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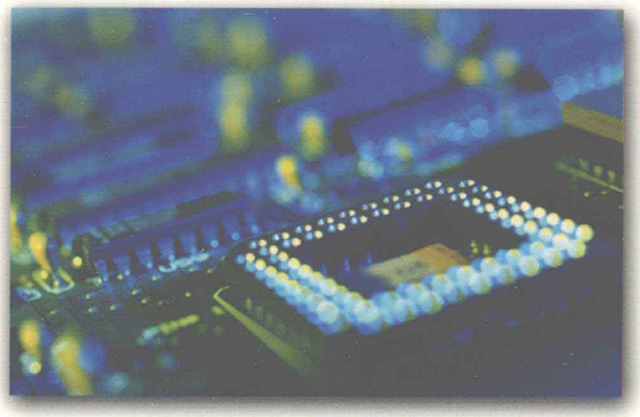
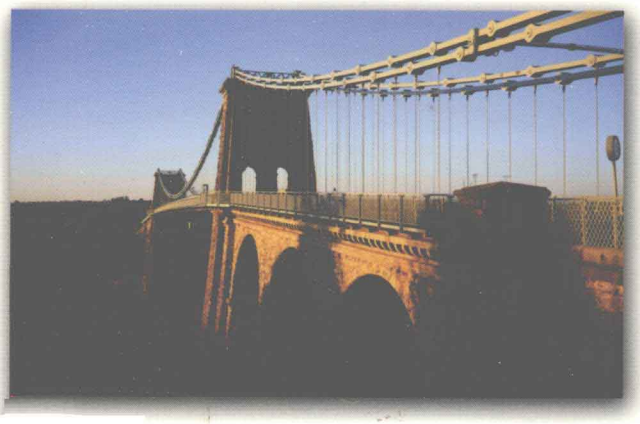
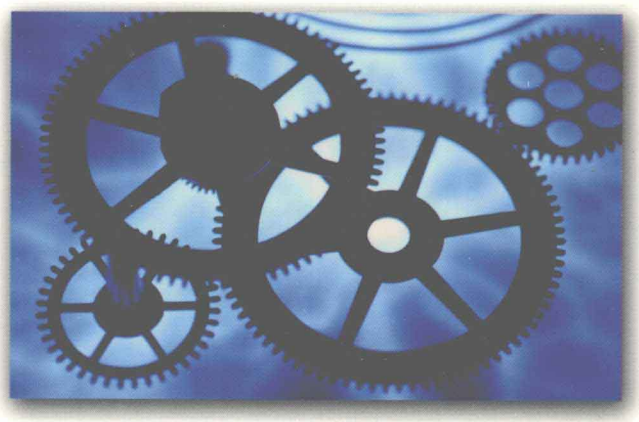
INTRODUCTION TO MATLAB 7 FOR ENGINEERS



WILLIAM J. PALM III

Introduction to MATLAB 7 for Engineers

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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 Professor of Mechanical Engineering and Applied Mechanics 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 33 years as a faculty member, he has 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* (McGraw-Hill, 2005). He wrote a chapter on control systems in the *Mechanical Engineers' Handbook* (M. Kutz, ed., Wiley, 1999), 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.

PREFACE

Formerly used mainly by specialists in signal processing and numerical analysis, MATLAB* in recent years has achieved widespread and enthusiastic acceptance throughout the engineering community. Many engineering schools now 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, such as Fortran, C, BASIC, and Pascal. Thus it can be used to teach programming principles. In most schools a MATLAB course has replaced the traditional Fortran course, and 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 20 "toolboxes" in various application areas can be used with MATLAB to add new commands and capabilities.

MATLAB is available for MS Windows and Macintosh personal computers and for other operating systems. It is compatible across all these platforms, which enables users to share their programs, insights, and ideas.

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 and at the end of each chapter, 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.

*MATLAB is a registered trademark of The MathWorks, Inc.

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

TEXT ORGANIZATION

This text is an update to the author's previous text.* In addition to providing new material based on MATLAB 7, the text incorporates the many suggestions made by reviewers and other users.

The text consists of 10 chapters. The first chapter 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 treats programming with MATLAB and covers relational and logical operators, conditional statements, for and while loops, and the switch structure. A major application of the chapter's material is in simulation, to which a section is devoted.

Chapter 5 treats 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. Function discovery, which uses data plots to discover a mathematical description of the data, 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 6 covers the solution of linear algebraic equations, which arise in applications in all fields of engineering. "Hand" solution methods are reviewed first. This review has proved helpful to many students in the author's classes. This coverage also establishes the terminology and some important concepts that are required to use the computer methods properly. The chapter then shows how to use MATLAB to solve systems of linear equations that have a unique solution. The use of MATLAB with underdetermined and overdetermined systems is covered in two optional sections.

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

* *Introduction to MATLAB 6 for Engineers,* McGraw-Hill, New York, 2000.

and cubic-spline interpolation. This chapter can be skipped if necessary. None of the following chapters depend on it.

Chapter 8 covers numerical methods for calculus and differential equations. Analytical methods are reviewed to provide a foundation for understanding and interpreting the numerical methods. 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.

Chapter 9 introduces Simulink,* which is a graphical interface for building simulations of dynamic systems. The coverage of Simulink has been expanded to a separate chapter in light of its growing popularity, as evidenced by recent workshops held by various professional organizations such as the ASEE. This chapter need not be covered to read Chapter 10.

Chapter 10 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 or the Student Edition of MATLAB.

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 summarizes functions for creating formatted output. Appendix D is a list of references. Appendix E, which is available on the text's website, contains some suggestions for course projects and is based on the author's experience in teaching a freshman MATLAB course. 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.

The first four chapters constitute a course in the essentials of MATLAB. The remaining six chapters are independent of each other, and may be covered in any order, or may be omitted if necessary. These chapters provide additional coverage and examples of plotting and model building, linear algebraic equations, probability and statistics, calculus and differential equations, Simulink, and symbolic processing, respectively.

*Simulink is a registered trademark of The MathWorks, Inc.

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.
- At the end of each chapter is a guide to tables in that chapter. These master tables will help the reader find descriptions of specific MATLAB commands.
- 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 introduced.
- At the end of each chapter is a list of the key terms introduced in the chapter, with the page number referenced.
- Key terms have been placed in the margin or in section headings where they are introduced.
- The index has four sections: a listing of symbols, an alphabetical list of MATLAB commands and functions, a list of Simulink blocks, 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 the inside front cover.

- 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.

An Instructor's Manual is available online for instructors who have adopted this text for a course. This manual contains the complete solutions to all the **Test Your Understanding** exercises and to all the chapter problems. The text website (at http://www.mhhe.com/palm) also has downloadable files containing the major programs in the text, PowerPoint slides keyed to the text, and suggestions for projects.

ACKNOWLEDGMENTS

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 following people, as well as several anonymous reviewers, patiently reviewed the manuscript and suggested many helpful corrections and additions.

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My sisters, Linda and Chris, and my mother Lillian, have always been there, cheering my efforts. My father was always there for support before he 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.

William J. Palm III
Kingston, Rhode Island
April, 2004

CONTENTS

Introduction to MATLAB 7 for Engineers

Photo courtesy of NASA Jet Propulsion Laboratory.

Engineering in the 21st Century...

Remote Exploration

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.

About the size of a golf cart, the new rovers have six wheels, each with its own motors. They have a top speed of 5 centimeters per second on flat hard ground and can travel up to about 100 meters per day. Needing 100 watts to move, they obtain power from solar arrays that generate 140 watts during a four-hour window each day. The sophisticated temperature control system must not only protect against nighttime temperatures of -96°C, but must also prevent the rover from overheating.

The robotic arm has three joints (shoulder, elbow, and wrist), driven by five motors, and it has a reach of 90 centimeters. The arm carries four tools and instruments for geological studies. Nine cameras provide hazard avoidance, navigation, and panoramic views. The on-board computer has 128 MB of DRAM and coordinates all the subsystems including communications.

All engineering disciplines were involved with the rovers' design and launch. The MATLAB Neural Network, Signal Processing, Image Processing, PDE, and various control system toolboxes are well suited to assist designers of probes and autonomous vehicles like the Mars rovers. ■

CHAPTER 1

An Overview of MATLAB®*

OUTLINE

This is the most important chapter in the book. By the time you have finished this chapter, you will be able to use MATLAB to solve many kinds of engineering problems. Section 1.1 provides a "quick-start" introduction to MATLAB as an interactive calculator. Section 1.2 covers the main menus and toolbar. Section 1.3 gives an overview of MATLAB, and directs the reader to the appropriate chapter where more detailed information is available. Section 1.4 discusses how to create, edit, and save MATLAB programs. Section 1.5 introduces the extensive MATLAB Help System. Section 1.6 treats the use of conditional statements and loops. Section 1.7 discusses methodologies for approaching engineering problems, with particular emphasis on a methodology to use with computer software such as MATLAB. A number of practice problems are given at the end of the chapter.

*MATLAB is a registered trademark of The MathWorks, Inc.

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 user-defined functions. Chapter 4 covers programming using relational and logical operators, conditional statements, and loops.

Use Section 1.3 to determine those MATLAB features for which you want more detailed information. This section will guide you to the appropriate chapter.

Chapters 5 through 10 are independent chapters that can be covered in any order, or can be omitted. They contain in-depth discussions of how to use MATLAB to solve several common types of engineering problems. Chapter 5 covers two- and three-dimensional plots in more detail, and shows how to use plots to build mathematical models from data. Chapter 6 treats the solution of linear algebraic equations, including cases having nonunique solutions. Chapter 7 covers probability, statistics, and interpolation applications. Chapter 8 introduces numerical methods for calculus and ordinary differential equations. Chapter 9 covers Simulink®,* which is a graphical user interface for solving differential equation models. Chapter 10 covers symbolic processing in MATLAB, with applications to algebra, calculus, differential equations, linear algebra, and transforms.

Reference and Learning Aids

The book has been designed as a reference as well as a learning tool. The special features useful for these purposes are as follows.

- Throughout each chapter margin notes identify where new terms are introduced.
- Throughout each chapter short Test Your Understanding exercises appear. Where appropriate, answers immediately follow the exercise so you can measure your mastery of the material.
- Homework exercises conclude each chapter. These usually require more effort than the Test Your Understanding exercises.
- Each chapter contains tables summarizing the MATLAB commands introduced in that chapter.
- At the end of each chapter is:
  - A summary guide to the commands covered in that chapter,
  - A summary of what you should be able to do after completing that chapter, and
  - A list of key terms you should know.
- Appendix A contains tables of MATLAB commands, grouped by category, with the appropriate page references.

*Simulink is a registered trademark of The MathWorks, Inc.

- Two indexes are included. The first is an index of MATLAB commands and symbols; the second is an index of topics.

Software Updates and Accuracy

Software publishers can release software updates faster than book publishers can release new editions. This text documents the pre-release version of MATLAB 7 as of the spring of 2004. There will be additional updates, numbered 7.1, 7.2, and so forth, that will change some of the program's features. The best way to protect yourself against obsolete information is to check the "What's New?" file provided with the program, and to learn how to use the extensive MATLAB Help System, which is covered in Section 1.5.

MATLAB and Related Software

MATLAB is both a computer programming language and a software environment for using that language effectively. It is maintained and sold by The MathWorks, Inc., of Natick, Massachusetts, and is available for MS Windows and other computer systems. The MATLAB interactive environment allows you to manage variables, import and export data, perform calculations, generate plots, and develop and manage files for use with MATLAB. The language was originally developed in the 1970s for applications involving matrices, linear algebra, and numerical analysis (the name MATLAB stands for "Matrix Laboratory"). Thus the language's numerical routines have been well-tested and improved through many years of use, and its capabilities have been greatly expanded.

MATLAB has a number of add-on software modules, called *toolboxes,* that perform more specialized computations. They can be purchased separately, but all run under the core MATLAB program. Toolboxes deal with applications such as image and signal processing, financial analysis, control systems design, and fuzzy logic. An up-to-date list can be found at The MathWorks website, which is discussed later in this chapter. This text uses material from the core MATLAB program, from two of the toolboxes (the Control Systems toolbox, in Chapter 8, and the Symbolic Math toolbox, in Chapter 10), and from Simulink (in Chapter 9). All of the examples and problems in the first seven chapters can be done with the core MATLAB program.

On MS Windows systems MATLAB 7 requires Windows XP or Windows NT to run. The Student Edition of MATLAB contains the core MATLAB program, some commands from two toolboxes (the Signal Processing toolbox and the Symbolic Math toolbox), and the Simulink program. The Simulink program is based on MATLAB, and requires MATLAB to run.

This book does not explain how to install MATLAB. If you purchased it for your own computer, the installation is easily done with the instructions that come with the software. If you will be using MATLAB in a computer lab, it will have been installed for you.

In the next section we introduce MATLAB by means of some simple sessions to illustrate its interactive nature, basic syntax, and features.