION



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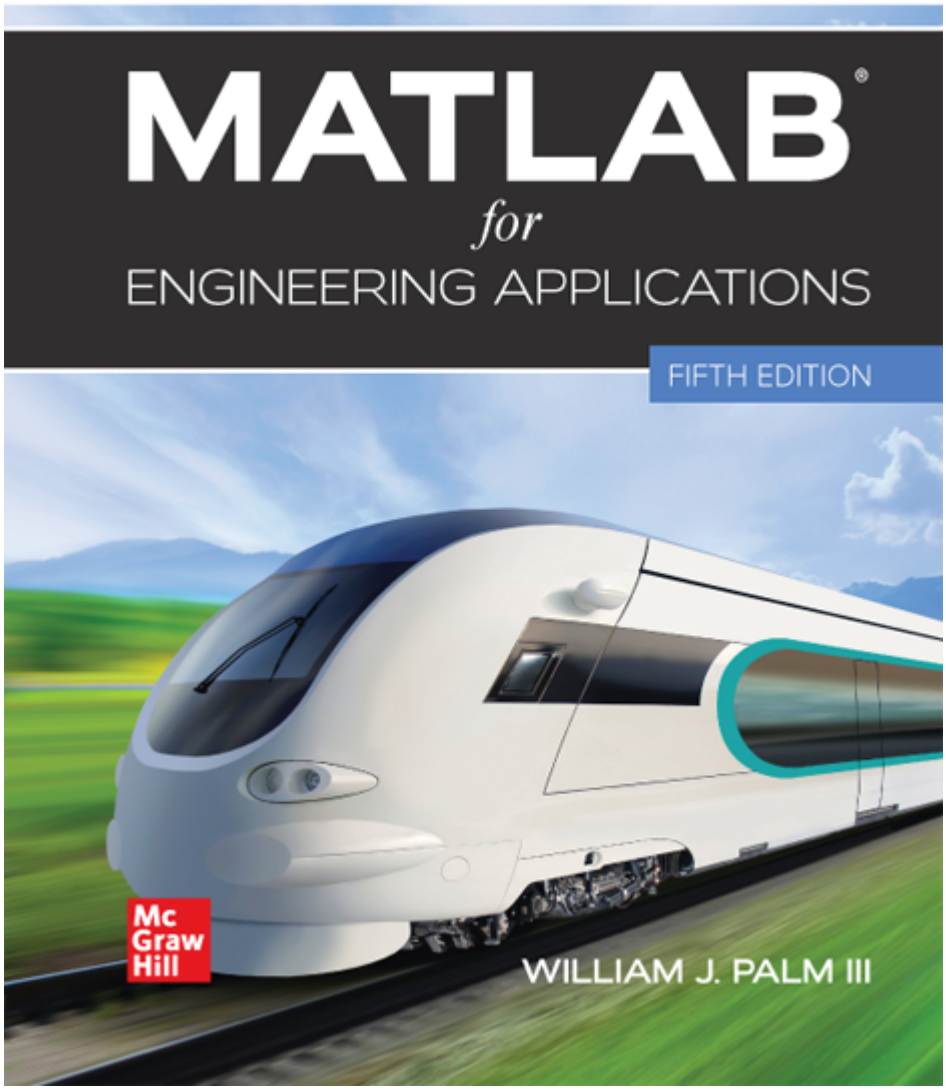

MATLAB® for Engineering Applications

William J. Palm III
University of Rhode Island

MATLAB® FOR ENGINEERING APPLICATIONS

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To my sisters, Linda and Chris, and to my parents, Lillian and William

ABOUT THE AUTHOR

William J. Palm III is Emeritus Professor of Mechanical Engineering at the University of Rhode Island. In 1966 he received a B.S. from Loyola College in Baltimore, and in 1971 a Ph.D. in Mechanical Engineering and Astronautical Sciences from Northwestern University in Evanston, Illinois.

During his 44 years as a faculty member, he taught 19 courses. One of these is a freshman MATLAB course, which he helped develop. He has authored eight textbooks dealing with modeling and simulation, system dynamics, control systems, and MATLAB. These include *System Dynamics,* 4th ed. (McGraw Hill, 2021). He wrote a chapter on control systems in the *Mechanical Engineers' Handbook,* 3rd ed. (M. Kutz, ed., Wiley, 2016), and was a special contributor to the fifth editions of *Statics* and *Dynamics,* both by J. L. Meriam and L. G. Kraige (Wiley, 2002).

Professor Palm's research and industrial experience are in control systems, robotics, vibrations, and system modeling. He was the Director of the Robotics Research Center at the University of Rhode Island from 1985 to 1993, and is the coholder of a patent for a robot hand. He served as Acting Department Chair from 2002 to 2003. His industrial experience is in automated manufacturing; modeling and simulation of naval systems, including underwater vehicles and tracking systems; and design of control systems for underwater-vehicle engine-test facilities.

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PREFACE

Formerly used mainly by specialists in signal processing and numerical analysis, MATLAB® has achieved widespread and enthusiastic acceptance throughout the engineering community. Many engineering schools require a course based entirely or in part on MATLAB early in the curriculum. MATLAB is programmable and has the same logical, relational, conditional, and loop structures as other programming languages. Thus it can be used to teach programming principles. In most engineering schools, MATLAB is the principal computational tool used throughout the curriculum. In some technical specialties, such as signal processing and control systems, it is the standard software package for analysis and design.

The popularity of MATLAB is partly due to its long history, and thus it is well developed and well tested. People trust its answers. Its popularity is also due to its user interface, which provides an easy-to-use interactive environment that includes extensive numerical computation and visualization capabilities. Its compactness is a big advantage. For example, you can solve a set of many linear algebraic equations with just three lines of code, a feat that is impossible with traditional programming languages. MATLAB is also extensible; currently more than 30 “toolboxes” in various application areas can be used with MATLAB to add new commands and capabilities.

MATLAB is available for a number of operating systems. It is compatible across all these platforms, which enables users to share their programs, insights, and ideas. This text is based on release R2021a of the software. This includes MATLAB version 9.10. Some of the material in Chapter 9 is based on the Control System toolbox, Version 10.10. Chapter 10 is based on Version 10.3 of Simulink®, and Chapter 11 is based on Version 8.7 of the Symbolic Math toolbox.

TEXT OBJECTIVES AND PREREQUISITES

This text is intended as a stand-alone introduction to MATLAB. It can be used in an introductory course, as a self-study text, or as a supplementary text. The text's material is based on the author's experience in teaching a required two-credit semester course devoted to MATLAB for engineering freshmen. In addition, the text can serve as a reference for later use. The text's many tables and its referencing system in an appendix have been designed with this purpose in mind. A secondary objective is to introduce and reinforce the use of problem-solving methodology as practiced by the engineering profession in general and as applied to the use of computers to solve problems in particular. This methodology is introduced in Chapter 1.

The reader is assumed to have some knowledge of algebra and trigonometry; knowledge of calculus is not required for the first eight chapters. Some knowledge of high school chemistry and physics, primarily simple electric circuits, and basic statics and dynamics, is required to understand some of the examples.

TEXT ORGANIZATION

In addition to updating material from the previous edition to include new features, new functions, and changes in syntax and function names, the text incorporates the many suggestions made by reviewers and other users. More examples and homework problems have been added.

The text consists of 12 chapters. The first five chapters constitute a basic course in MATLAB. The remaining seven chapters are independent of each other and cover more advanced applications of MATLAB, the Control Systems toolbox, Simulink, and the Symbolic Math toolbox.

Chapter 1 gives an overview of MATLAB features, including its windows and menu structures. It also introduces the problem-solving methodology.

Chapter 2 introduces the concept of an array, which is the fundamental data element in MATLAB, and describes how to use numeric arrays, cell arrays, and structure arrays for basic mathematical operations.

Chapter 3 discusses the use of functions and files. MATLAB has an extensive number of built-in math functions, and users can define their own functions and save them as a file for reuse.

Chapter 4 introduces programming with MATLAB and covers relational and logical operators, conditional statements, for and while loops, and the

switch structure.

Chapter 5 deals with two- and three-dimensional plotting. It first establishes standards for professional-looking, useful plots. In the author's experience, beginning students are not aware of these standards, so they are emphasized. The chapter then covers MATLAB commands for producing different types of plots and for controlling their appearance. The Live Editor, which is a major addition to MATLAB, is covered in Section 5.1.

Chapter 6 covers function discovery, which uses data plots to discover a mathematical description of the data and is a useful tool for model building. It is a common application of plotting, and a separate section is devoted to this topic. The chapter also treats polynomial and multiple linear regression as part of its modeling coverage.

Chapter 7 reviews basic statistics and probability and shows how to use MATLAB to generate histograms, perform calculations with the normal distribution, and create random number simulations. The chapter concludes with linear and cubic spline interpolation.

Chapter 8 covers the solution of linear algebraic equations, which arise in applications in all fields of engineering. This coverage establishes the terminology and some important concepts required to use the computer methods properly. The chapter then shows how to use MATLAB to solve underdetermined and overdetermined systems of linear equations.

Chapter 9 covers numerical methods for calculus and differential
equations. Numerical integration and differentiation methods are treated. Ordinary differential equation solvers in the core MATLAB program are covered, as well as the linear system solvers in the Control System toolbox. For those readers not familiar with differential equations, this chapter provides some background for Chapter 10.

Chapter 10 introduces Simulink, which is a graphical interface for building simulations of dynamic systems. Simulink has increased in popularity and has seen increased use in industry. The MathWorks provides Simulink support packages for computer hardware such as LEGO© MINDSTORMS©, Arduino©, and Raspberry Pi©, which are popular with researchers and hobbyists for controlling drones and robots. These packages let you develop and simulate algorithms that run standalone on the supported hardware. They include a library of Simulink blocks for configuring and accessing the hardware's sensors, actuators, and

communication interfaces. You can also tune parameters live from your Simulink model while your algorithm runs on the hardware. The MathWorks supports an active user community online where you can see applications and download files. Chapter 10 discusses some of the robotic vehicle applications.

Chapter 11 covers symbolic methods for manipulating algebraic expressions and for solving algebraic and transcendental equations, calculus, differential equations, and matrix algebra problems. The calculus applications include integration and differentiation, optimization, Taylor series, series evaluation, and limits. Laplace transform methods for solving differential equations are also introduced. This chapter requires the use of the Symbolic Math toolbox.

Chapter 12 introduces MATLAB Mobile, which is an application available from The Mathworks that enables you to connect a mobile device like a smartphone to a MATLAB session running on the MathWorks Computing Cloud or on your computer. The chapter shows how to use smartphone sensors, such as an accelerometer, to collect data in the field. The chapter also contains some suggestions for course projects, based on the author's experience in teaching a freshman MATLAB course. The chapter concludes with a brief introduction to the MATLAB App Designer.

Appendix A contains a guide to the commands and functions introduced in the text. Appendix B is an introduction to producing animation and sound with MATLAB. While not essential to learning MATLAB, these features are helpful for generating student interest. Appendix C is a list of references. Appendix D summarizes functions for creating formatted output. Answers to selected problems and an index appear at the end of the text.

All figures, tables, equations, and exercises have been numbered according to their chapter and section. For example, Figure 3.4–2 is the second figure in Chapter 3, Section 4. This system is designed to help the reader locate these items. The end-of-chapter problems are the exception to this numbering system. They are numbered 1, 2, 3, and so on to avoid confusion with the in-chapter exercises.

NEW TO THIS EDITION

As well as updating the coverage to include changes in MATLAB syntax and MATLAB screens, this edition includes 20 percent more numbered, major engineering examples. Also, 30 percent of the chapter problems are new. A new chapter has been added, Chapter 12 Projects with MATLAB, which introduces MATLAB Mobile and the MATLAB App Designer, and which covers programming for game projects in MATLAB.

SPECIAL REFERENCE FEATURES

The text has the following special features, which have been designed to enhance its usefulness as a reference.

- Throughout each of the chapters, numerous tables summarize the commands and functions as they are introduced.
- Appendix A is a complete summary of all the commands and functions described in the text, grouped by category, along with the number of the page on which they are described.
- At the end of the chapter is a list of the key terms introduced in the chapter, with a reference to where they are introduced.
- The index has four sections: a listing of MATLAB symbols, an alphabetical list of MATLAB commands and functions, a list of Simulink block names, and an alphabetical list of topics.

PEDAGOGICAL AIDS

The following pedagogical aids have been included:

- Each chapter begins with an overview.
- Test Your Understanding exercises appear throughout the chapters near the relevant text. These relatively straightforward exercises allow readers to assess their grasp of the material as soon as it is covered. In most cases the answer to the exercise is given with the exercise. Students should work these exercises as they are encountered.
- Each chapter ends with numerous problems, grouped according to the relevant section.
- Each chapter contains numerous practical examples. The major examples are numbered.
- Each chapter has a summary section that reviews the chapter's objectives.

- Answers to many end-of-chapter problems appear at the end of the text. These problems are denoted by an asterisk next to their number (for example, 15*).

Two features have been included to motivate the student toward MATLAB and the engineering profession:

- Most of the examples and the problems deal with engineering applications. These are drawn from a variety of engineering fields and show realistic applications of MATLAB. A guide to these examples appears on page vii.

- The facing page of each chapter contains a photograph of a recent engineering achievement that illustrates the challenging and interesting opportunities that await engineers in the 21st century. A description of the achievement, its related engineering disciplines, and a discussion of how MATLAB can be applied in those disciplines accompanies each photo.

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ONLINE RESOURCES

An Instructor's Manual is available online for instructors who have adopted this text. This manual contains the complete solutions to all of the Test Your Understanding exercises and to all of the chapter problems. The text website also has downloadable files containing the major programs and PowerPoint slides keyed to the text.

MATLAB INFORMATION

For MATLAB and Simulink product information, please contact:

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Many individuals are due credit for this text. Working with faculty at the University of Rhode Island in developing and teaching a freshman course based on MATLAB has greatly influenced this text. Email from many users contained useful suggestions. The author greatly appreciates their contributions.

The MathWorks, Inc., has always been very supportive of educational publishing. I especially want to thank Naomi Fernandes of The MathWorks, Inc., for her help. Theresa Collins, Maria McGreal, and Beth Bettcher of McGraw Hill Education and Beth Baugh efficiently handled the manuscript reviews and guided the text through production.

My sisters, Linda and Chris, have always been there, cheering my efforts. My parents, Lillian and William, were always there for support before they passed away. Finally, I want to thank my wife, Mary Louise, and my children, Aileene, Bill, and Andy, for their understanding and support of this project over the last 25 years.

William J. Palm III
Kingston, Rhode Island
March 2021

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Engineering in the 21st Century. . .

Remote Exploration

Source: NASA

It will be many years before humans can travel to other planets. In the meantime, unmanned probes have been rapidly increasing our knowledge of the universe. Their use will increase in the future as our technology develops to make them more reliable and more versatile. Better sensors are expected for imaging and other data collection. Improved robotic devices will make these probes more autonomous, and more capable of interacting with their environment, instead of just observing it.

NASA's planetary rover *Sojourner* landed on Mars on July 4, 1997, and excited people on Earth while they watched it successfully explore the Martian surface to determine wheel-soil interactions, to analyze rocks and soil, and to return images of the lander for damage assessment.

Then in early 2004, two improved rovers, *Spirit* and *Opportunity,* landed on opposite sides of the planet. In one of the major discoveries of the 21st century, they obtained strong evidence that water once existed on Mars in significant amounts. Although planned to operate for only 90 Martian days, *Spirit* operated for seven years. The rover likely lost power due to excessively cold internal temperatures. *Opportunity* went inactive in 2018, having already exceeded its planned operational life by many Earth years.

The rover *Curiosity* used the innovative "skycrane" to land on Mars in 2012 less than 2.4 km (1.5 mi) from its intended target after a 563,000,000 km (350,000,000 mi) journey. It was designed to investigate the Martian climate and geology; to assess whether the Gale crater ever had an environment suitable for microbial life, and to determine the habitability of the site for future human exploration. *Curiosity* has a mass of 899 kg (1,982 lb) including 80 kg (180 lb) of instruments. The rover is 2.9 m (9.5 ft) long by 2.7 m (8.9 ft) wide by 2.2 m (7.2 ft) in height. It discovered unexplained variations in oxygen and methane, and found remnants of an ancient oasis.

Perseverance is a car-sized rover designed to explore the crater Jezero on Mars. It was launched in July 2020 and successfully landed in February 2021. *Perseverance* has a design similar to *Curiosity*, but also carries the experimental mini-helicopter *Ingenuity* that was able to fly in the weak Martian atmosphere. The rover is intended to seek out evidence of former microbial life, to collect rock and soil samples to store for retrieval by a future mission, and to test oxygen production from the Martian atmosphere in support of future crewed missions.

All engineering disciplines were involved with the rover projects. From the design of the rocket propulsion of the launch vehicles and the calculation of the interplanetary trajectories, to the design of the rovers' systems, MATLAB was used in many of these applications, and it is well suited to assist designers of future probes and autonomous vehicles like the Mars rovers. ■

CHAPTER

1

An Overview of MATLAB®*

OUTLINE

1.1 MATLAB Interactive Sessions
1.2 The Toolstrip
1.3 Built-In Functions, Arrays, and Plots
1.4 Working with Files
1.5 The MATLAB Help System
1.6 Problem-Solving Methodologies
1.7 Summary
Problems

This chapter covers many of the basic features of MATLAB. After you have finished this chapter, you will be able to use MATLAB to solve many kinds of problems. Section 1.1 provides an introduction to MATLAB as an interactive calculator. Section 1.2 covers the main menus and the Toolstrip. Section 1.3 introduces built-in functions, arrays, and plots. Section 1.4 discusses how to create, edit, and save MATLAB programs. Section 1.5 introduces the extensive MATLAB Help System and Section 1.6 introduces the methodology of engineering problem solving, with emphasis on the use of computers.

How to Use This Book

The book's chapter organization is flexible enough to accommodate a variety of users. However, it is important to cover at least the first four chapters, in that order. Chapter 2 covers *arrays,* which are the basic building blocks in MATLAB. Chapter 3 covers file usage, functions built into MATLAB, and