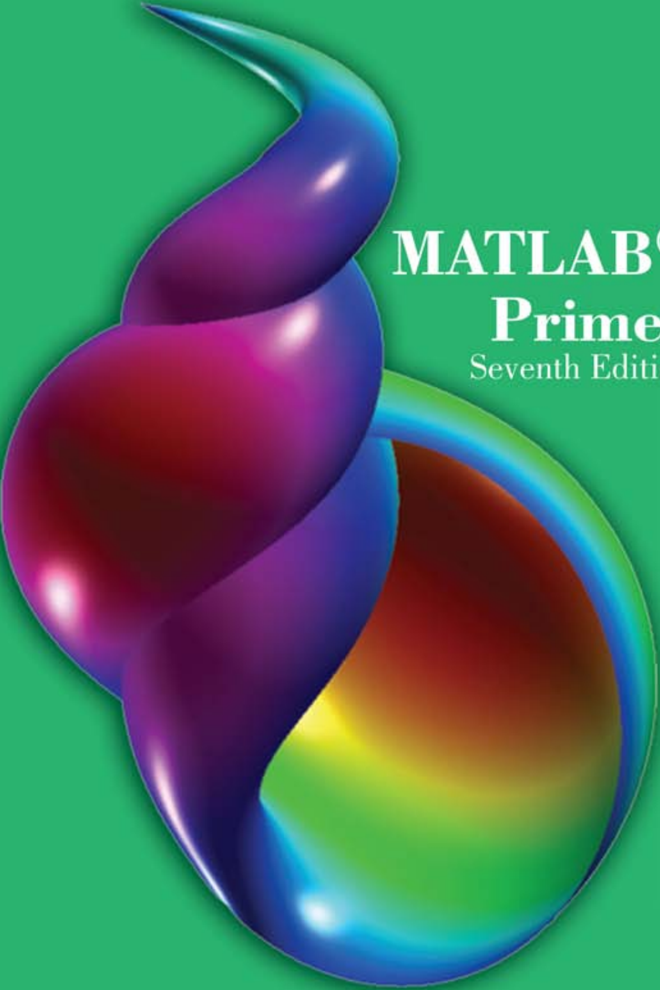
Timothy A. Davis *and* Kermit Sigmon

MATLAB® Primer

Seventh Edition



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Preface

Kermit Sigmon, author of the MATLAB® Primer, passed away in January 1997. Kermit was a friend, colleague, and fellow avid bicyclist (although I'm a mere 10-mile-a-day commuter) with whom I shared an appreciation for the contribution that MATLAB has made to the mathematics, engineering, and scientific community. MATLAB is a powerful tool, and my hope is that in revising our book for MATLAB 7.0, you will be able to learn how to apply it to solving your own challenging problems in mathematics, science, and engineering.

A team at The MathWorks, Inc. revised the Fifth Edition for MATLAB Version 5 in November of 1997. I carried on Kermit's work by creating the Sixth Edition of this book for MATLAB 6.1 in October 2001, and now this Seventh Edition for MATLAB Version 7.0.

This edition highlights the many new features of MATLAB 7.0, and includes new chapters on features that were in prior versions of MATLAB but not in prior editions of this book. New or revised topics in this edition include:

- calling Java from MATLAB, and using Java objects inside the MATLAB workspace
- many more graphics examples, including the seashell on the cover of the book
- cell publishing for reports in HTML, LaTeX, Microsoft Word, and Microsoft Powerpoint
- powerful suite of code development tools (such as the M-Lint code checker, the file dependency and comparison reports, and a profile coverage report)

- volume and vector visualization
- calling Fortran code from MATLAB
- parametric curves and surfaces, and polar plots of symbolic functions
- polynomials, interpolation, and numeric integration
- solving non-linear equations with `fzero`
- solving ordinary differential equations with `ode45`
- the revised MATLAB Desktop
- short-circuit logical operators
- integers and single precision floating-point
- more details on the colon operator
- `linsolve`, for solving specific linear systems
- the new block comment syntax
- function handles (`@`), which are now simpler to use
- anonymous functions
- `image`, and a pretty Mandelbrot set example
- the new 4-output sparse `lu`
- abstract symbolic functions
- nicely-formatted tables using `fprintf`
- a revised list of all primary functions and operators in MATLAB.

I would like to thank Penny Anderson at The MathWorks, Inc. for her detailed review of this book.

Tim Davis
Associate Professor, Department of Computer and Information Science and Engineering, University of Florida, http://www.cise.ufl.edu/research/sparse

Introduction

MATLAB®, developed by The MathWorks, Inc., integrates computation, visualization, and programming in a flexible, open environment. It offers engineers, scientists, and mathematicians an intuitive language for expressing problems and their solutions mathematically and graphically. Complex numeric and symbolic problems can be solved in a fraction of the time required with a programming language such as C, Fortran, or Java.

How to use this book: The purpose of this Primer is to help you begin to use MATLAB. It is not intended to be a substitute for the online help facility or the MATLAB documentation (such as *Getting Started with MATLAB*, available in printed form and online). The Primer can best be used hands-on. You are encouraged to work at the computer as you read the Primer and freely experiment with the examples. This Primer, along with the online help facility, usually suffices for students in a class requiring the use of MATLAB.

Start with the examples at the beginning of each chapter. In this way, you will create all of the matrices and M-files used in the examples. Some examples depend on code you write in previous chapters.

Larger examples (M-files and MEX-files) are on the web at http://www.cise.ufl.edu/research/sparse/MATLAB and http://www.crcpress.com.

Pull-down menu selections are described using the following style. Selecting the `Desktop` menu, and then the `Desktop Layout` submenu, and then the `Default` menu item is written as `Desktop` ► `Desktop Layout` ► `Default`.

You should liberally use the online help facility for more detailed information. Pressing the F1 key or selecting `Help` ► `MATLAB Help` brings up the Help window. You can also type `help` or `doc` in the Command window. See Sections 2.1 or 22.26 for more information on how to use the online help.

How to obtain MATLAB: Version 7.0 (Release 14) of MATLAB is available for Microsoft Windows (XP, 2000, and NT 4.0), Unix (Linux, Solaris 2.8 and 2.9, and HP-UX 11 or 11i), and the Macintosh (OS X 10.3.2 Panther). A Student Version is available for all but Solaris and HP-UX; it includes MATLAB, Simulink, and key functions of the Symbolic Math Toolbox. Everything discussed in this book can be done in the Student Version of MATLAB, with the exception of advanced features of the Symbolic Math Toolbox discussed in Section 16.13.

 For more information on MATLAB, contact:

The MathWorks, Inc.
3 Apple Hill Drive
Natick, MA, 01760-2098 USA
Phone: 508–647–7000
Fax: 508–647–7101
Web: http://www.mathworks.com

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1. Accessing MATLAB

On Unix systems you can enter MATLAB with the system command `matlab` and exit MATLAB with the MATLAB command `quit` or `exit`. In Microsoft Windows and the Macintosh, just double-click on the MATLAB icon:

2. The MATLAB Desktop

MATLAB has an extensive graphical user interface. When MATLAB starts, the MATLAB window will appear, with several subwindows and menu bars.

All of MATLAB's windows in the default desktop are docked, which means that they are tiled on the main MATLAB window. You can undock a window by selecting the menu item `Desktop ► Undock` or by clicking its undock button:

Dock it with `Desktop ► Dock`... or the dock button:

Close a window by clicking its close button:

Reshape the window tiling by clicking on and dragging the window edges.

The menu bar at the top of the MATLAB window contains a set of buttons and pull-down menus for working with M-files, windows, preferences and other settings, web resources for MATLAB, and online MATLAB help. If a window is docked and selected, its menu bar appears at the top of the MATLAB window.

If you prefer a simpler font than the default one, select `File` ► `Preferences`, and click on ⊞ `Fonts`. Select `Lucida Console` (on a PC) or `DialogInput` (on Unix) in place of the default `Monospaced` font, and click `OK`.

2.1 Help window

This window is the most useful window for beginning MATLAB users, and MATLAB experts continue to use it heavily. Select `Help` ► `MATLAB Help` or type `doc`. The Help window has most of the features you would see in any web browser (clickable links, a back button, and a search engine, for example). The Help Navigator on the left shows where you are in the MATLAB online documentation. Online Help sections are referred to as `Help`: `MATLAB`: `Getting Started`: `Introduction`, for example. Click on the ⊞ beside `MATLAB` in the Help Navigator, and you will see the MATLAB Roadmap (or `Help`: `MATLAB` for short). Printable versions of the documentation are available under this category (see `Help`: `MATLAB`: `Printable Documentation (PDF)`).

You can also use the `help` command, typed in the Command window. For example, the command `help eig` will give information about the eigenvalue function `eig`. See the list of functions in Chapter 22 for a brief summary of help for a function. `doc` is similar, except that it displays information in the Help Browser. You can also preview some of the features of MATLAB by first entering the command `demo` or by selecting `Help` ▸ `Demos`, and then selecting from the options offered.

2.2 Start button

The Start button in the bottom left corner of the MATLAB Desktop allows you to start up demos, tools, and other windows not present when you start MATLAB. Try `Start`: `MATLAB`: `Demos` and run one of the demos from the MATLAB Demo window.

2.3 Command window

MATLAB expressions and statements are evaluated as you type them in the Command window, and results of the computation are displayed there too. Expressions and statements are also used in M-files (more on this in Chapter 7). They are usually of the form:

```
variable = expression
```

or simply:

```
expression
```

Expressions are usually composed from operators, functions, and variable names. Evaluation of the expression produces a matrix (or other data type), which is then displayed on the screen or assigned to a variable for future use. If the variable name and = sign are omitted, a variable `ans` (for answer) is automatically created to which the result is assigned.

A statement is normally terminated at the end of the line. However, a statement can be continued to the next line with three periods (`...`) at the end of the line. Several statements can be placed on a single line separated by commas or semicolons. If the last character of a statement is a semicolon, display of the result is suppressed, but the assignment is carried out. This is essential in suppressing unwanted display of intermediate results.

Click on the Workspace tab to bring up the Workspace window (it starts out underneath the Current Directory window in the default layout) so you can see a list of the variables you create, and type this command in the Command window:

```
A = [1 2 3 ; 4 5 6 ; -1 7 9]
```

or this one:

```
A = [
1 2 3
4 5 6
-1 7 9]
```

in the Command window. Either one creates the obvious 3-by-3 matrix and assigns it to a variable `A`. Try it. You will see the array `A` in your Workspace window. MATLAB is case-sensitive in the names of commands, functions, and variables, so `A` and `a` are two different variables. A comma or blank separates the elements within a row of a matrix (sometimes a comma is necessary to split the expressions, because a blank can be ambiguous). A semicolon ends a row. When listing a number in exponential form (e.g., `2.34e-9`), blank spaces must be avoided in the middle (before the `e`, for example). Matrices can also be constructed from other matrices. If `A` is the 3-by-3 matrix shown above, then:

```
C = [A, A' ; [12 13 14], zeros(1,3)]
```

creates a 4-by-6 matrix. Try it to see what `C` is. The quote mark in `A'` means the transpose of `A`. Be sure to use the correct single quote mark (just to the left of the enter or return key on most keyboards). Since a blank separates elements in a row, parentheses are sometimes needed around expressions if they would otherwise be ambiguous. See Section 5.1 for the `zeros` function.

When you typed the last two commands, the matrices `A` and `C` were created and displayed in the Workspace window.

You can save the Command window dialog with the `diary` command:

diary *filename*

This causes what appears subsequently in the Command window to be written to the named file (if the *filename* is omitted, it is written to a default file named `diary`) until you type the command `diary off`; the command `diary on` causes writing to the file to resume. When finished, you can edit the file as desired and print it out. For hard copy of graphics, see Section 12.10.

The command line in MATLAB can be easily edited in the Command window. The cursor can be positioned with the left and right arrows and the Backspace (or Delete) key used to delete the character to the left of the cursor.

A convenient feature is use of the up and down arrows to scroll through the stack of previous commands. You can, therefore, recall a previous command line, edit it, and execute the revised line. Try this by first modifying the matrix `A` by adding one to each of its elements:

```
A = A + 1
```

You can change `C` to reflect this change in `A` by retyping the lengthy command `C =` … above, but it is easier to hit the up arrow key until you see the command you want, and then hit enter.

You can clear the Command window with the `clc` command or with `Edit` ► `Clear Command Window`.

The format of the displayed output can be controlled by the following commands:

`format short`	fixed point, 5 digits
`format long`	fixed point, 15 digits
`format short e`	scientific notation, 5 digits
`format long e`	scientific notation, 15 digits
`format short g`	fixed or floating-point, 5 digits
`format long g`	fixed or floating-point, 15 digits
`format hex`	hexadecimal format
`format '+'`	+, -, and blank
`format bank`	dollars and cents
`format rat`	approximate integer ratio

`format short` is the default. Once invoked, the chosen format remains in effect until changed. These commands only modify the display, not the precision of the number or its computation. Most numeric computations in MATLAB are done in double precision, which has about 16 digits of accuracy.

The command `format compact` suppresses most blank lines, allowing more information to be placed on the screen or page. The command `format loose` returns to the non-compact format. These two commands are independent of the other format commands.

You can pause the output in the Command window with the `more on` command. Type `more off` to turn this feature off.

2.4 Workspace window

The Workspace window lists variables that you have either entered or computed in your MATLAB session.

There are many fundamental data types (or classes) in MATLAB, each one a multidimensional array. The classes that we will concern ourselves with most are rectangular numerical arrays with possibly complex entries, and possibly sparse. An array of this type is called a matrix. A matrix with only one row or one column is called a vector (row vectors and column vectors behave differently; they are more than mere one-dimensional arrays). A 1-by-1 matrix is called a scalar.

Arrays can be introduced into MATLAB in several different ways. They can be entered as an explicit list of elements (as you did for matrix `A`), generated by statements and functions (as you did for matrix `C`), created in a file with your favorite text editor, or loaded from external data files or applications (see `Help`: `MATLAB`: `Getting Started`: `Manipulating Matrices`). You can also write your own functions (M-files, mexFunctions in C or Fortran, or Java) that create and operate on matrices. All the matrices and other variables that you create, except those internal to M-files, are shown in your Workspace window.

The command `who` (or `whos`) lists the variables currently in the workspace. Try typing `whos`; you should see a list of variables including `A` and `C`, with their type and size. A variable or function can be cleared from the workspace with the command `clear` *`variablename`* or by right-clicking the variable in the Workspace editor and selecting `Delete`. The command `clear` alone clears all variables from the workspace.

When you log out or exit MATLAB, all variables are lost. However, invoking the command `save` before exiting causes all variables to be written to a machine-readable file named `matlab.mat` in the current working directory. When you later reenter MATLAB, the command `load` will restore the workspace to its former state. Commands `save` and `load` take file names and variable names as optional arguments (type `doc save` and `doc load`). Try typing the commands `save`, `clear`, and then `load`, and watch what happens in the Workspace window after each command.

2.5 Command History window

This window lists the commands typed in so far. You can re-execute a command from this window by double-clicking or dragging the command into the Command window. Try double-clicking on the command:

```
A = A + 1
```

shown in your Command History window. For more options, select and right-click on a line of the Command window.

2.6 Array Editor window

Once an array exists, it can be modified with the Array Editor, which acts like a spreadsheet for matrices. Go to the Workspace window and double-click on the matrix `C`. Click on an entry in `C` and change it, and try changing the size of `C`. Go back to the Command window and type:

```
C
```

and you will see your new array `C`. You can also edit the matrix `C` by typing the command `openvar('C')`.

2.7 Current Directory window

Your current directory is where MATLAB looks for your M-files, and for workspace (`.mat`) files that you `load` and `save`. You can also load and save matrices as ASCII files and edit them with your favorite text editor. The file should consist of a rectangular array of just the numeric matrix entries. Use a text editor to create a file in your current directory called `mymatrix.txt` (or type `edit mymatrix.txt`) that contains these 2 lines:

```
22 67
12 33
```

Type the command `load mymatrix.txt`, and the file will be loaded from the current directory to the variable `mymatrix`. The file extension (`.txt` in this example) can be anything except `.mat`.

You can use the menus and buttons in the Current Directory window to peruse your files, or you can use commands typed in the Command window. The command `pwd` returns the name of the current directory, and `cd` will change the current directory. The command `dir` lists the contents of the working directory, whereas the command `what` lists only the MATLAB-specific files in the directory, grouped by file type. The MATLAB commands `delete` and `type` can be used to delete a file and display a file in the Command window, respectively.

The Current Directory window includes a suite of useful code development tools, described in Chapter 21.

3. Matrices and Matrix Operations

You have now seen most of MATLAB's windows and what they can do. Now take a look at how you can use MATLAB to work on matrices and other data types.

3.1 Referencing individual entries

Individual matrix and vector entries can be referenced with indices inside parentheses. For example, `A(2,3)` denotes the entry in the second row, third column of matrix `A`. Try:

```
A = [1 2 3 ; 4 5 6 ; -1 7 9]
A(2,3)
```

Next, create a column vector, `x`, with:

```
x = [3 2 1]'
```

or equivalently:

```
x = [3 ; 2 ; 1]
```

With this vector, x(3) denotes the third coordinate of vector x, with a value of 1. Higher dimensional arrays are similarly indexed. An array accepts only positive integers as indices.

An array with two or more dimensions can be indexed as if it were a one-dimensional vector. If A is m-by-n, then A(i,j) is the same as A(i+(j-1)*m). This feature is most often used with the find function (see Section 5.6).

3.2 Matrix operators

The following matrix operators are available in MATLAB:

+	addition or unary plus
-	subtraction or negation
*	multiplication
^	power
'	transpose (real) or conjugate transpose (complex)
.'	transpose (real or complex)
\	left division (*backslash* or mldivide)
/	right division (*slash* or mrdivide)

These matrix operators apply, of course, to scalars (1-by-1 matrices) as well. If the sizes of the matrices are incompatible for the matrix operation, an error message will result, except in the case of scalar-matrix operations (for addition, subtraction, division, and multiplication, in which case each entry of the matrix is operated on by the scalar, as in A=A+1). Not all scalar-matrix operations are valid. For example, magic(3)/pi is valid but pi/magic(3) is not. Also try the commands:

```
A^2
A*x
```

If x and y are both column vectors, then x'*y is their inner (or dot) product, and x*y' is their outer (or cross) product. Try these commands:

```
y = [1 2 3]'
x'*y
x*y'
```

3.3 Matrix division (slash and backslash)

The matrix "division" operations deserve special comment. If A is an invertible square matrix and b is a compatible column vector, or respectively a compatible row vector, then x=A\b is the solution of A*x=b, and x=b/A is the solution of x*A=b. These are also called the backslash (\) and slash operators (/); they are also referred to as the mldivide and mrdivide functions.

If A is square and non-singular, then A\b and b/A are mathematically the same as inv(A)*b and b*inv(A), respectively, where inv(A) computes the inverse of A. The left and right division operators are more accurate and efficient. In left division, if A is square, then it is factorized (if necessary), and these factors are used to solve A*x=b. If A is not square, the under- or over-determined system is solved in the least squares sense. Right division is defined in terms of left division by b/A = (A'\b')'. Try this:

```
A = [1 2 ; 3 4]
b = [4 10]'
x = A\b
```

The solution to A*x=b is the column vector x=[2;1].

Backslash is a very powerful general-purpose method for solving linear systems. Depending on the matrix, it selects forward or back substitution for triangular matrices (or permuted triangular matrices), Cholesky factorization for symmetric matrices, LU factorization for square matrices, or QR factorization for rectangular matrices. It has a special solver for Hessenberg matrices. It can also exploit sparsity, with either sparse versions of the above list, or special-case solvers when the sparse matrix is diagonal, tridiagonal, or banded. It selects the best method automatically (sometimes trying one method and then another if the first method fails). This can be overkill if you already know what kind of matrix you have. It can be much faster to use the `linsolve` function described in Section 5.5.

3.4 Entry-wise operators

Matrix addition and subtraction already operate entry-wise, but the other matrix operations do not. These other operators (`*`, `^`, `\`, and `/`) can be made to operate entry-wise by preceding them by a period. For example, either:

```
[1 2 3 4] .* [1 2 3 4]
[1 2 3 4] .^ 2
```

will yield `[1 4 9 16]`. Try it. This is particularly useful when using MATLAB graphics.

Also compare `A^2` with `A.^2`.

3.5 Relational operators

The relational operators in MATLAB are:

```
<       less than
>       greater than
<=      less than or equal
>=      greater than or equal
==      equal
~=      not equal
```

They all operate entry-wise. Note that = is used in an assignment statement whereas == is a relational operator. Relational operators may be connected by logical operators:

```
&       and
|       or
~       not
&&      short-circuit and
||      short-circuit or
```

The result of a relational operator is of type `logical`, and is either `true` (one) or `false` (zero). Thus, `~0` is `1`, `~3` is `0`, and `4 & 5` is `1`, for example. When applied to scalars, the result is a scalar. Try entering `3 < 5, 3 > 5, 3 == 5`, and `3 == 3`. When applied to matrices of the same size, the result is a matrix of ones and zeros giving the value of the expression between corresponding entries. You can also compare elements of a matrix with a scalar. Try:

```
A = [1 2 ; 3 4]
A >= 2
B = [1 3 ; 4 2]
A < B
```

The short-circuit operator && acts just like its non-short-circuited counterpart (&), except that it evaluates its left expression first, and does not evaluate the right expression if the first expression is `false`. This is useful for partially-defined functions. Suppose `f(x)` returns a logical value but generates an error if `x` is zero. The expression `(x~=0) && f(x)` returns `false` if `x` is zero, without calling `f(x)` at all. The short-circuit or (`||`) acts similarly. It does not evaluate the right expression if the left is `true`. Both && and `||` require their operands to be scalar and convertible to logical, while & and `|` can operate on arrays.

3.6 Complex numbers

MATLAB allows complex numbers in most of its operations and functions. Three convenient ways to enter complex matrices are:

```
B = [1 2 ; 3 4] + i*[5 6 ; 7 8]
B = [1+5i, 2+6i ; 3+7i, 4+8i]
B = complex([1 2 ; 3 4], [5 6 ; 7 8])
```

Either `i` or `j` may be used as the imaginary unit. If, however, you use `i` and `j` as variables and overwrite their values, you may generate a new imaginary unit with, say, `ii=sqrt(-1)`. You can also use `1i` or `1j`, which cannot be reassigned and are always equal to the imaginary unit. Thus,

```
B = [1 2 ; 3 4] + 1i*[5 6 ; 7 8]
```

generates the same matrix `B`, even if `i` has been reassigned. See Section 8.2 for how to find out if `i` has been reassigned.

3.7 Strings

Enclosing text in single quotes forms strings with the `char` data type:

```
S = 'I love MATLAB'
```

To include a single quote inside a string, use two of them together, as in:

```
S = 'Green''s function'
```

Strings, numeric matrices, and other data types can be displayed with the function `disp`. Try `disp(S)` and `disp(B)`.

3.8 Other data types

MATLAB supports many other data types, including logical variables, integers of various sizes, single-precision floating-point variables, sparse matrices, multidimensional arrays, cell arrays, and structures.

The default data type is `double`, a 64-bit IEEE floating-point number. The `single` type is a 32-bit IEEE floating-point number which should be used only if you are desperate for memory. A `double` can represent integers in the range -2^{53} to 2^{53} without any roundoff error, and a `double` holding an integer value is typically used for loop and array indices. An integer value stored as a `double` is nicknamed a *flint*. Integer types are only needed in special cases such as signal processing, image processing, encryption, and bit string manipulation. Integers come in signed and unsigned flavors, and in sizes of 8, 16, 32, and 64 bits. Integer arithmetic is not modular, but saturates on overflow. If you want a warning to be generated when integers overflow, use `intwarning on`. See `doc int8` and `doc single` for more information.

A sparse matrix is not actually its own data type, but an attribute of the `double` and `logical` matrix types. Sparse matrices are stored in a special way that does not require space for zero entries. MATLAB has efficient methods of operating on sparse matrices. Type `doc sparse`, and `doc full`, look in `Help`: `MATLAB`: `Mathematics`: `Sparse Matrices`, or see Chapter 15. Sparse matrices are allowed as arguments for most, but not all, MATLAB operators and functions where a normal matrix is allowed.

`D=zeros(3,5,4,2)` creates a 4-dimensional array of size 3-by-5-by-4-by-2. Multidimensional arrays may also be built up using `cat` (short for concatenation).

Cell arrays are collections of other arrays or variables of varying types and are formed using curly braces. For example,

```
c = {[3 2 1] ,'I love MATLAB'}
```

creates a cell array. The expression `c{1}` is a row vector of length 3, while `c{2}` is a string.

A `struct` is variable with one or more parts, each of which has its own type. Try, for example,

```
x.particle = 'electron'
x.position = [2 0 3]
x.spin = 'up'
```

The variable `x` describes an object with several characteristics, each with its own type.

You may create additional data objects and classes using overloading (see `help class` or `doc class`).

4. Submatrices and Colon Notation

Vectors and submatrices are often used in MATLAB to achieve fairly complex data manipulation effects. Colon notation (which is used to both generate vectors and reference submatrices) and subscripting by integral vectors are keys to efficient manipulation of these objects. Creative use of these features minimizes the use of loops (which can slow MATLAB) and makes code simple and readable. Special effort should be made to become familiar with them.

4.1 Generating vectors

The expression `1:5` is the row vector `[1 2 3 4 5]`. The numbers need not be integers, and the increment need not be one. For example, `0:0.2:1` gives `[0 0.2 0.4 0.6 0.8 1]` with an increment of `0.2` and `5:-1:1` gives `[5 4 3 2 1]` with an increment of `-1`. These vectors are commonly used in `for` loops, described in Section 6.1. Be careful how you mix the colon operator with other operators. Compare `1:5-3` with `(1:5)-3`.

In general, the expression `lo:hi` is the sequence `[lo, lo+1, lo+2, …, hi]` except that the last term in the sequence is always less than or equal to `hi` if either one are not integers. Thus, `1:4.9` is `[1 2 3 4]` and `1:5.1` is `[1 2 3 4 5]`. The sequence is empty if `lo` > `hi`.

If an increment is provided, as in `lo:inc:hi`, then the sequence is `[lo, lo+inc, lo+2*inc, …, lo+m*inc]` where `m=fix((hi-lo)/inc)` and `fix` is a function that rounds a real number towards zero. The length of the sequence is `m+1`, and the sequence is empty if `m<0`. Thus, the sequence `5:-1:1` has `m=4` and is of length 5, but `5:1:1` has `m=-4` and is thus empty. The default increment is 1.

If you want specific control over how many terms are in the sequence, use `linspace` instead of the colon operator. The expression `linspace(lo,hi)` is identical to `lo:inc:hi`, except that `inc` is chosen so that the vector always has exactly 100 entries (even if `lo` and `hi` are equal). The last entry in the sequence is always `hi`. To generate a sequence with `n` terms instead of the default of 100, use `linspace(lo,hi,n)`. Compare `linspace(1,5.1,5)` with `1:5.1`.

4.2 Accessing submatrices

Colon notation can be used to access submatrices of a matrix. To try this out, first type the two commands:

```
A = rand(6,6)
B = rand(6,4)
```

which generate a random 6-by-6 matrix `A` and a random 6-by-4 matrix `B`.

`A(1:4,3)` is the column vector consisting of the first four entries of the third column of `A`.

A colon by itself denotes an entire row or column: `A(:,3)` is the third column of `A`, and `A(1:4,:)` is the first four rows.

Arbitrary integral vectors can be used as subscripts: `A(:,[2 4])` contains as columns, columns 2 and 4 of `A`. Such subscripting can be used on both sides of an assignment statement:

```
A(:,[2 4 5]) = B(:,1:3)
```

replaces columns `2,4,5` of `A` with the first three columns of `B`. Try it. Note that the entire altered matrix `A` is displayed and assigned. Columns 2 and 4 of `A` can be multiplied on the right by the matrix `[1 2 ; 3 4]`:

```
A(:,[2 4]) = A(:,[2 4]) * [1 2 ; 3 4]
```

Once again, the entire altered matrix is displayed and assigned. Submatrix operations are a convenient way to perform many useful computations. For example, a Givens rotation of rows 3 and 5 of the matrix `A` to zero out the `A(3,1)` entry can be written as:

```
a = A(5,1)
b = A(3,1)
G = [a b ; -b a] / norm([a b])
A([5 3], :) = G * A([5 3], :)
```

(assuming `norm([a b])` is not zero). You can also assign a scalar to all entries of a submatrix. Try:

```
A(:, [2 4]) = 99
```

You can delete rows or columns of a matrix by assigning the empty matrix ([]) to them. Try:

```
A(:, [2 4]) = []
```

In an array index expression, `end` denotes the index of the last element. Try:

```
x = rand(1,5)
x = x(end:-1:1)
```

To appreciate the usefulness of these features, compare these MATLAB statements with a C, Fortran, or Java routine to do the same operation.

5. MATLAB Functions

MATLAB has a wide assortment of built-in functions. You have already seen some of them, such as `zeros`, `rand`, and `inv`. This section describes the more common matrix manipulation functions. For a more complete list, see Chapter 22, or `Help`: `MATLAB`: `Functions -- Categorical List`.

5.1 Constructing matrices

Convenient matrix building functions include:

`eye`	identity matrix
`zeros`	matrix of zeros
`ones`	matrix of ones
`diag`	create or extract diagonals
`triu`	upper triangular part of a matrix
`tril`	lower triangular part of a matrix
`rand`	randomly generated matrix
`hilb`	Hilbert matrix
`magic`	magic square
`toeplitz`	Toeplitz matrix
`gallery`	a wide range of interesting matrices

The command `rand(n)` creates an `n`-by-`n` matrix with randomly generated entries distributed uniformly between 0 and 1 while `rand(m,n)` creates an `m`-by-`n` matrix (`m` and `n` are non-negative integers). Try:

```
A = rand(3)
```

`rand('state',0)` resets the random number generator. `zeros(m,n)` produces an `m`-by-`n` matrix of zeros, and `zeros(n)` produces an `n`-by-`n` one. If `A` is a matrix, then `zeros(size(A))` produces a matrix of zeros having the same size as `A`. If `x` is a vector, `diag(x)` is the diagonal matrix with `x` down the diagonal; if `A` is a matrix, then `diag(A)` is a vector consisting of the diagonal of `A`. Try:

```
x = 1:3
diag(x)
diag(A)
diag(diag(A))
```

Matrices can be built from blocks. Try creating this 5-by-5 matrix.

```
B = [A zeros(3,2) ; pi*ones(2,3), eye(2)]
```

`magic(n)` creates an `n`-by-`n` matrix that is a magic square (rows, columns, and diagonals have common sum); `hilb(n)` creates the `n`-by-`n` Hilbert matrix, a very ill-conditioned matrix. Matrices can also be generated with a `for` loop (see Section 6.1). `triu` and `tril` extract upper and lower triangular parts of a matrix. Try:

```
triu(A)
triu(A) == A
```

The `gallery` function can generate a matrix from any one of over 60 different matrix classes. Many have interesting eigenvalue or singular value properties, provide interesting counter-examples, or are difficult matrices for various linear algebraic methods. The Rosser matrix challenges many eigenvalue solvers:

```
A = gallery('rosser')
eig(A)
eigs(A)
```

The Parter matrix has many singular values close to π:

```
A = gallery('parter', 6)
svd(A)
```

The `eig`, `eigs`, and `svd` functions are discussed below.

5.2 Scalar functions

Certain MATLAB functions operate essentially on scalars but operate entry-wise when applied to a vector or matrix. Some of the most common such functions are:

```
abs   ceil   floor  rem    sqrt
acos  cos    log    round  tan
asin  exp    log10  sign
atan  fix    mod    sin
```

The following statements will generate a sine table:

```
x = (0:0.1:2)'
y = sin(x)
[x y]
```

Note that because `sin` operates entry-wise, it produces a vector `y` from the vector `x`.

5.3 Vector functions and data analysis

Other MATLAB functions operate essentially on a vector (row or column) but act on an `m`-by-`n` matrix (`m` > `2`) in a column-by-column fashion to produce a row vector containing the results of their application to each column. Row-by-row action can be obtained by using the transpose (`mean(A')'`, for example) or by specifying the dimension along which to operate (`mean(A,2)`, for example). Most of these functions perform basic statistical computations (`std` computes the standard deviation and `prod` computes the product of the elements in the vector, for example). The primary functions are:

```
max   sum   median  any   sort   var
min   prod  mean    all   std
```

The maximum entry in a matrix `A` is given by `max(max(A))` rather than `max(A)`. Try it. The `any` and `all` functions are discussed in Section 6.6.

5.4 Matrix functions

Much of MATLAB's power comes from its matrix functions. Here is a partial list of the most common ones:

`eig`	eigenvalues and eigenvectors
`eigs`	like `eig`, for large sparse matrices
`chol`	Cholesky factorization
`svd`	singular value decomposition
`svds`	like `svd`, for large sparse matrices
`inv`	inverse
`lu`	LU factorization
`qr`	QR factorization
`hess`	Hessenberg form
`schur`	Schur decomposition
`rref`	reduced row echelon form
`expm`	matrix exponential
`sqrtm`	matrix square root
`poly`	characteristic polynomial
`det`	determinant
`size`	size of an array
`length`	length of a vector

`norm`	1-norm, 2-norm, Frobenius-norm, ∞-norm
`normest`	2-norm estimate
`cond`	condition number in the 2-norm
`condest`	condition number estimate
`rank`	rank
`kron`	Kronecker tensor product
`find`	find indices of nonzero entries
`linsolve`	solve a special linear system

MATLAB functions may have single or multiple output arguments. Square brackets are used to the left of the equal sign to list the outputs. For example,

```
y = eig(A)
```

produces a column vector containing the eigenvalues of `A`, whereas:

```
[V, D] = eig(A)
```

produces a matrix `V` whose columns are the eigenvectors of `A` and a diagonal matrix `D` with the eigenvalues of `A` on its diagonal. Try it. The matrix `A*V-V*D` will have small entries.

5.5 The linsolve function

The matrix divide operators (\ or /) are usually enough for solving linear systems. They look at the matrix and try to pick the best method. The `linsolve` function acts like \, except that you can tell it about your matrix. Try:

```
A = [1 2 ; 3 4]
b = [4 10]'
A\b
linsolve(A,b)
```

In both cases, you get solution x=[2;1] to the linear system A*x=b.

If A is symmetric and positive definite, one explicit solution method is to perform a Cholesky factorization, followed by two solves with triangular matrices. Try:

```
C = [2 1 ; 1 2]
x = C\b
```

Here is an equivalent method:

```
R = chol(C)
y = R'\b
x = R\y
```

The matrix R is upper triangular, but MATLAB explicitly transposes R and then determines for itself that R' is lower triangular. You can save MATLAB some work by using linsolve with an optional third argument, opts. Try this:

```
opts.UT = true
opts.TRANSA = true
y = linsolve(R,b,opts)
```

which gives the same answer as y=R'\b. The difference in run time can be high for large matrices (see Chapter 10 for more details). The fields for opts are UT (upper triangular), LT (lower triangular), UHESS (upper Hessenberg), SYM (symmetric), POSDEF (positive definite), RECT (rectangular), and TRANSA (whether to solve A*x=b or A'*x=b). All opts fields are either true or false. Not all combinations are supported (type doc linsolve for a list). linsolve does not work on sparse matrices.

5.6 The find function

The `find` function is unlike the other matrix and vector functions. `find(x)`, where `x` is a vector, returns an array of indices of nonzero entries in `x`. This is often used in conjunction with relational operators. Suppose you want a vector `y` that consists of all the values in `x` greater than `1`. Try:

```
x = 2*rand(1,5)
y = x(find(x > 1))
```

With three output arguments, you get more information:

```
A = rand(3)
[i,j,x] = find(A)
```

returns three vectors, with one entry in `i`, `j`, and `x` for each nonzero in `A` (row index, column index, and numerical value, respectively). With this matrix `A`, try:

```
[i,j,x] = find(A > .5)
[i j x]
```

and you will see a list of pairs of row and column indices where `A` is greater than `.5`. However, `x` is a vector of values from the matrix expression `A > .5`, not from the matrix `A`. Getting the values of `A` that are larger than `.5` without a loop requires one-dimensional array indexing:

```
k = find(A > .5)
A(k)
A(k) = A(k) + 99
```

Section 6.1 shows the loop-based version of this code.

Here is a more complex example. A square matrix A is diagonally dominant if

$$|a_{ii}| > \sum_{j \neq i} |a_{ij}| \qquad \text{for each row } i.$$

First, enter a matrix that is not diagonally dominant. Try:

```
A = [
-1  2  3 -4
 0  2 -1  0
 1  2  9  1
-3  4  1  1]
```

These statements compute a vector i containing indices of rows that violate diagonal dominance (rows 1 and 4 for this matrix A).

```
d = diag(A)
a = abs(d)
f = sum(abs(A), 2) - a
i = find(f >= a)
```

Next, modify the diagonal entries to make the matrix just barely diagonally dominant, while still preserving the sign of the diagonal:

```
[m n] = size(A)
k = i + (i-1)*m
tol = 100 * eps
s = 2 * (d(i) >= 0) - 1
A(k) = (1+tol) * s .* max(f(i), tol)
```

The variable eps (epsilon) gives the smallest value such that 1+eps > 1, about 10^{-16} on most computers. It is useful in specifying tolerances for convergence of iterative processes and in problems like this one. The odd-looking statement that computes `s` is nearly the same as `s=sign(d(i))`, except that here we want `s` to be one when `d(i)` is zero. We will come back to this diagonal dominance problem later on.

6. Control Flow Statements

In their basic forms, these MATLAB flow control statements operate like those in most computer languages. Indenting the statements of a loop or conditional statement is optional, but it helps readability to follow a standard convention.

6.1 The for loop

This loop:

```
n = 10
x = []
for i = 1:n
    x = [x, i^2]
end
```

produces a vector of length `10`, and

```
n = 10
x = []
for i = n:-1:1
    x = [i^2, x]
end
```

produces the same vector. Try them. The vector `x` grows in size at each iteration. Note that a matrix may be empty (such as `x=[]`). The statements:

```
m = 6
n = 4
for i = 1:m
    for j = 1:n
```

```
        H(i,j) = 1/(i+j-1) ;
    end
end
H
```

produce and display in the Command window the 6-by-4 Hilbert matrix. The last `H` displays the final result. The semicolon on the inner statement is essential to suppress the display of unwanted intermediate results. If you leave off the semicolon, you will see that `H` grows in size as the computation proceeds. This can be slow if `m` and `n` are large. It is more efficient to preallocate the matrix `H` with the statement `H=zeros(m,n)` before computing it. Type the command `doc hilb` and `type hilb` to see a more efficient way to produce a square Hilbert matrix.

Here is the counterpart of the one-dimensional indexing exercise from Section 5.6. It adds `99` to each entry of the matrix that is larger than `.5`, using two `for` loops instead of a single `find`. This method is slower:

```
A = rand(3)
[m n] = size(A) ;
for j = 1:n
    for i = 1:m
        if (A(i,j) > .5)
            A(i,j) = A(i,j) + 99 ;
        end
    end
end
A
```

The `for` statement permits any matrix expression to be used instead of `1:n`. The index variable consecutively assumes the value of each column of the expression. For example,

```
s = 0 ;
for c = H
    s = s + sum(c) ;
end
```

computes the sum of all entries of the matrix `H` by adding its column sums (of course, `sum(sum(H))` does it more efficiently; see Section 5.3). Each iteration of the `for` loop assigns a successive column of `H` to the variable `c`. In fact, since `1:n` = `[1 2 3` ... `n]`, this column-by-column assignment is what occurs with `for i = 1:n`.

6.2 The while loop

The general form of a `while` loop is:

```
while expression
    statements
end
```

The *`statements`* will be repeatedly executed as long as the *`expression`* remains true. For example, for a given number `a`, the following computes and displays the smallest nonnegative integer `n` such that $2^n > a$:

```
a = 1e9
n = 0
while 2^n <= a
    n = n + 1 ;
end
n
```

Note that you can compute the same value `n` more efficiently by using the `log2` function:

```
[f,n] = log2(a)
```

You can terminate a `for` or `while` loop with the `break` statement and skip to the next iteration with the `continue` statement. Here is an example for both. It prints the odd integers from 1 to 7 by skipping over the even iterations and then terminates the loop when `i` is 7.

```
for i = 1:10
    if (mod(i,2) == 0)
        continue
    end
    i
    if (i == 7)
        break
    end
end
```

6.3 The if statement

The general form of a simple `if` statement is:

```
if expression
    statements
end
```

The *`statements`* will be executed only if the *`expression`* is true. Multiple conditions also possible:

```
for n = -2:5
    if n < 0
        parity = 0 ;
    elseif rem(n,2) == 0
        parity = 2 ;
    else
        parity = 1 ;
    end
    disp([n parity])
end
```

The `else` and `elseif` are optional. If the `else` part is used, it must come last.

6.4 The switch statement

The `switch` statement is just like the `if` statement. If you have one expression that you want to compare against several others, then a `switch` statement can be more concise than the corresponding `if` statement. See `help switch` for more information.

6.5 The try/catch statement

Matrix computations can fail because of characteristics of the matrices that are hard to determine before doing the computation. If the failure is severe, your script or function (see Chapter 7) may be terminated. The `try/catch` statement allows you to compute optimistically and then recover if those computations fail. The general form is:

```
try
    statements
catch
    statements
end
```

The first block of statements is executed. If an error occurs, those statements are terminated, and the second block of statements is executed. You cannot do this with an `if` statement. See `doc try`. See Section 11.5 for an example of `try` and `catch`.

6.6 Matrix expressions (if and while)

A matrix expression is interpreted by `if` and `while` to be true if ***every*** entry of the matrix expression is nonzero. Enter these two matrices:

```
A = [ 1 2 ; 3 4 ]
B = [ 2 3 ; 3 5 ]
```

If you wish to execute a statement when matrices `A` and `B` are equal, you could type:

```
if A == B
    disp('A and B are equal')
end
```

If you wish to execute a statement when `A` and `B` are not equal, you would type:

```
if any(any(A ~= B))
    disp('A and B are not equal')
end
```

or, more simply,

```
if A == B else
    disp('A and B are not equal')
end
```

Note that the seemingly obvious:

```
if A ~= B
    disp('not what you think')
end
```

will not give what is intended because the statement would execute only if each of the corresponding entries of `A` and `B` differ. The functions `any` and `all` can be creatively used to reduce matrix expressions to vectors or scalars. Two `any`s are required above because `any` is a vector operator (see Section 5.3). In logical terms, `any` and `all` correspond to the existential ($\exists$) and universal ($\forall$) quantifiers, respectively, applied to each column of a matrix or each entry of a row or column vector. Like most vector functions, `any` and `all` can be applied to dimensions of a matrix other than the columns.

An `if` statement with a two-dimensional matrix *expression* is equivalent to:

```
if all(all(expression))
    statement
end
```

6.7 Infinite loops

With loops, it is possible to execute a command that will never stop. Typing Ctrl-C stops a runaway display or computation. Try:

```
i = 1
while i > 0
    i = i + 1
end
```

then type Ctrl-C to terminate this loop.

7. M-files

MATLAB can execute a sequence of statements stored in files. These are called M-files because they must have the file type `.m` as the last part of their filename.

7.1 M-file Editor/Debugger window

Much of your work with MATLAB will be in creating and refining M-files. M-files are usually created using your favorite text editor or with MATLAB's M-file Editor/Debugger. See also `Help`: `MATLAB`: `Desktop Tools and Development Environment`: `Editing and Debugging M-Files`.

There are two types of M-files: script files and function files. In this exercise, you will incrementally develop and debug a script and then a function for making a matrix diagonally dominant. Create a new M-file, either with the `edit` command, by selecting the `File` ▶ `New` ▶ `M-file` menu item, or by clicking the new-file button:

Type in these lines in the Editor,

```
f = sum(A, 2) ;
A = A + diag(f) ;
```

and save the file as `ddom.m` by clicking:

You have just created a MATLAB script file.[1] The semicolons are there because you normally do not want to see the results of every line of a script or function.

7.2 Script files

A script file consists of a sequence of normal MATLAB statements. Typing `ddom` in the Command window causes the statements in the script file `ddom.m` to be executed. Variables in a script file refer to variables in the main workspace, so changing them will change your workspace variables. Type:

```
A = rand(3)
ddom
A
```

[1] See http://www.cise.ufl.edu/research/sparse/MATLAB or http://www.crcpress.com for the M-files and MEX-files used in this book.

in the Command window. It seems to work; the matrix `A` is now diagonally dominant. If you type this in the Command window, though,

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

then the diagonal of `A` just got worse. What happened? Click on the Editor window and move the mouse to point to the variable `f`, anywhere in the script. You will see a yellow pop-up window with:

```
f =
      -1
       0
```

Oops. `f` is supposed to be a sum of absolute values, so it cannot be negative. Change the first line of `ddom.m` to:

```
f = sum(abs(A), 2) ;
```

save the file, and run it again on the original matrix `A=[1 -2;-1 1]`. This time, instead of typing in the command, try running the script by clicking:

in the Editor window. This is a shortcut to typing `ddom` in the Command window. The matrix `A` is now diagonally dominant. Run the script again, though, and you will see that A is modified even if it is already diagonally dominant. Fix this by modifying only those rows that violate diagonal dominance.

Set `A` to `[1 -2;-1 1]` by clicking on the command in the Command History window. Modify `ddom.m` to be:

```
d = diag(A) ;
a = abs(d) ;
f = sum(abs(A), 2) - a ;
i = find(f >= a) ;
A(i,i) = A(i,i) + diag(f(i)) ;
```

Save and run the script by clicking:

Run it again; the matrix does not change.

Try it on the matrix `A=[-1 2;1 -1]`. The result is wrong. To fix it, try another debugging method: setting breakpoints. A breakpoint causes the script to pause, and allows you to enter commands in the Command window, while the script is paused (it acts just like the `keyboard` command).

Click on line 5 and select `Debug` ► `Set/Clear Breakpoint` in the Editor or click:

A red dot appears in a column to the left of line 5. You can also set and clear breakpoints by clicking on the red dots or dashes in this column. In the Command window, type:

```
clear
A = [-1 2 ; 1 -1]
ddom
```

A green arrow appears at line 5, and the prompt `K>>` appears in the Command window. Execution of the script has paused, just before line 5 is executed. Look at the variables `A` and `f`. Since the diagonal is negative, and `f` is an absolute value, we should subtract `f` from `A` to preserve the sign. Type the command:

```
A = A - diag(f)
```

The matrix is now correct, although this works only if all of the rows need to be fixed and all diagonal entries are negative. Stop the script by selecting `Debug` ▶ `Exit Debug Mode` or by clicking:

Clear the breakpoint. Replace line 5 with:

```
s = sign(d(i)) ;
A(i,i) = A(i,i) + diag(s .* f(i)) ;
```

Type `A=[-1 2;1 -1]` and run the script. The script seems to work, but it modifies `A` more than is needed. Try the script on `A=zeros(4)`, and you will see that the matrix is not modified at all, because `sign(0)` is zero. Fix the script so that it looks like this:

```
d = diag(A) ;
a = abs(d) ;
f = sum(abs(A), 2) - a ;
i = find(f >= a) ;
[m n] = size(A) ;
k = i + (i-1)*m ;
tol = 100 * eps ;
s = 2 * (d(i) >= 0) - 1 ;
A(k) = (1+tol) * s .* max(f(i), tol) ;
```

which is the code you typed in Section 5.6.

7.3 Function files

Function files provide extensibility to MATLAB. You can create new functions specific to your problem, which will then have the same status as other MATLAB functions. Variables in a function file are by default local. A variable can, however, be declared global (see `doc global`). Use global variables with caution; they can be a symptom of bad program design and can lead to hard-to-debug code.

Convert your `ddom.m` script into a function by adding these lines at the beginning of `ddom.m`:

```
function B = ddom(A)
% B = ddom(A) returns a diagonally
% dominant matrix B by modifying the
% diagonal of A.
```

and add this line at the end of your new function:

```
B = A ;
```

You now have a MATLAB function, with one input argument and one output argument. To see the difference between global and local variables as you do this exercise, type `clear`. Functions do not modify their inputs, so:

```
C = [1 -2 ; -1 1]
D = ddom(C)
```

returns a matrix `D` that is diagonally dominant. The matrix `C` in the workspace does not change, although a copy of it local to the `ddom` function, called `A`, is modified as the function executes. Note that the other variables, `a`, `d`, `f`, `i`, `k` and `s` no longer appear in your main workspace. Neither do `A` and `B`. These are local to the `ddom` function.

The first line of the function declares the function name, input arguments, and output arguments; without this line the file would be a script file. Then a MATLAB statement `D=ddom(C)`, for example, causes the matrix `C` to be passed as the variable `A` in the function and causes the output result to be passed out to the variable `D`. Since variables in a function file are local, their names are independent of those in the current MATLAB workspace. Your workspace will have only the matrices `C` and `D`. If you want to modify `C` itself, then use `C=ddom(C)`.

Lines that start with `%` are comments; more on this in Section 7.6. An optional `return` statement causes the function to finish and return its outputs. An M-file can reference other M-files, including itself recursively.

7.4 Multiple inputs and outputs

A function may also have multiple output arguments. For example, it would be useful to provide the caller of the `ddom` function some control over how strong the diagonal is to be and to provide more results, such as the list of rows (the variable `i`) that violated diagonal dominance. Try changing the first line to:

```
function [B,i] = ddom(A, tol)
```

and add a `%` at the beginning of the line that computes `tol`. Single assignments can also be made with a function having multiple output arguments. For example, with this version of `ddom`, the statement `D=ddom(C,0.1)` will assign the modified matrix to the variable D without returning the vector i. Try it on C=[1 -2 ; -1 1].

7.5 Variable arguments

Not all inputs and outputs of a function need be present when the function is called. The variables nargin and nargout can be queried to determine the number of inputs and outputs present. For example, we could use a default tolerance if tol is not present. Add these statements in place of the line that computed tol:

```
if (nargin == 1)
    tol = 100 * eps ;
end
```

Section 8.1 gives an example of nargin and nargout.

7.6 Comments and documentation

The % symbol indicates that the rest of the line is a comment; MATLAB will ignore the rest of the line. Moreover, the first contiguous comment lines are used to document the M-file. They are available to the online help facility and will be displayed if help ddom or doc ddom are entered. Such documentation should always be included in a function file. Since you have modified the function to add new inputs and outputs, edit your script to describe the variables i and tol. Be sure to state what the default value of tol is. Next, type help ddom or doc ddom.

Block comments are useful for lengthy comments or for disabling code. A block comment starts with a line containing only %{ and ends with a line containing only %}. Block comments in an M-file are not printed by the help or doc commands.

A line starting with two percent signs (%%) denotes the beginning of a MATLAB code *cell*. This type of cell has nothing to do with cell arrays, but defines a section of code in an M-file. Cells can be executed by themselves, and cell publishing (discussed in Chapter 20) generates reports whose sections are defined by an M-file's cells.

7.7 MATLAB's path

M-files must be in a directory accessible to MATLAB. M-files in the current directory are always accessible. The current list of directories in MATLAB's search path is obtained by the command `path`. This command can also be used to add or delete directories from the search path. See `doc path`. The command `which` locates functions and files on the path. For example, type `which hilb`. You can modify your MATLAB path with the command `path`, or `pathtool`, which brings up another window. You can also select `File` ▸ `Set Path`.

8. Advanced M-file Features

This section describes advanced M-file techniques, such as how to pass a function as an argument to another function and how to write high-performance code in MATLAB.

8.1 Function handles and anonymous functions

A function handle (`@`) is a reference to a function that can then be treated as a variable. It can be copied, placed in cell array, and evaluated just like a regular function. For example,

```
f = @sqrt
f(2)
sqrt(2)
```

The `str2func` function converts a string to a function handle. For example,

```
f = str2func('sqrt')
f(2)
```

Function handles can refer to built-in MATLAB functions, to your own function in an M-file, or to anonymous functions. An anonymous function is defined with a one-line expression, rather than by an M-file. Try:

```
g = @(x) x^2-5*x+6-sin(9*x)
g(1)
```

Some MATLAB functions that operate on function handles need to evaluate the function on a vector, so it is often better to define an anonymous function (or M-file) so that it can operate entry-wise on scalars, vectors, or matrices. Try this instead:

```
g = @(x) x.^2-5*x+6-sin(9*x)
g(1)
```

The general syntax for an anonymous function is

```
handle = @(arg1, arg2, ...) expression
```

Here is an example with two input arguments:

```
norm2 = @(x,y) sqrt(x^2 + y^2)
norm2(4, 5)
norm([4 5])
```

One advantage of anonymous functions is that they can implicitly refer to variables in the workspace or the calling function without having to use the `global` statement. Try this example:

```
A = [3 2 ; 1 3]
b = [3 ; 4]
y = A\b
resid = @(x) A*x-b
resid(y)
A*y-b
```

In this case, `x` is an argument, but `A` and `b` are defined in the calling workspace.

To find out what a function handle refers to, use `func2str` or `functions`. Try these examples:

```
func2str(f)
func2str(g)
func2str(norm2)
func2str(resid)
functions(f)
```

Cell arrays can contain function handles. They can be indexed and the function evaluated in a single expression. Try this:

```
h{1} = f
h{2} = g
h{1}(2)
f(2)
h{2}(1)
g(1)
```

Here is a more useful example. The `bisect` function, below, solves the nonlinear equation $f(x)=0$. It takes a function handle or a string as one of its inputs. If the function is a string, it is converted to a function handle with `str2func`. `bisect` also gives you an example of `nargin` and `nargout` (see also Section 7.5). Compare `bisect` with the built-in `fzero` discussed in Section 18.4.

```
function [b, steps] = bisect(f,x,tol)
% BISECT:  zero of a function of one
% variable via the bisection method.
% bisect(f,x) returns a zero of the
% function f.  f is a function
% handle or a string with the name of a
% function.  x is an array of length 2;
% f(x(1)) and f(x(2)) must differ in
% sign.
%
% An optional third input argument sets
% a tolerance for the relative accuracy
% of the result.  The default is eps.
% An optional second output argument
% gives a matrix containing a trace of
% the steps; the rows are of the form
% [c f(c)].

if (nargin < 3)
    % default tolerance
    tol = eps ;
end
trace = (nargout == 2) ;
if (ischar(f))
    f = str2func(f) ;
end
a = x(1) ;
b = x(2) ;
fa = f(a) ;
fb = f(b) ;
if (trace)
    steps = [a fa ; b fb] ;
end
% main loop
while (abs(b-a) > 2*tol*max(abs(b),1))
    c = a + (b-a)/2 ;
    fc = f(c) ;
    if (trace)
        steps = [steps ; [c fc]] ;
    end
```

```
    if (fb > 0) == (fc > 0)
        b = c ;
        fb = fc ;
    else
        a = c ;
        fa = fc ;
    end
end
```

Type in `bisect.m`, and then try:

```
bisect(@sin, [3 4])
bisect('sin', [3 4])
bisect(g, [0 3])
g(ans)
```

Some of MATLAB's functions are built in; others are distributed as M-files. The actual listing of any M-file, MATLAB's or your own, can be viewed with the MATLAB command `type`. Try entering `type eig`, `type vander`, and `type rank`.

8.2 Name resolution

When MATLAB comes upon a new name, it resolves it into a specific variable or function by checking to see if it is a variable, a built-in function, a file in the current directory, or a file in the MATLAB path (in order of the directories listed in the path). MATLAB uses the first variable, function, or file it encounters with the specified name. There are other cases; see `Help`: `MATLAB`: `Desktop Tools and Development Environment`: `Workspace, Search Path, and File Operations`: `Search Path`. You can use the command `which` to find out what a name is. Try this:

```
clear
i
which i
```

```
i = 3
which i
```

8.3 Error and warning messages

Error messages are best displayed with the function `error`. For example,

```
A = rand(4,3)
[m n] = size(A) ;
if m ~= n
    error('A must be square') ;
end
```

aborts execution of an M–file if the matrix `A` is not square. This is a useful thing to add to the `ddom` function that you developed in Chapter 7, since diagonal dominance is only defined for square matrices. Try adding it to `ddom` (excluding the `rand` statement, of course), and see what happens if you call `ddom` with a rectangular matrix.

If you want to print a warning, but continue execution, use the `warning` statement instead, as in:

```
warning('A singular; computing anyway')
```

The warning function can also turn on or off the warnings that MATLAB provides. If you know that a divide by zero is safe in your application, use

```
warning('off', 'MATLAB:divideByZero')
```

Try computing `1/0` both before and after you type in the above `warning` statement. Use `'on'` in the first argument to turn the warning back on for subsequent division by zero. `warning`, with no arguments, displays a list of disabled warnings.

See Section 6.5 (`try/catch`) for one way to deal with errors in functions you call.

8.4 User input

In an M-file the user can be prompted to interactively enter input data, expressions, or commands. When, for example, the statement:

```
iter = input('iteration count: ') ;
```

is encountered, the prompt message is displayed and execution pauses while the user keys in the input data (or, in general, any MATLAB expression). Upon pressing the return or entry key, the data is assigned to the variable `iter` and execution resumes. You can also input a string; see `help input`.

An M-file can be paused until a return is typed in the Command window with the `pause` command. It is a good idea to display a message, as in:

```
disp('Hit enter to continue: ') ;
pause
```

A Ctrl-C will terminate the script or function that is paused. A more general command, `keyboard`, allows you to type any number of MATLAB commands. See `doc keyboard`.

8.5 Performance measures

Time and space are the two basic measures of an algorithm's efficiency. In MATLAB, this translates into the number of floating-point operations (flops) performed, the elapsed time, the CPU time, and the memory space used. MATLAB no longer provides a flop count because it uses high-performance block matrix algorithms that make it difficult to count the actual flops performed. On current computers with deep memory hierarchies, flop count is less useful as a performance predictor than it once was. See `help flops`.

The elapsed time (in seconds) can be obtained with `tic` and `toc`; `tic` starts the timer and `toc` returns the elapsed time since the last `tic`. Hence:

```
tic ; statement ; t = toc
```

will return the elapsed time `t` for execution of the *`statement`*. Type it as one line in the Command window. Otherwise, the timer records the time you took to type the statement. The elapsed time for solving a linear system above can be obtained, for example, with:

```
n = 1000 ;
A = rand(n) ;
b = rand(n,1) ;
tic ; x = A\b ; t = toc
r = norm(A*x-b)
(2/3)*n^3 / t
```

The norm of the residual is also computed, and the last line reports the approximate flop rate. You may wish to compare `x=A\b` with `x=inv(A)*b` for solving the linear system. Try it. You will generally find `A\b` to be faster and more accurate.

If there are other programs running at the same time on your computer, elapsed time will not be an accurate measure of performance. Try using `cputime` instead. See `doc cputime`.

MATLAB runs faster if you can restructure your computations to use less memory. Type the following and select `n` to be some large integer, such as:

```
n = 16000 ;
a = rand(n,1) ;
b = rand(1,n) ;
c = rand(n,1) ;
```

Here are three ways of computing the same vector `x`. The first one uses hardly any extra memory, the second and third use a huge amount. Try them:

```
x = a*(b*c) ;
x = (a*b)*c ;
x = a*b*c ;
```

No measure of peak memory usage is provided. You can find out the total size of your workspace, in bytes, with the command `whos`. The total can also be computed:

```
s = whos
space = sum([s.bytes])
```

Try it. This does not give the peak memory used while inside a MATLAB operator or function, though. Type `doc memory` for more memory usage options.

8.6 Efficient code

The function `ddom.m` that you wrote in Chapter 7 and 8 illustrates some of the MATLAB features that can be used to produce efficient code. All operations are "vectorized," and loops are avoided. We could have written the ddom function using nested for loops:

```
function B = ddomloops(A,tol)
% B = ddomloops(A) returns a
% diagonally dominant matrix B by modifying
% the diagonal of A.
[m n] = size(A) ;
if (nargin == 1)
    tol = 100 * eps ;
end
for i = 1:n
    d = A(i,i) ;
    a = abs(d) ;
    f = 0 ;
    for j = 1:n
        if (i ~= j)
            f = f + abs(A(i,j)) ;
        end
    end
    if (f >= a)
        aii = (1 + tol) * max(f, tol) ;
        if (d < 0)
            aii = -aii ;
        end
        A(i,i) = aii ;
    end
end
B = A ;
```

The non-vectorized ddomloops function is only slightly slower than the vectorized ddom. In earlier versions of MATLAB, the non-vectorized version would be very slow. MATLAB 6.5 and subsequent versions include an accelerator that greatly improves the performance of non-vectorized code. Try:

```
A = rand(1000) ;
tic ; B = ddom(A) ; toc
tic ; B = ddomloops(A) ; toc
```

Only simple for loops can be accelerated. Loops that operate on sparse matrices are not accelerated, for example (sparse matrices are discused in Chapter 15). Try:

```
A = sparse(A) ;
tic ; B = ddom(A) ; toc
tic ; B = ddomloops(A) ; toc
```

Since not every loop can be accelerated, writing code that has no `for` or `while` loops is still important. As you become practiced in writing without loops and reading loop-free MATLAB code, you will also find that the loop-free version is often easier to read and understand.

If you cannot vectorize a loop, you can speed it up by preallocating any vectors or matrices in which output is stored. For example, by including the second statement below, which uses the function `zeros`, space for storing `E` in memory is preallocated. Without this, MATLAB must resize `E` one column larger in each iteration, slowing execution.

```
M = magic(6) ;
E = zeros(6,50) ;
for j = 1:50
    E(:,j) = eig(M^j) ;
end
```

9. Calling C from MATLAB

There are times when MATLAB itself is not enough. You may have a large application or library written in another language that you would like to use from MATLAB, or it might be that the performance of your M-file is not what you would like.

MATLAB can call routines written in C, Fortran, or Java. Similarly, programs written in C and Fortran can call

MATLAB. In this chapter, we will just look at how to call a C routine from MATLAB. For more information, see `Help`: `MATLAB`: `External Interfaces`, or see the online MATLAB documents *External Interfaces* and *External Interfaces Reference*. This discussion assumes that you already know C.

9.1 A simple example

A routine written in C that can be called from MATLAB is called a MEX-file. The routine must always have the name `mexFunction`, and the arguments to this routine are always the same. Here is a very simple MEX-file; type it in as the file `hello.c` in your favorite text editor.

```
#include "mex.h"
void mexFunction
(
    int nargout,
    mxArray *pargout [ ],
    int nargin,
    const mxArray *pargin [ ]
)
{
    mexPrintf ("hello world\n") ;
}
```

Compile and run it by typing:

```
mex hello.c
hello
```

If this is the first time you have compiled a C MEX-file on a PC with Microsoft Windows, you will be prompted to select a C compiler. MATLAB for the PC comes with its own C compiler (`lcc`). The arguments `nargout` and `nargin` are the number of outputs and inputs to the function (just as an M-file function), and `pargout` and `pargin` are pointers to the arguments themselves (of type mxArray). This hello.c MEX-file does not have any inputs or outputs, though.

The mexPrintf function is just the same as printf. You can also use printf itself; the mex command redefines it as mexPrintf when the program is compiled with a #define. This way, you can write a routine that can be used from MATLAB or from a stand-alone C application, without MATLAB.

9.2 C versus MATLAB arrays

MATLAB stores its arrays in column major order, while the convention for C is to store them in row major order. Also, the number of columns in an array is not known until the mexFunction is called. Thus, two-dimensional arrays in MATLAB must be accessed with one-dimensional indexing in C (see also Section 5.6). In the example in the next section, the INDEX macro helps with this translation.

Array indices also appear differently. MATLAB is written in C, and it stores all of its arrays internally using zero-based indexing. An m-by-n matrix has rows 0 to m-1 and columns 0 to n-1. However, the user interface to these arrays is always one-based, and index vectors in MATLAB are always one-based. In the example below, one is added to the List array returned by diagdom to account for this difference.

9.3 A matrix computation in C

In Chapters 7 and 8, you wrote the function ddom.m. Here is the same function written as an ANSI C MEX-file. Compare the diagdom routine with the loop-based version `ddomloops.m` in Section 8.6. MATLAB `mx` and `mex` routines are described in Section 9.4.

```
#include "mex.h"
#include "matrix.h"
#include <stdlib.h>
#include <float.h>
#define INDEX(i,j,m) ((i)+(j)*(m))
#define ABS(x) ((x) >= 0 ? (x) : -(x))
#define MAX(x,y) (((x)>(y)) ? (x):(y))

void diagdom
(
    double *A, int n, double *B,
    double tol, int *List, int *nList
)
{
    double d, a, f, bij, bii ;
    int i, j, k ;
    for (k = 0 ; k < n*n ; k++)
    {
        B [k] = A [k] ;
    }
    if (tol < 0)
    {
        tol = 100 * DBL_EPSILON ;
    }
    k = 0 ;
    for (i = 0 ; i < n ; i++)
    {
        d = B [INDEX (i,i,n)] ;
        a = ABS (d) ;
        f = 0 ;
        for (j = 0 ; j < n ; j++)
        {
            if (i != j)
            {
                bij = B [INDEX (i,j,n)] ;
                f += ABS (bij) ;
            }
        }
        if (f >= a)
        {
            List [k++] = i ;
            bii = (1 + tol) * MAX (f, tol) ;
            if (d < 0)
            {
```

```
                bii = -bii ;
            }
            B [INDEX (i,i,n)] = bii ;
        }
    }
    *nList = k ;
}

void error (char *s)
{
    mexPrintf
    ("Usage: [B,i] = diagdom (A,tol)\n") ;
    mexErrMsgTxt (s) ;
}

void mexFunction
(
    int nargout, mxArray *pargout [ ],
    int nargin,  const mxArray *pargin [ ]
)
{
    double tol, *A, *B, *I ;
    int n, k, *List, nList ;

    /* get inputs A and tol */
    if (nargout > 2 || nargin > 2 || nargin==0)
    {
        error ("Wrong number of arguments") ;
    }
    if (mxIsSparse (pargin [0]))
    {
        error ("A cannot be sparse") ;
    }
    n = mxGetN (pargin [0]) ;
    if (n != mxGetM (pargin [0]))
    {
        error ("A must be square") ;
    }
    A = mxGetPr (pargin [0]) ;
    tol = -1 ;
    if (nargin > 1)
    {
        if (!mxIsEmpty (pargin [1]) &&
           mxIsDouble (pargin [1]) &&
           !mxIsComplex (pargin [1]) &&
           mxIsScalar (pargin [1]))
        {
            tol = mxGetScalar (pargin [1]) ;
        }
```

```
        else
        {
            error ("tol must be scalar") ;
        }
    }

    /* create output B */
    pargout [0] =
        mxCreateDoubleMatrix (n, n, mxREAL) ;
    B = mxGetPr (pargout [0]) ;

    /* get temporary workspace */
    List = (int *) mxMalloc (n * sizeof (int)) ;

    /* do the computation */
    diagdom (A, n, B, tol, List, &nList) ;

    /* create output I */
    pargout [1] =
        mxCreateDoubleMatrix (nList, 1, mxREAL);
    I = mxGetPr (pargout [1]) ;
    for (k = 0 ; k < nList ; k++)
    {
        I [k] = (double) (List[k] + 1) ;
    }

    /* free the workspace */
    mxFree (List) ;
}
```

Type it in as the file `diagdom.c` (or get it from the web), and then type:

```
mex diagdom.c
A = rand(6) ;
B = ddom(A) ;
C = diagdom(A) ;
```

The matrices `B` and `C` will be the same (round-off error might cause them to differ slightly). The C mexFunction `diagdom` is about 3 times faster than the M-file `ddom` for large matrices.

9.4 MATLAB mx and mex routines

In the last example, the C routine calls several MATLAB routines with the prefix `mx` or `mex`. Routines with `mx` prefixes operate on MATLAB matrices and include:

`mxIsEmpty`	1 if the matrix is empty, 0 otherwise
`mxIsSparse`	1 if the matrix is sparse, 0 otherwise
`mxGetN`	number of columns of a matrix
`mxGetM`	number of rows of a matrix
`mxGetPr`	pointer to the real values of a matrix
`mxGetScalar`	the value of a scalar
`mxCreateDoubleMatrix`	create MATLAB matrix
`mxMalloc`	like `malloc` in ANSI C
`mxFree`	like `free` in ANSI C

Routines with `mex` prefixes operate on the MATLAB environment and include:

`mexPrintf`	like `printf` in C
`mexErrMsgTxt`	like MATLAB's `error` statement
`mexFunction`	the gateway routine from MATLAB

You will note that all of the references to MATLAB's `mx` and `mex` routines are limited to the `mexFunction` gateway routine. This is not required; it is just a good idea. Many other `mx` and `mex` routines are available.

The memory management routines in MATLAB (`mxMalloc`, `mxFree`, and `mxCalloc`) are much easier to use than their ANSI C counterparts. If a memory allocation request fails, the `mexFunction` terminates and control is passed backed to MATLAB. Any workspace allocated by `mxMalloc` that is not freed when the `mexFunction` returns or terminates is automatically freed by MATLAB. This is why no memory allocation error checking is included in `diagdom.c`; it is not necessary.

9.5 Online help for MEX routines

Create an M-file called `diagdom.m`, with only this:

```
function [B,i] = diagdom(A,tol)
%DIAGDOM:  modify the matrix A
% [B,i] = diagdom(A,tol) returns a
% diagonally dominant matrix B by
% modifying the diagonal of A.  i is a
% list of modified diagonal entries.
error('diagdom mexFunction not found');
```

Now type `help diagdom` or `doc diagdom`. This is a simple method for providing online help for your own MEX-files.

If both `diagdom.m` and the compiled `diagdom` mexFunction are in MATLAB's path, then the `diagdom` mexFunction is called. If only the M-file is in the path, it is called instead; thus the error statement in `diagdom.m` above.

9.6 Larger examples on the web

The `colamd` and `symamd` routines in MATLAB are C MEX-files. The source code for these routines is on the web at http://www.cise.ufl.edu/research/sparse/colamd. Like the example in the previous section, they are split into a `mexFunction` gateway routine and another set of routines that do not make use of MATLAB. A simpler example is a sparse LDL^T factorization routine that takes less memory than MATLAB's `chol`, at http://www.cise.ufl.edu/research/sparse/ldl.

10. Calling Fortran from MATLAB

C is a great language for numerical calculations, particularly if the data structures are complicated. MATLAB itself is written in C. No single language is best for all tasks, however, and that holds for C as well. In this chapter we will look at how to call a Fortran subroutine from MATLAB. A Fortran subroutine is accessed via a mexFunction in much the same way as a C subroutine is called. Normally, the mexFunction acts as a gateway routine that gets its input arguments from MATLAB, calls a computational routine, and then returns its output arguments to MATLAB, just like the C example in the previous chapter.

10.1 Solving a transposed system

The `linsolve` function was introduced in Section 5.5. Here is a Fortran subroutine `utsolve` that computes `x=A'\b` when `A` is dense, square, real, and upper triangular. It has no calls to MATLAB-specific `mx` or `mex` routines.

```
      subroutine utsolve (n, x, A, b)
      integer n
      real*8 x(n), A(n,n), b(n), xi
      integer i, j
      do 1 i = 1,n
        xi = b(i)
        do 2 j = 1,i-1
          xi = xi - A(j,i) * x(j)
    2   continue
        x(i) = xi / A(i,i)
    1 continue
      return
      end
```

10.2 A Fortran mexFunction with %val

To call this computational subroutine from MATLAB as x=utsolve(A,b), we need a gateway routine, the first lines of which must be:

```
      subroutine mexFunction
     $ (nargout, pargout, nargin, pargin)
      integer nargout, nargin
      integer pargout (*), pargin (*)
```

where the $ is in column 6. These lines must be the same for any Fortran mexFunction (you do not need to split the first line). Note that pargin and pargout are arrays of integers. MATLAB passes its inputs and outputs as pointers to objects of type mxArray, but Fortran cannot handle pointers. Most Fortran compilers can convert integer "pointers" to references to Fortran arrays via the non-standard %val construct. We will use this in our gateway routine. The next two lines of the gateway routine declare some MATLAB mx-routines.

```
      integer mxGetN, mxGetPr
      integer mxCreateDoubleMatrix
```

This is required because Fortran has no include-file mechanism. The next lines determine the size of the input matrix and create the n-by-1 output vector x.

```
      integer n
      n = mxGetN (pargin (1))
      pargout (1) =
     $ mxCreateDoubleMatrix (n, 1, 0)
```

We can now convert "pointers" into Fortran array references and call the computational routine.

```
 call utsolve (n,
$ %val (mxGetPr (pargout (1))),
$ %val (mxGetPr (pargin (1))),
$ %val (mxGetPr (pargin (2))))
  return
  end
```

The arrays in both MATLAB and Fortran are column-oriented and one-based, so translation is not necessary as it was in the C mexFunction.

Combine the two routines into a single file called `utsolve.f` and type:

```
mex utsolve.f
```

in the MATLAB command window. Error checking could be added to ensure that the two input arguments are of the correct size and type. The code would look much like the C example in Chapter 9, so it is not included. Test this routine on as large a matrix that your computer can handle.

```
n = 5000
A = triu(rand(n,n)) ;
b = rand(n,1) ;
tic ; x = A'\b ; toc
opts.UT = true
opts.TRANSA = true
tic ; x2 = linsolve(A,b,opts) ; toc
tic ; x3 = utsolve(A,b) ; toc
norm(x-x2)
norm(x-x3)
```

The solutions should agree quite closely. On a Pentium 4, both `linsolve` and `utsolve` are about 15 times faster than `x=A'\b`. They require less memory, as well, since they do not have to construct `A'`.

10.3 If you cannot use %val

If your Fortran compiler does not support the `%val` construct, then you will need to call MATLAB `mx`-routines to copy the MATLAB arrays into Fortran arrays, and vice versa. The GNU `f77` compiler supports `%val`, but issues a warning that you can safely ignore.

In this `utsolve` example, add this to your `mexFunction` gateway routine:

```
      integer nmax
      parameter (nmax = 5000)
      real*8 A(nmax,nmax), x(nmax), b(nmax)
```

where `nmax` is the largest dimension you want your function to handle. Unless you want to live dangerously, you should check `n` to make sure it is not too big:

```
      if (n .gt. nmax) then
         call mexErrMsgTxt ("n too big")
      endif
```

Replace the call to `utsolve` with this code.

```
      call mxCopyPtrToReal8
     $ (mxGetPr (pargin (1)), A, n**2)
      call mxCopyPtrToReal8
     $ (mxGetPr (pargin (2)), b, n)
      call lsolve (n, x, A, b)
      call mxCopyReal8ToPtr
     $ (x, mxGetPr (pargout (1)), n)
```

This copies the input MATLAB arrays `A` and `b` to their Fortran counterparts, calls the `utsolve` routine, and then copies the solution `x` to its MATLAB counterpart. Although this is more portable, it takes more memory and is significantly slower. If possible, use `%val`.

11. Calling Java from MATLAB

While C and Fortran excel at numerical computations, Java is well-suited to web-related applications and graphical user interfaces. MATLAB can handle native Java objects in its workspace and can directly call Java methods on those objects. No mexFunction is required.

11.1 A simple example

Try this in the MATLAB Command window

```
t = 'hello world'
s = java.lang.String(t)
s.indexOf('w') + 1
find(s == 'w')
whos
```

You have just created a Java string in the MATLAB workspace, and determined that the character `'w'` appears as the seventh entry in the string using both the `indexOf` Java method and the `find` MATLAB function.

11.2 Encryption/decryption

MATLAB can handle strings on its own, without help from Java, of course. Here is a more interesting example. Type in the following as the M-file `getkey.m`.

```
function key = getkey(password)
%GETKEY: key = getkey(password)
% Converts a string into a key for use
% in the encrypt and decrypt functions.
% Uses triple DES.
import javax.crypto.spec.*
b = int8(password) ;
n = length(b) ;
b((n+1):24) = 0 ;
b = b(1:24) ;
key = SecretKeySpec(b, 'DESede') ;
```

The `getkey` routine takes a password string and converts it into a 24-byte triple DES key using the `javax.crypto` package. You can then encrypt a string with the `encrypt` function:

```
function e = encrypt(t, key)
%ENCRYPT: e = encrypt(t, key)
% Encrypt the plaintext string t into
% the encrypted byte array e using a key
% from getkey.
import javax.crypto.*
cipher = Cipher.getInstance('DESede') ;
cipher.init(Cipher.ENCRYPT_MODE, key) ;
e = cipher.doFinal(int8(t))' ;
```

Except for the function statement and the comments, this looks almost exactly the same as the equivalent Java code. This is not a Java program, however, but a MATLAB M-file that uses Java objects and methods. Finally, the `decrypt` function undoes the encryption: .

```
function t = decrypt(e, key)
%DECRYPT: t = decrypt(e, key)
% Decrypt the encrypted byte array e
% into to plaintext string t using a key
% from getkey.
import javax.crypto.*
cipher = Cipher.getInstance('DESede') ;
cipher.init(Cipher.DECRYPT_MODE, key) ;
t = char(cipher.doFinal(e))' ;
```

With these three functions in place, try:

```
k = getkey('this is a secret password')
e = encrypt('a hidden message',k)
decrypt(e,k)
```

Now you encrypt and decrypt strings in MATLAB.

11.3 MATLAB's Java class path

If you define your own Java classes that you want to use within MATLAB, you need to modify your Java class path. This path is different than the path used to find M-files. You can add directories to the static Java path by editing the file `classpath.txt`, or you can add them to your dynamic Java path with the command

```
javaaddpath directory
```

where *directory* is the name of a directory containing compiled Java classes. `javaclasspath` lists the directories where MATLAB looks for Java classes.

If you do not have write permission to `classpath.txt`, you need to type the `javaaddpath` command every time you start MATLAB. You can do this automatically by creating an M-file script called `startup.m` and placing in it the `javaaddpath` command. Place this file in one of the directories in your MATLAB path, or in the directory in which you launch MATLAB, and it will be executed whenever MATLAB starts.

11.4 Calling your own Java methods

To write your own Java classes that you can call from MATLAB, you must first download and install the Java 2 SDK (Software Development Kit) Version 1.4 (or later) from java.sun.com. Edit your operating system's `PATH` variable so that you can type the command `javac` in your operating system command prompt.

MATLAB includes two M-files that can download a web page into either a string (`urlread`) or a file (`urlwrite`). Try:

```
s = urlread('http://www.mathworks.com')
```

The `urlread` function is an M-file. You can take a look at it with the command `edit urlread`. It uses a Java package from The MathWorks called `mlwidgets.io.InterruptibleStreamCopier`, but only the compiled class file is distributed, not the Java source file. Create your own URL reader, a purely Java program, and put it in a file called `myreader.java`:

```
import java.io.* ;
import java.net.* ;
public class myreader
{
  public static void main (String [ ] args)
  {
    geturl (args [0], args [1]) ;
  }
  public static void geturl (String u, String f)
  {
    try
    {
      URL url = new URL (u) ;
      InputStream i = url.openStream ();
      OutputStream o = new FileOutputStream (f);
      byte [ ] s = new byte [4096] ;
      int b ;
      while ((b = i.read (s)) != -1)
      {
        o.write (s, 0, b) ;
      }
      i.close ( ) ;
      o.close ( ) ;
    }
    catch (Exception e)
    {
      System.out.println (e) ;
    }
  }
}
```

The `geturl` method opens the URL given by the string `u`, and copies it into a file whose name is given by the string f. In either Linux/Unix or Windows, you can compile this Java program and run it by typing these commands at your operating system command prompt:

```
javac myreader.java
java myreader http://www.google.com my.txt
```

The second command copies Google's home page into your own file called my.txt. You can also type the commands in the MATLAB Command window, as in:

```
!javac myreader.java
```

Now that you have your own Java method, you can call it from MATLAB just as the java.lang.String and javax.crypto.* methods. In the MATLAB command window, type (as one line):

```
myreader.geturl
('http://www.google.com','my.txt')
```

11.5 Loading a URL as a matrix

An even more interesting use of the myreader.geturl method is to load a MAT-file or ASCII file from a web page directly into the MATLAB workspace as a matrix. Here is a simple loadurl M-file that does just that. It can read compressed files; the Java method uncompresses the URL automatically if it is compressed.

```
function result = loadurl(url)
% result = loadurl(url)
% Reads the URL given by the input
% string, url, into a temporary file
% using myread.java, loads it into a
% MATLAB variable, and returns the
% result. The URL can contain a MATLAB-
% readable text file, or a MAT-file.
t = tempname ;
```

```
myreader.geturl(url, t) ;
% load the temporary file, if it exists
try
    % try loading as an ascii file first
    result = load(t) ;
catch
    % try as a MAT file if ascii fails
    try
        result = load('-mat', t) ;
    catch
        result = [ ] ;
    end
end
% delete the temporary file
if (exist(t, 'file'))
    delete(t) ;
end
```

Try it with a simple text file (type this in as one line):

```
w = loadurl('http://www.cise.ufl.edu/
research/sparse/MATLAB/w')
```

which loads in a 2-by-2 matrix. Also try it with this rather lengthy URL (type the string on one line):

```
s = loadurl('http://www.cise.ufl.edu/
research/sparse/mat/HB/west0479.mat.gz')
prob = s.Problem
spy(prob.A)
title([prob.name ': ' prob.title])
```

MATLAB 7.0 can create compressed MAT-files, so in the future you may need to exclude the `.gz` extension in this URL. `spy` plots a sparse matrix (see Section 15.5).

12. Two-Dimensional Graphics

MATLAB can produce two-dimensional plots. The primary command for this is `plot`. Chapter 13 discusses three-dimensional graphics. To preview some of these capabilities, enter the command `demo` and select some of the visualization and graphics demos. See Chapter 16 for a discussion of how to plot symbolic functions. Just like any other window, a Figure window can be docked in the main MATLAB window (except on the Macintosh).

12.1 Planar plots

The `plot` command creates linear *x–y* plots; if `x` and `y` are vectors of the same length, the command `plot(x,y)` opens a graphics window and draws an *x–y* plot of the elements of `y` versus the elements of `x`. You can, for example, draw the graph of the sine function over the interval -4 to 4 with the following commands:

```
x = -4:0.01:4 ;
y = sin(x) ;
plot(x, y) ;
```

Try it. The vector `x` is a partition of the domain with mesh size `0.01`, and `y` is a vector giving the values of sine at the nodes of this partition (recall that `sin` operates entry-wise). When plotting a curve, the `plot` routine is actually connecting consecutive points induced by the partition with line segments. Thus, the mesh size should be chosen sufficiently small to render the appearance of a smooth curve.

The next example draws the graph of $y = e^{-x^2}$ over the interval -3 to 3. Note that you must precede `^` by a period to ensure that it operates entry-wise:

```
x = -3:.01:3 ;
y = exp(-x.^2) ;
plot(x, y) ;
```

Select `Tools` ▶ `Zoom In` or `Tools` ▶ `Zoom Out` in the Figure window to zoom in or out, or click these buttons (or see the `zoom` command):

12.2 Multiple figures

You can have several concurrent Figure windows, one of which will at any time be the designated current figure in which graphs from subsequent plotting commands will be placed. If, for example, Figure 1 is the current figure, then the command `figure(2)` (or simply `figure`) will open a second figure (if necessary) and make it the current figure. The command `figure(1)` will then expose Figure 1 and make it again the current figure. The command `gcf` returns the current figure number, and `figure(gcf)` brings the current figure window up.

MATLAB does not draw a plot right away. It waits until all computations are finished, until a `figure` command is encountered, or until the script or function requests user input (see Section 8.4). To force MATLAB to draw a plot right away, use the command `drawnow`. This does not change the current figure.

12.3 Graph of a function

MATLAB supplies a function `fplot` to plot the graph of a function. For example, to plot the graph of the function above, you can first define the function in an M-file called, say, `expnormal.m` containing:

```
function y = expnormal(x)
y = exp(-x.^2) ;
```

Then:

```
fplot(@expnormal, [-3 3])
```

will produce the graph over the indicated *x*-domain.

Using an anonymous function gives the same result without creating `expnormal.m`:

```
f = @(x) exp(-x.^2)
fplot(f, [-3 3])
```

12.4 Parametrically defined curves

Plots of parametrically defined curves can also be made:

```
t = 0:.001:2*pi ;
x = cos(3*t) ;
y = sin(2*t) ;
plot(x, y) ;
```

12.5 Titles, labels, text in a graph

The graphs can be given titles, axes labeled, and text placed within the graph with the following commands, which take a string as an argument.

`title`	graph title
`xlabel`	*x*-axis label
`ylabel`	*y*-axis label
`gtext`	place text on graph using the mouse
`text`	position text at specified coordinates

For example, the command:

```
title('A parametric cos/sin curve')
```

gives a graph a title. The command `gtext('The Spot')` lets you interactively place the designated text on the current graph by placing the mouse crosshair at the desired position and clicking the mouse. It is a good idea to prompt the user before using `gtext`. To place text in a graph at designated coordinates, use the command `text` (see `doc text`). These commands are also in the `Insert` menu in the Figure window. Select `Insert` ► `TextBox`, click on the figure, type something, and then click somewhere else to finish entering the text. If the edit-figure button  is depressed (or select `Tools` ► `Edit Plot`), you can right-click on anything in the figure and see a pop-up menu that gives you options to modify the item you just clicked. You can click and drag objects on the figure. Selecting `Edit` ► `Axes Properties` brings up a window with many more options. For example, clicking the 

boxes adds grid lines (as does the `grid` command).

12.6 Control of axes and scaling

By default, MATLAB scales the axes itself (auto-scaling). This can be overridden by the command `axis` or by selecting `Edit` ► `Axes Properties`. Some features of the `axis` command are:

`axis([xmin xmax ymin ymax])`	sets the axes
`axis manual`	freezes the current axes for new plots
`axis auto`	returns to auto-scaling
`v = axis`	vector v shows current scaling
`axis square`	axes same size (but not scale)
`axis equal`	same scale and tic marks on axes

```
axis off        removes the axes
axis on         restores the axes
```

The `axis` command should be given after the `plot` command. Try `axis([-2 2 -3 3])` with the current figure. You will note that text entered on the figure using the `text` or `gtext` moves as the scaling changes (think of it as attached to the data you plotted). Text entered via `Insert` ► `TextBox` stays put.

12.7 Multiple plots

Here is one way to make multiple plots on a single graph:

```
x = 0:.01:2*pi;
y1 = sin(x) ;
y2 = sin(2*x) ;
y3 = sin(4*x) ;
plot(x, y1, x, y2, x, y3)
```

Another method uses a matrix `Y` containing the functional values as columns:

```
x = (0:.01:2*pi)' ;
y = [sin(x), sin(2*x), sin(4*x)] ;
plot(x, y)
```

The `x` and `y` pairs must have the same length, but each pair can have different lengths. Try:

```
plot(x, y, [0 2*pi], [0 0])
```

The command `hold on` freezes the current graphics screen so that subsequent plots are superimposed on it. The axes may, however, become rescaled. Entering `hold off` releases the hold. `clf` clears the figure. `legend` places a legend in the current figure to identify the different graphs. See `doc legend`.

12.8 Line types, marker types, colors

You can override the default line types, marker types, and colors. For example,

```
x = 0:.01:2*pi ;
y1 = sin(x) ;
y2 = sin(2*x) ;
y3 = sin(4*x) ;
plot(x,y1, '--', x,y2, ':', x,y3, 'o')
```

renders a dashed line and dotted line for the first two graphs, whereas for the third the symbol `o` is placed at each node. The line types are:

`'-'`	solid	`':'`	dotted
`'--'`	dashed	`'-.'`	dashdot

and the marker types are:

`'.'`	point	`'o'`	circle
`'x'`	x-mark	`'+'`	plus
`'*'`	star	`'s'`	square
`'d'`	diamond	`'v'`	triangle-down
`'^'`	triangle-up	`'<'`	triangle-left
`'>'`	triangle-right	`'p'`	pentagram
`'h'`	hexagram		

Colors can be specified for the line and marker types:

`'y'`	yellow	`'m'`	magenta
`'c'`	cyan	`'r'`	red
`'g'`	green	`'b'`	blue
`'w'`	white	`'k'`	black

Thus, plot(x,y1,'r--') plots a red dashed line.

12.9 Subplots and specialized plots

The command subplot(m,n,p) partitions a single figure into an m-by-n array of panes, and makes pane p the current plot. The panes are numbered left to right. A subplot can span multiple panes by specifying a vector p. Here the last example, with each data set plotted in a separate subplot:

```
subplot(2,2,1)
plot(x,y1, '--')
subplot(2,2,2)
plot(x,y2, ':')
subplot(2,2,[3 4])
plot(x,y3, 'o')
```

Other specialized planar plotting functions you may wish to explore via help are:

```
bar       fill    quiver
compass   hist    rose
feather   polar   stairs
```

12.10 Graphics hard copy

Select File ► Print or click the print button

in the Figure window to send a copy of your figure to your default printer. Layout options and selecting a printer can be done with File ► Page Setup and File ► Print Setup.

You can save the figure as a file for later use in a MATLAB Figure window. Try the save button

or File ▶ Save. This saves the figure as a .fig file, which can be later opened in the Figure window with the open button

or with File ▶ Open. Selecting File ▶ Export Setup or File ▶ Save As allows you to convert your figure to many other formats.

13. Three-Dimensional Graphics

MATLAB's primary commands for creating three-dimensional graphics of numerically-defined functions are plot3, mesh, surf, and light. Plotting of symbolic functions is discussed in Chapter 16. The menu options and commands for setting axes, scaling, and placing text, labels, and legends on a graph also apply for 3-D graphs. A zlabel can be added. The axis command requires a vector of length 6 with a 3-D graph.

13.1 Curve plots

Completely analogous to plot in two dimensions, the command plot3 produces curves in three-dimensional space. If x, y, and z are three vectors of the same size, then the command plot3(x,y,z) produces a perspective plot of the piecewise linear curve in three-space passing through the points whose coordinates are the respective elements of x, y, and z. These vectors are usually defined parametrically. For example,

```
t = .01:.01:20*pi ;
x = cos(t) ;
```

```
y = sin(t) ;
z = t.^3 ;
plot3(x, y, z)
```

produces a helix that is compressed near the *x*-*y* plane (a "slinky"). Try it.

13.2 Mesh and surface plots

The `mesh` command draws three-dimensional wire mesh surface plots. The command `mesh(z)` creates a three-dimensional perspective plot of the elements of the matrix `z`. The mesh surface is defined by the *z*-coordinates of points above a rectangular grid in the *x*-*y* plane. Try `mesh(eye(20))`.

Similarly, three-dimensional faceted surface plots are drawn with the command `surf`. Try `surf(eye(20))`.

To draw the graph of a function $z = f(x, y)$ over a rectangle, first define vectors `xx` and `yy`, which give partitions of the sides of the rectangle. The function `[x,y]=meshgrid(xx,yy)` then creates a matrix `x`, each row of which equals `xx` (whose column length is the length of `yy`) and similarly a matrix `y`, each column of which equals `yy`. A matrix `z`, to which `mesh` or `surf` can be applied, is then computed by evaluating the function `f` entry-wise over the matrices `x` and `y`.

You can, for example, draw the graph of $z = e^{-x^2-y^2}$ over the square [-2, 2] x [-2, 2] as follows:

```
xx = -2:.2:2 ;
yy = xx ;
[x, y] = meshgrid(xx, yy) ;
z = exp(-x.^2 - y.^2) ;
mesh(z)
```

Try this plot with `surf` instead of `mesh`. Note that you must use `x.^2` and `y.^2` instead of `x^2` and `y^2` to ensure that the function acts entry-wise on `x` and `y`.

13.3 Parametrically defined surfaces

Plots of parametrically defined surfaces can also be made. See the MATLAB functions `sphere` and `cylinder` for example. The next example displays the cover of this book, with lighting, color, and viewpoint defined in Section 13.6. First, start a figure and set up the mesh:

```
figure(1) ; clf
t = linspace(0, 2*pi, 512) ;
[u,v] = meshgrid(t) ;
```

Next, define the surface:[2]

```
a = -0.2 ; b = .5 ; c = .1 ;
n = 2 ;
x = (a*(1-v/(2*pi)).*(1+cos(u)) + c) ...
    .* cos(n*v) ;
y = (a*(1-v/(2*pi)).*(1+cos(u)) + c) ...
    .* sin(n*v) ;
z = b*v/(2*pi) + ...
    a*(1-v/(2*pi)) .* sin(u) ;
```

Plot the surface, using `y` to define the color, and turn off the mesh lines on the surface:

```
surf(x,y,z,y)
shading interp
```

Also try `a=-0.5`, which gives the back cover.

---

[2] von Seggern, CRC Standard Curves and Surfaces, 2nd ed., CRC Press, 1993, pp. 306-307.

Other three-dimensional plotting functions you may wish to explore via `help` or `doc` are `meshz`, `surfc`, `surfl`, `contour`, and `pcolor`. For plotting symbolically defined parametric surfaces (including the same seashell you plotted above), see Section 16.7.

13.4 Volume and vector visualization

MATLAB has an extensive suite of volume and vector visualization tools. The following example evaluates a function of three variables, *v=f(x,y,z)*, that represents a fluid flow problem. It returns both `v` and the coordinates (`x`, `y`, and `z`) at which the function was evaluated.

```
[x,y,z,v] = flow ;
```

Now try visualizing it. The first method plots the surface at which `v` is -3; the second plots slices of the data:

```
figure(1) ; clf
isosurface(x, y, z, v, -3)
figure(2) ; clf
slice(x, y, z, v, [3 8], 0, 0)
```

Type `doc specgraph` for more volume and vector visualization tools.

13.5 Color shading and color profile

The color shading of surfaces is set by the `shading` command. There are three settings for shading: `faceted` (default), `interpolated`, and `flat`. These are set by the commands:

```
shading faceted
shading interp
shading flat
```

Note that on surfaces produced by surf, the settings interpolated and flat remove the superimposed mesh lines. Experiment with various shadings on the surface produced above. The command shading (as well as colormap and view described below) should be entered after the surf command.

The color profile of a surface is controlled by the colormap command. Available predefined color maps include hsv (the default), hot, cool, jet, pink, copper, flag, gray, bone, prism, and white. The command colormap(cool), for example, sets a certain color profile for the current figure. Experiment with various color maps on the surface produced above. See also help colorbar.

13.6 Perspective of view

The Figure window provides a wide range of controls for viewing the figure. Select View ▶ Camera Toolbar to see these controls, or pull down the Tools menu. Try, for example, selecting Tools ▶ Rotate 3D, and then click the mouse in the Figure window and drag it to rotate the object. Some of these options can be controlled by the view and rotate3d commands, respectively.

The MATLAB function peaks generates an interesting surface on which to experiment with shading, colormap, and view. Type peaks, select Tools ▶ Rotate 3D, and click and drag the figure to rotate it.

In MATLAB, light sources and camera position can be set. Taking the peaks surface from the example above, select Insert ▶ Light, or type light to add a light source. See the online document *Using MATLAB Graphics* for camera and lighting help.

This example defines the color, shading, lighting, surface material, and viewpoint for the cover of the book:

```
axis off
axis equal
colormap(hsv(1024))
shading interp
material shiny
lighting gouraud
lightangle(80, -40)
lightangle(-90, 60)
view([-150 10])
```

14. Advanced Graphics

MATLAB possesses a number of other advanced graphics capabilities. Significant ones are bitmapped images, object-based graphics, called Handle Graphics®, and Graphical User Interface (GUI) tools.

14.1 Handle Graphics

Beyond those just described, MATLAB's graphics system provides low-level functions that let you control virtually all aspects of the graphics environment to produce sophisticated plots. The commands `set` and `get` allow access to all the properties of your plots. Try `set(gcf)` to see some of the properties of a figure that you can control. `set(gca)` lists the properties of the current axes (see Section 14.3 for an example). This system is called Handle Graphics. See *Using MATLAB Graphics* for more information.

14.2 Graphical user interface

MATLAB's graphics system also provides the ability to add sliders, push-buttons, menus, and other user interface controls to your own figures. For information on creating user interface controls, try `doc uicontrol`. This allows you to create interactive graphical-based applications. Try `guide` (short for Graphic User Interface Development Environment). This brings up MATLAB's Layout Editor window that you can use to interactively design a graphic user interface. Also see the online document *Creating Graphical User Interfaces*.

14.3 Images

The `image` function plots a matrix, where each entry in the matrix defines the color of a single pixel or block of pixels in the figure. `image(K)` paints the (i,j)th block of the figure with color `K(i,j)` taken from the `colormap`. Here is an example of the Mandelbrot set. The bottom left corner is defined as `(x0,y0)`, and the upper right corner is `(x0+d,y0+d)`. Try changing `x0`, `y0`, and `d` to explore other regions of the set (`x0=-.38`, `y0=.64`, `d=.03` is also very pretty). This is also a good example of one-dimensional indexing:

```
x0 = -2 ; y0 = -1.5 ; d = 3 ; n = 512 ;
maxit = 256 ;

x = linspace(x0, x0+d, n) ;
y = linspace(y0, y0+d, n) ;
[x,y] = meshgrid(x, y) ;
C = x + y*1i ;
Z = C ;
K = ones(n, n) ;
for k = 1:maxit
    a = find((real(Z).^2 + imag(Z).^2) < 4);
    Z(a) = (Z(a)).^2 + C(a) ;
    K(a) = k ;
```

```
end
figure(1) ; clf
colormap(jet(maxit)) ;
image(x0 + [0 d], y0 + [0 d], K) ;
set(gca, 'YDir', 'normal') ;
axis equal
axis tight
```

`image`, by default, reverses the *y* direction and plots the `K(1,1)` entry at the top left of the figure (just like the `spy` function described in Section 15.5). The `set` function resets this to the normal direction, so that `K(1,1)` is plotted in the bottom left corner.

Try replacing the fourth argument in `surf`, for the seashell example, with `K`, to paint the seashell surface with the Mandelbrot set.

15. Sparse Matrix Computations

A sparse matrix is one with mostly zero entries. MATLAB provides the capability to take advantage of the sparsity of matrices.

15.1 Storage modes

MATLAB has two storage modes, full and sparse, with full the default. Currently, only `double` or `logical` vectors or two-dimensional arrays can be stored in the sparse mode. The functions `full` and `sparse` convert between the two modes. Nearly all MATLAB operators and functions operate seamlessly on both full and sparse matrices. For a matrix `A`, full or sparse, `nnz(A)` returns the number of nonzero elements in A. An `m`-by-`n` sparse matrix is stored in three or four one-dimensional arrays. For a real sparse matrix, numerical values and their row indices are stored in two arrays of size `nnzmax(A)` each, but only the first `nnz(A)` entries are used (complex matrices use three arrays). All entries in any given column are stored contiguously and in sorted order. A third array of size `n+1` holds the positions in the other two arrays of the first nonzero entry in each column. Thus, if `A` is sparse, then `x=A(9,:)` takes much more time than `x=A(:,9)`, and `s=A(4,5)` is also slow. To get high performance when dealing with sparse matrices, use matrix expressions instead of `for` loops and vector or scalar expressions. If you must operate on the rows of a sparse matrix `A`, work with the columns of `A'` instead.

If a full tridiagonal matrix `F` is created via, say,

```
F = floor(10 * rand(6))
F = triu(tril(F,1), -1)
```

then the statement `S=sparse(F)` will convert `F` to sparse mode. Try it. Note that the output lists the nonzero entries in column major order along with their row and column indices because of how sparse matrices are stored. The statement `F=full(S)` returns `F` in full storage mode. You can check the storage mode of a matrix `A` with the command `issparse(A)`.

15.2 Generating sparse matrices

A sparse matrix is usually generated directly rather than by applying the function `sparse` to a full matrix. A sparse banded matrix can be easily created via the function `spdiags` by specifying diagonals. For example, a familiar sparse tridiagonal matrix is created by:

```
m = 6 ;
n = 6 ;
e = ones(n,1) ;
d = -2*e ;
T = spdiags([e d e], [-1 0 1], m, n)
```

Try it. The integral vector `[-1 0 1]` specifies in which diagonals the columns of `[e d e]` should be placed (use `full(T)` to see the full matrix `T` and `spy(T)` to view `T` graphically). Experiment with other values of `m` and `n` and, say, `[-3 0 2]` instead of `[-1 0 1]`. See `doc spdiags` for further features of `spdiags`.

The sparse analogs of `eye`, `zeros`, and `rand` for full matrices are, respectively, `speye`, `sparse`, and `sprand`. The `spones` and `sprand` functions take a matrix argument and replace only the nonzero entries with ones and uniformly distributed random numbers, respectively. `sparse(m,n)` creates a sparse zero matrix. `sprand` also permits the sparsity structure to be randomized. This is a useful method for generating simple sparse test matrices, but be careful. Random sparse matrices are not truly "sparse" because they experience catastrophic fill-in when factorized. Sparse matrices arising in real applications typically do not share this characteristic.[3]

The versatile function `sparse` also permits creation of a sparse matrix via listing its nonzero entries:

```
i = [1 2 3 4 4 4] ;
j = [1 2 3 1 2 3] ;
s = [5 6 7 8 9 10] ;
S = sparse(i, j, s, 4, 3)
full(S)
```

The last two arguments to `sparse` in the example above are optional. They tell `sparse` the dimensions of the matrix; if not present, then `S` will be `max(i)` by `max(j)`. If there are repeated entries in `[i j]`, then the entries are

---

[3] http://www.cise.ufl.edu/research/sparse/matrices.

added together. The commands below create a matrix whose diagonal entries are 2, 1, and 1.

```
i = [1 2 3 1] ;
j = [1 2 3 1] ;
s = [1 1 1 1] ;
S = sparse(i, j, s)
full(S)
```

The entries in i, j, and s can be in any order (the same order for all three arrays, of course), but sparse(i,j,s) is faster if the entries are sorted in column-major order (ascending column index j, and entries in each column with ascending row index i) and with no duplicate entries. In general, if the vector s lists the nonzero entries of S and the integral vectors i and j list their corresponding row and column indices, then sparse(i,j,s,m,n) will create the desired sparse m-by-n matrix S. As another example try:

```
n = 6 ;
e = floor(10 * rand(n-1,1)) ;
E = sparse(2:n, 1:n-1, e, n, n)
```

Creating a sparse matrix by assigning values to it one at a time is exceedingly slow; ***never*** do it. The next example constructs the same matrix as A=sparse(i,j,s,m,n) (except for handling duplicate entries), but it should never be used:

```
A = sparse(m,n) ;
for k = 1:length(s)
    A(i(k),j(k)) = s(k) ;
end
```

15.3 Computation with sparse matrices

The arithmetic operations and most MATLAB functions can be applied independent of storage mode. The storage mode of the result depends on the storage mode of the operands or input arguments. Operations on full matrices always give full results. If `F` is a full matrix, `S` and `Z` are sparse matrices, and `n` is a scalar, then these operations give sparse results:

```
S+S         S*S         S.*S        S.*F
S-S         S^n         S.^n        S\Z
-S          S'          S.'         S/Z
inv(S)      chol(S)     lu(S)
diag(S)     max(S)      sum(S)
```

These give full results:

```
S+F        F\S        S/F
S*F        S\F        F/S
```

except if `F` is a scalar, `S*F`, `F\S`, and `S/F` are sparse.

A matrix built from blocks, such as `[A, B; C, D]`, is stored in sparse mode if any constituent block is sparse. To compute the eigenvalues or singular values of a sparse matrix `S`, you must convert `S` to a full matrix and then use `eig` or `svd`, as `eig(full(S))` or `svd(full(S))`. If `S` is a large sparse matrix and you wish only to compute some of the eigenvalues or singular values, then you can use the `eigs` or `svds` functions (`eigs(S)` or `svds(S)`).

15.4 Ordering methods

When MATLAB solves a sparse linear system (`x=A\b`), it typically starts by computing the LU, QR, or Cholesky factorization of `A`. This usually leads to fill-in, or the creation of new nonzeros in the factors that do not appear in A. MATLAB provides several methods that attempt to reduce fill-in by reordering the rows and columns of A, Finding the best ordering is impossible in general, so fast non-optimal heuristics are used:

q=colamd(A)	column approximate min. degree
q=colperm(A)	sort columns by number of nonzeros
p=symamd(A)	symmetric approximate min. degree
p=symrcm(A)	reverse Cuthill-McKee
[L,U,P,Q]=lu(A)	UMFPACK's internal ordering

The first two find a column ordering of A and are best used for lu or qr of A(:,q). The next two are primarily used for chol(A(p,p)). Each method returns a permutation vector. The sparse lu function[4] can find its own sparsity-preserving orderings, returning them as permutation matrices P and Q (where L*U=P*A*Q). Its ordering method is based on colamd, but it also permutes P for both sparsity and numerical robustness. Try this example west0479, a chemical engineering matrix:

```
load west0479
A = west0479 ;
spy(A)
[L,U,P] = lu(A) ;
spy(L|U)
[L,U,P] = lu(A(:,colperm(A))) ;
spy(L|U)
[L,U,P] = lu(A(:,colamd(A))) ;
spy(L|U)
[L,U,P,Q] = lu(A) ;
spy(L|U)
```

[4] http://www.cise.ufl.edu/research/sparse/umfpack. MATLAB 7.0 uses UMFPACK 4.0. UMFPACK 4.3 includes multiple ordering strategies and selects among them automatically.

15.5 Visualizing matrices

The `spy` function introduced in the last section plots the nonzero pattern of a sparse matrix. `spy` can also be used on full matrices. It is useful for matrix expressions coming from relational operators. Try this example (see Chapter 7 for the `ddom` function):

```
A = [
-1  2  3 -4
 0  2 -1  0
 1  2  9  1
-3  4  1  1]
C = ddom(A)
figure(2)
spy(A ~= C)
spy(A > 2)
```

What you see is a picture of where `A` and `C` differ, and another picture of which entries of `A` are greater than `2`.

16. The Symbolic Math Toolbox

The Symbolic Math Toolbox, which utilizes the Maple® kernel as its computer algebra engine, lets you perform symbolic computation from within MATLAB. Under this configuration, MATLAB's numeric and graphic environment is merged with Maple's symbolic computation capabilities. The toolbox M-files that access these symbolic capabilities have names and syntax that will be natural for the MATLAB user. Key features of the Symbolic Math Toolbox are included in the Student Version of MATLAB. Since the Symbolic Math Toolbox is not part of the Professional Version of MATLAB (by default), it may not be installed on your system, in which case this chapter will not apply.

Many of the functions in the Symbolic Math Toolbox have the same names as their numeric counterparts. MATLAB selects the correct one depending on the type of inputs to the function. Typing `doc eig` and `doc symbolic/eig` displays the help for the numeric eigenvalue function and its symbolic counterpart, respectively.

16.1 Symbolic variables

You can declare a variable as symbolic with the `syms` statement. For example,

```
syms x
```

creates a symbolic variable `x`. The statement:

```
syms x real
```

declares to Maple that `x` is a symbolic variable with no imaginary part. Maple has its own workspace. The statements `clear` or `clear x` do not undo this declaration, because it clears MATLAB's variable `x` but not Maple's variable `s`. Use `syms x unreal`, which declares to Maple that `x` may now have a nonzero imaginary part. The `clear all` statement clears all variables in both MATLAB and Maple, and thus also resets the `real` or `unreal` status of `x`. You can also assert to Maple that `x` is always positive, with `syms x positive`.

Symbolic variables can be constructed from existing numeric variables using the `sym` function. Try:

```
z = 1/10
a = sym(z)
```

```
y = rand(1)
b = sym(y, 'd')
```

although better ways to create a include:

```
a = sym('1/10')
a = 1 / sym(10)
```

If you want to ensure a precise symbolic expression, you must avoid numeric computations. Compare these three expressions. The first is only accurate to MATLAB's double-precision numeric computation (about 16 digits). The second and third avoid numeric computation completely.

```
sym(log(2))
sym('log(2)')
log(sym(2))
```

You can create a symbolic abstract function. This example declares f(x) as some unknown function of x:

```
syms x
f = sym('f(x)')
```

The syms command and sym function have many more options. See doc syms and doc sym.

16.2 Calculus

The function diff computes the symbolic derivative of a function defined by a symbolic expression. First, to define a symbolic expression, you should create symbolic variables and then proceed to build an expression as you would mathematically. For example,

```
syms x
f = x^2 * exp(x)
diff(f)
```

creates a symbolic variable x, builds the symbolic expression $f = x^2\ e^x$, and returns the symbolic derivative of f with respect to x: `2*x*exp(x)+x^2*exp(x)` in MATLAB notation. Try it. Next,

```
syms t
diff(sin(pi*t))
```

returns the derivative of $\sin(\pi t)$, as a function of t.

Here are examples of taking the derivative of an abstract function, illustrating the product, quotient, and reciprocal rules of calculus, and a special case of the chain rule. The function `pretty` displays a symbolic expression in an easier-to-read form resembling typeset mathematics. See Section 16.5 for `simple`.

```
syms x n
f = sym('f(x)')
g = sym('g(x)')
pretty(diff(f*g))
pretty(diff(f/g))
pretty(diff(1/f))
pretty(simple(diff(f^n)))
```

Formats in addition to pretty include `latex`, `ccode`, and `fortran`. Try, for example,

```
syms x a b
f = x/(a*x+b)
pretty(f)
g = int(f)
pretty(g)
latex(g)
ccode(g)
```

```
fortran(g)
int(g)
pretty(ans)
```

Partial derivatives can also be computed. Try:

```
syms x y
g = x*y + x^2
diff(g)          % computes ∂g/∂x
diff(g, x)       % also ∂g/∂x
diff(g, y)       % ∂g/∂y
```

To permit omission of the second argument for functions such as the above, MATLAB chooses a default symbolic variable for the symbolic expression. The `findsym` function returns MATLAB's choice. Its rule is, roughly, to choose that lower case letter, other than `i` and `j`, nearest `x` in the alphabet. The status of a variable (`real`, `unreal`, `positive`) affects its order in the list returned by `findsym`. You can, of course, override the default choice as shown above. Try, for example,

```
syms x x1 x2 theta
F = x * (x1*x2 + x1 - 2)
findsym(F,1)
diff(F, x)           % ∂F/∂x
diff(F, x1)          % ∂F/∂x1
diff(F, x2)          % ∂F/∂x2
G = cos(theta*x)
diff(G, theta)       % ∂G/∂theta
```

`diff` can compute second or higher-order derivatives. The second derivative of sin(2*x*) is given by either of the following two examples:

```
diff(sin(2*x), 2)
diff(sin(2*x), x, 2)
```

With a numeric argument, `diff` is the difference operator of basic MATLAB, which can be used to numerically approximate the derivative of a function. See `doc diff` or `help diff` for the numeric function, and `doc symbolic/diff` or `help sym/diff` for the symbolic derivative function.

The function `int` attempts to compute the indefinite integral (antiderivative) of a function defined by a symbolic expression. Try, for example,

```
syms a b t x y z theta
int(sin(a*t + b))
int(sin(a*theta + b), theta)
int(x*y^2 + y*z, y)
int(x^2 * sin(x))
```

Note that, as with `diff`, when the second argument of `int` is omitted, the default symbolic variable (as selected by `findsym`) is chosen as the variable of integration.

In some instances, `int` will be unable to give a result in terms of elementary functions. Consider, for example,

```
int(exp(-x^2))
int(sqrt(1 + x^3))
```

In the first case the result is given in terms of the error function `erf`, whereas in the second, the result is given in terms of `EllipticF`, a function defined by an integral.

Here is a basic integral rule with an abstract function:

```
f = sym('f(x)')
int(diff(f) / f)
```

Definite integrals can also be computed by using additional input arguments. Try, for example,

```
int(sin(x), 0, pi)
int(sin(theta), theta, 0, pi)
```

In the first case, the default symbolic variable `x` was used as the variable of integration to compute:

$$\int_0^{\pi} \sin x dx$$

whereas in the second `theta` was chosen. Other definite integrals you can try are:

```
int(x^5, 1, 2)
int(log(x), 1, 4)
int(x * exp(x), 0, 2)
int(exp(-x^2), 0, inf)
```

It is important to realize that the results returned are symbolic expressions, not numeric ones. The function `double` will convert these into MATLAB floating-point numbers, if desired. For example, the result returned by the first integral above is `21/2`. Entering `double(ans)` then returns the MATLAB numeric result `10.5000`.

Alternatively, you can use the function `vpa` (variable precision arithmetic; see Section 16.3) to convert the expression into a symbolic number of arbitrary precision. For example,

```
int(exp(-x^2), 0, inf)
```

gives the result:

```
1/2*pi^(1/2)
```

Then the statement:

```
vpa(ans, 25)
```

symbolically gives the result to 25 significant digits:

```
.8862269254527580136490835
```

You may wish to contrast these techniques with the MATLAB numerical integration functions `quad` and `quadl` (see Section 17.4).

The `limit` function is used to compute the symbolic limits of various expressions. For example,

```
syms h n x
limit((1 + x/n)^n, n, inf)
```

computes the limit of $(1 + x/n)^n$ as $n \to \infty$. You should also try:

```
limit(sin(x), x, 0)
limit((sin(x+h)-sin(x))/h, h, 0)
```

The `taylor` function computes the Maclaurin and Taylor series of symbolic expressions. For example,

```
taylor(cos(x) + sin(x))
```

returns the fifth order Maclaurin polynomial approximating $\cos(x) + \sin(x)$. This returns the eighth degree Taylor approximation to $\cos(x^2)$ centered at the point $x_0 = \pi$:

```
taylor(cos(x^2), 8, x, pi)
```

16.3 Variable precision arithmetic

Three kinds of arithmetic operations are available:

numeric	MATLAB's floating-point arithmetic
rational	Maple's exact symbolic arithmetic
VPA	Maple's variable precision arithmetic

One can obtain exact rational results with, for example,

```
s = simple(sym('13/17 + 17/23'))
```

You are already familiar with numeric computations. For example, with `format long`,

```
pi*log(2)
```

gives the numeric result `2.17758609030360`.

MATLAB's numeric computations are done in approximately 16 decimal digit floating-point arithmetic. With `vpa`, you can obtain results to arbitrary precision, within the limitations of time and memory. Try:

```
vpa('pi * log(2)')
vpa(sym(pi) * log(sym(2)))
vpa('pi * log(2)', 50)
```

The default precision for `vpa` is 32. Hence, the two results are accurate to 32 digits, whereas the third is accurate to the specified 50 digits. Ludolf van Ceulen (1540-1610) calculated π to 36 digits. The Symbolic Math Toolbox can quite easily compute π to 10,000 digits or more. Try:

```
pretty(vpa('pi', 10000))
```

The default precision can be changed with the function `digits`. While the rational and VPA computations can be more accurate, they are in general slower than numeric computations. If you pass a numeric expression to `vpa`, MATLAB will evaluate it numerically first, so use a symbolic expression or place the expression in quotes. Compare your results, above, with:

```
vpa(pi * log(2))
```

which is accurate to only about 16 digits (even though 32 digits are displayed). This is a common mistake with the use of `vpa` and the Symbolic Math Toolbox in general.

16.4 Numeric and symbolic subsitution

Once you have a symbolic expression, you can modify it or evaluate it numerically with the `subs` function. The function `subs` replaces all occurrences of the symbolic variable in an expression by a specified second expression. This corresponds to composition of two functions. Try, for example,

```
syms x s t
subs(sin(x), x, pi/3)
subs(sin(x), x, sym(pi)/3)
double(ans)
subs(g*t^2/2, t, sqrt(2*s))
subs(sqrt(1-x^2), x, cos(x))
subs(sqrt(1-x^2), 1-x^2, cos(x))
```

The general idea is that in the statement `subs(expr,old,new)` the third argument (`new`) replaces the second argument (`old`) in the first argument (`expr`). Compare the first two examples above. The result is numeric if all variables in the expression are substituted with numeric values, or symbolic otherwise.

You can substitute multiple symbolic expressions, numeric expressions, or any combination, using cell arrays of symbolic or numeric values. Try:

```
syms x y
S = x^y
subs(S, x, 3)
subs(S, {x y}, {3 2})
subs(S, {x y}, {3 x+1})
```

You perform multiple substitutions for any one symbolic variable, which returns a matrix of symbolic expressions or numeric values. Try this, which constructs a function `F`, finds its derivative `G`, and evaluates `G` at `x=0:.1:1`.

```
syms x
F = x^2 * sin(x)
G = diff(F)
subs(G, x, 0:.1:1)
```

Also try:

```
a = subs(S, y, 1:9)
a(3)
a = subs(S, {x y},{2*ones(9,1) (1:9)'})
```

The first expression returns a row vector containing the symbolic expressions `x`, `x^2`, ... `x^9`. The second substitution returns a numeric column vector containing the powers of 2 from 2 to 512. Each entry in the cell array must be of the same size.

Substitution acts just like composition in calculus. Taking the derivative of function composition illustrates the chain rule of calculus:

```
f = sym('f(x)')
g = sym('g(x)')
```

```
diff(subs(f, g))
pretty(ans)
```

16.5 Algebraic simplification

Convenient algebraic manipulations of symbolic expressions are available.

The function `expand` distributes products over sums and applies other identities, whereas `factor` attempts to do the reverse. The function `collect` views a symbolic expression as a polynomial in its symbolic variable (which may be specified) and collects all terms with the same power of the variable. To explore these capabilities, try the following:

```
syms a b x y z
expand((a + b)^5)
factor(ans)
expand(exp(x + y))
expand(sin(x + 2*y))
factor(x^6 - 1)
collect(x * (x * (x + 3) + 5) + 1)
horner(ans)
collect((x + y + z)*(x - y - z))
collect((x + y + z)*(x - y - z), y)
collect((x + y + z)*(x - y - z), z)
diff(x^3 * exp(x))
factor(ans)
```

The powerful function `simplify` applies many identities in an attempt to reduce a symbolic expression to a simple form. Try, for example,

```
simplify(sin(x)^2 + cos(x)^2)
simplify(exp(5*log(x) + 1))
d = diff((x^2 + 1)/(x^2 - 1))
simplify(d)
```

The alternate function `simple` computes several simplifications and chooses the shortest of them. It often gives better results on expressions involving trigonometric functions. Try the following commands:

```
simplify(cos(x) + (-sin(x)^2)^(1/2))
simple  (cos(x) + (-sin(x)^2)^(1/2))
simplify((1/x^3+6/x^2+12/x+8)^(1/3))
simple  ((1/x^3+6/x^2+12/x+8)^(1/3))
```

The function `factor` can also be applied to an integer argument to compute the prime factorization of the integer. Try, for example,

```
factor(sym('4248'))
factor(sym('4549319348693'))
factor(sym('4549319348597'))
```

16.6 Two-dimensional graphs

The MATLAB function `fplot` (see Section 12.3) provides a tool to conveniently plot the graph of a function. Since it is, however, the name or handle of the function to be plotted that is passed to `fplot`, the function must first be defined in an M-file (or else be a built-in function or anonymous function).

In the Symbolic Math Toolbox, `ezplot` lets you plot the graph of a function directly from its defining symbolic expression. For example, to plot a function of one variable try:

```
syms t x y
ezplot(sin(2*x))
ezplot(t + 3*sin(t))
ezplot(2*x/(x^2 - 1))
ezplot(1/(1 + 30*exp(-x)))
```

By default, the *x*-domain is `[-2*pi, 2*pi]`. This can be overridden by a second input variable, as with:

```
ezplot(x*sin(1/x), [-.2 .2])
```

You will often need to specify the *x*-domain and *y*-domain to zoom in on the relevant portion of the graph. Compare, for example,

```
ezplot(x*exp(-x))
ezplot(x*exp(-x), [-1 4])
```

`ezplot` attempts to make a reasonable choice for the *y*-axis. With the last figure, select `Edit` ► `Axes Properties` in the Figure window and modify the *y*-axis to start at `-3`, and hit enter. Changing the *x*-axis in the Property Editor does not cause the function to be reevaluated, however.

To plot an implicitly defined function of two variables:

```
ezplot(x^2 + y^2 - 1)
```

which plots the unit circle over the default *x*-domain and *y*-domain of `[-2*pi, 2*pi]`. Since this is too large for the unit circle, try this instead:

```
ezplot(x^2 + y^2 - 1, [-1 1 -1 1])
```

The first two entries in the second argument define the *x*-domain. The second two define the *y*-domain. If the *y*-domain is the same as the *x*-domain, then you only need to specify the *x*-domain (see the next example).

In both of the previous examples, you plotted a circle but it looks like an ellipse. This is because with auto-scaling, the *x* and *y* axes are not equal. Fix this by typing:

```
axis equal
```

To plot a parameterized function, provide two function arguments. Try this, which plots a cycloid over the domain -4π to 4π.

```
x = t-sin(t)
y = 1-cos(t)
ezplot(x,y, [-4*pi 4*pi])
```

The `ezpolar` function creates polar plots. Try creating a three-leaf rose and a hyperbolic spiral:

```
ezpolar(sin(3*t))
ezpolar(1/t, [1 10*pi])
```

Entering the command `funtool` (no input arguments) brings up three graphic figures, two of which will display graphs of functions and one containing a control panel. This function calculator lets you manipulate functions and their graphs for pedagogical demonstrations. Type `doc funtool` for details.

16.7 Three-dimensional surface graphs

MATLAB has several easy-to-use functions for creating three-dimensional surface graphs.

`ezcontour`	3-D contour plot
`ezcontourf`	3-D filled contour plot
`ezmesh`	3-D mesh plot
`ezmeshc`	3-D mesh and contour plot

`ezsurf`	3-D surface plot
`ezsurfc`	3-D surface and contour plot

Here is an interesting function to try:

```
syms x y
f = sin((x^2+y)/2)/(x^2-x+2)
ezsurfc(f)
```

Try each of these plotting functions with this function `f`. For this function, `ezcontourf` gives more information than `ezcontour` because the function fluctuates across a single contour in several regions. The default domain for x and y is -2π to 2π. You can change this with an optional second parameter. Try:

```
ezsurf(f, [-4 4 -pi pi])
```

which defines the x-domain as -4 to 4, and the y-domain as $-\pi$ to π. The appearance of the plots can be modified by the `shading` command after the figure is plotted (see Section 13.5).

Functions with discontinuities or singularities can cause difficulty for these graphing functions. Here is an example that is similar to the function `f` above,

```
f = sin(abs(sqrt(x^2+y)))/(x^2-x+2)
ezsurf(f)
```

Click the rotate button

in the figure window, then click and drag the graph itself. The function touches the $z=0$ plane along the curve defined by $y = -x^2$, but the graph does not capture this property very well because the gradient is not defined along that curve. To plot this function accurately, you would need to define your own mesh points, compute the function numerically, and use `surf` or another numerical graphing function instead.

The four mesh and surface functions listed above can also plot parameterized surface functions. The first three arguments are the *x(s,t)*, *y(s,t)*, and *z(s,t)* functions, and the last (optional) argument defines the domain. To create a symbolic seashell, start a new figure and define your symbolic variables:

```
figure(1) ; clf
syms u v x y z
```

Next, define `x`, `y`, and `z`, just as you did for the numeric seashell in Section 13.3. The MATLAB statements are the same, except that now these variables are defined symbolically, not numerically. Plot the symbolic surface:

```
ezsurfc(x,y,z,[0 2*pi])
```

Turn off the axis and set the shading, material, lighting, and viewpoint, just as you did in Section 13.3 and 13.6. You cannot change the `ezsurfc` color.

16.8 Three-dimensional curves

Parameterized 3-D curves are plotted with `ezplot3`. Try this example, which combines a folium of Descartes in the *x-y* plane with a sinusoid in the *z* direction:

```
syms x y z t
x = 3*t / (1+t^3)
y = 3*t^2 / (1+t^3)
```

```
z = sin(t)
ezplot3(x,y,z)
```

The default domain for t is 0 to 2π. Here is an example of how to change it:

```
ezplot3(x,y,z,[-.9 10])
```

The ezplot3 function can animate the plot so that you can observe how x, y, and z depend on t. Try both of these examples. The ball moves quickly over the first half of the curve but more slowly over the second half:

```
ezplot3(x,y,z,'animate')
ezplot3(x,y,z, [-.9 10], 'animate')
```

The 2-D curve plotting function ezplot cannot animate its plot, but you can do the same with ezplot3. Just give it a z argument of zero. Try:

```
syms z
z = 0
ezplot3(x,y,z,'animate')
```

and then rotate the graph so that you are viewing the *x*-*y* plane. Click the rotate button and drag the graph, or right-click the graph and select Go to X-Y view. Then click the Repeat button in the bottom left corner.

16.9 Symbolic matrix operations

This toolbox lets you represent matrices in symbolic form as well as MATLAB's numeric form. Given numeric matrix a, sym(a) converts a to a symbolic matrix. Try:

```
a = magic(3)
A = sym(a)
```

The function `double(A)` converts the symbolic matrix back to a numeric one.

Symbolic matrices can also be generated. Try, for example,

```
syms a b s
K = [a + b, a - b ; b - a, a + b]
G = [cos(s), sin(s); -sin(s), cos(s)]
```

Here `G` is a symbolic Givens rotation matrix.

Algebraic matrix operations with symbolic matrices are computed as you would in MATLAB:

`K+G`	matrix addition
`K-G`	matrix subtraction
`K*G`	matrix multiplication
`inv(G)`	matrix inversion
`K\G`	left matrix division
`K/G`	right matrix division
`G^2`	power
`G.'`	transpose
`G'`	conjugate transpose (Hermitian)

These operations are illustrated by the following, which use the matrices `K` and `G` generated above. The last expression demonstrates that `G` is orthogonal.

```
L = K^2
collect(L)
factor(L)
diff(L, a)
int(K, a)
J = K/G
simplify(J*G)
simplify(G*(G.'))
```

The initial result of the basic operations may not be in the form desired for your application; so it may require further processing with `simplify`, `collect`, `factor`, or `expand`. These functions, as well as `diff` and `int`, act entry-wise on a symbolic matrix.

16.10 Symbolic linear algebraic functions

The primary symbolic matrix functions are:

`det`	determinant
`.'`	transpose
`'`	Hermitian (conjugate transpose)
`inv`	inverse
`null`	basis for nullspace
`colspace`	basis for column space
`eig`	eigenvalues and eigenvectors
`poly`	characteristic polynomial
`svd`	singular value decomposition
`jordan`	Jordan canonical form

These functions will take either symbolic or numeric arguments. Computations with symbolic rational matrices can be carried out exactly. Try, for example,

```
c = floor(10*rand(4))
D = sym(c)
A = inv(D)
inv(A)
inv(A) * A
det(A)
b = ones(1,4)
x = b/A
x*A
A^3
```

These functions can, of course, be applied to general symbolic matrices. For the matrices K and G defined in the previous section, try:

```
inv(K)
simplify(inv(G))
p = poly(G)
simplify(p)
factor(p)
X = solve(p)
for j = 1:4
    X = simple(X)
end
pretty(X)
e = eig(G)
for j = 1:4
    e = simple(e)
end
pretty(e)
y = svd(G)
for j = 1:4
    y = simple(y)
end
pretty(y)
syms s real
r = svd(G)
r = simple(r)
pretty(r)
syms s unreal
```

The `simple` function had to be repeated several times for some of the examples to get the simplest possible result.

Compare `y` and `r`. If you do not declare `s` as `real`, the `svd` of the 2-by-2 Givens rotation matrix does not demonstrate that the singular values are all equal to one.

A typical exercise in a linear algebra course is to determine those values of `t` so that, say,

```
A = [t 1 0 ; 1 t 1 ; 0 1 t]
```

is singular. The following simple computation:

```
syms t
A = [t 1 0 ; 1 t 1 ; 0 1 t]
p = det(A)
solve(p)
```

shows that this occurs for t = 0, $\sqrt{2}$, and $\sqrt{-2}$. See Section 16.11 for the `solve` function.

The function `eig` attempts to compute the eigenvalues and eigenvectors in an exact closed form. Try, for example,

```
for n = 4:6
    A = sym(magic(n))
    [V, D] = eig(A)
end
```

Except in special cases, however, the result is usually too complicated to be useful. Try, for example, executing:

```
A = sym(floor(10 * rand(3)))
[V, D] = eig(A)
pretty(V)
```

a few times. The eigenvectors `V` are not very pretty. For this reason, it is usually more efficient to do the computation in variable-precision arithmetic, as is illustrated by:

```
A = vpa(floor(10 * rand(3)))
[V, D] = eig(A)
```

The comments above regarding `eig` apply as well to the computation of the singular values of a matrix by `svd`, as can be observed by repeating some of the computations above using `svd` instead of `eig`.

16.11 Solving algebraic equations

For a symbolic expression S, the statement solve(S) will attempt to find the values of the symbolic variable for which the symbolic expression is zero. The solve function cannot solve all equations. It does well with polynomial equations, but can have difficulty with trigonometric or other transcendental equations. If an exact symbolic solution is indeed found, you can convert it to a floating-point solution, if desired. If an exact symbolic solution cannot be found, then a variable precision one is computed. Here are three similar equations. The first returns a symbolic result, the second a numeric result, and the last one fails.

```
syms x b
solve(2^x - b)
solve(2^x + 3^x - 1)
solve(2^x + 3^x - b)
```

If you have an expression that contains several symbolic variables, you can solve for a particular variable by including it as an input argument in solve. The default variable solved for is x, or the one closest (alphabetically) to x if x is not a variable in the equation.

Try this example; note that X contains four solutions:

```
syms x y z
f = cos(x) + tan(x)
X = solve(f)
pretty(X)
double(X)
vpa(X)
for i = 1:4
   s = simple(subs(f, x, X(i)))
end
```

Here are some more examples:

```
Y = solve(cos(x) - x)
Z = solve(x^2 + 2*x - 1)
pretty(Z)
a = solve(x^2 + y^2 + z^2 + x*y*z)
pretty(a)
b = solve(x^2 + y^2 + z^2 + x*y*z, y)
pretty(b)
```

`a` is a solution in the variable `x`, and `b` is a solution in `y`.

The inputs to `solve` can be quoted strings or symbolic expressions. To solve an equation whose right-hand side is not zero, use a quoted string or rearrange the equation:

```
X = solve('log(x) = x - 2')
X = solve(log(x) - x + 2)
vpa(X)
X = solve('2^x = x + 2')
X = solve(2^x - x - 2)
vpa(X)
```

This solves for the variable `a`:

```
solve('1 + (a+b)/(a-b) = b', 'a')
```

This solves the same for `b`, finding two solutions:

```
solve('1 + (a+b)/(a-b) = b', 'b')
```

The solution to the next example should be familiar. Try:

```
syms a b c x
solve(a*x^2 + b*x + c, x)
pretty(ans)
```

The function `solve` can also compute solutions of systems of general algebraic equations. To solve, for example, the nonlinear system below, it is convenient to first express the equations as strings.

```
S1 = 'x^2 + y^2 + z^2 = 2'
S2 = 'x + y = 1'
S3 = 'y + z = 1'
```

The solutions are then computed by:

```
[X, Y, Z] = solve(S1, S2, S3)
```

If you request the set of solutions in a single output with multiple unknowns, a `struct` is returned. Try

```
a = solve(S1, S2, S3)
a.x
a.y
a.z
```

If you alter `S2` to:

```
S2 = 'x + y + z = 1'
```

then the solution computed by:

```
[X, Y, Z] = solve(S1, S2, S3)
```

will be given in terms of square roots. If you prefer solving symbolic expressions instead of strings, try

```
syms x y z
S1 = x^2 + y^2 + z^2 - 2
S2 = x + y - 1
S3 = y + z - 1
a = solve(S1, S2, S3)
```

The output of `solve` is in alphabetical order. For example, if you changed the name of `z` to `w` in these three equations the results would be returned in the order `[W,X,Y]`. The `solve` function can take quoted strings or symbolic expressions as input arguments, but you cannot mix the two types of inputs.

16.12 Solving differential equations

The function `dsolve` solves ordinary differential equations. The symbolic differential operator is `D`:

```
Y = dsolve('Dy = x^2*y', 'x')
```

produces the solution `C1*exp(1/3*x^3)` to the differential equation $y' = x^2 y$. The solution to an initial value problem can be computed by adding a second symbolic expression giving the initial condition.

```
Y = dsolve('Dy = x^2*y', 'y(0)=4', 'x')
```

Notice that in both examples above, the final input argument, `'x'`, is the independent variable of the differential equation. If no independent variable is supplied to `dsolve`, then it is assumed to be `t`. The higher order symbolic differential operators `D2`, `D3`, … can be used to solve higher order equations. Try:

```
dsolve('D2y + y = 0')
dsolve('D2y + y = x^2', 'x')
dsolve('D2y + y = x^2', ...
    'y(0) = 4', 'Dy(0) = 1', 'x')
dsolve('D2y - Dy = 2*y')
dsolve('D2y + 6*Dy = 13*y')
dsolve('D3y - 3*Dy = 2*y')
pretty(ans)
```

Systems of differential equations can also be solved:

```
E1 = 'Dx = -2*x + y'
E2 = 'Dy = x - 2*y + z'
E3 = 'Dz = y - 2*z'
```

The solutions are then computed with:

```
[x, y, z] = dsolve(E1, E2, E3)
pretty(x)
pretty(y)
pretty(z)
```

You can explore further details with `doc dsolve`.

16.13 Further Maple access

The following features are not available in the Student Version of MATLAB.

Over 50 special functions of classical applied mathematics are available in the Symbolic Math Toolbox. Enter `doc mfunlist` to see a list of them. These functions can be accessed with the function `mfun`, for which you are referred to `doc mfun` for further details. The `maple` function allows you to use expressions and programming constructs in Maple's native language, which gives you full access to Maple's functionality. See `doc maple`, or `mhelp` *`topic`*, which displays Maple's help text for the specified topic. The Extended Symbolic Math Toolbox provides access to a number of Maple's specialized libraries of procedures. It also provides for use of Maple programming features.

17. Polynomials, Interpolation, and Integration

Polynomial functions are frequently used by numerical methods, and thus MATLAB provides several routines that operate on polynomials and piece-wise polynomials.

17.1 Representing polynomials

Polynomials are represented as vectors of their coefficients, so $f(x)=x^3-15x^2-24x+360$ is simply

```
p = [1 -15 -24 360]
```

The roots of this polynomial (15, √24, and -√24):

```
r = roots(p)
```

Given a vector of roots `r`, `poly(r)` constructs the coefficients of the polynomial with those roots. With a little bit of roundoff error, you should see the original polynomial. Try it.

The `poly` function also computes the characteristic polynomial of a matrix whose roots are the eigenvalues of the matrix. The polynomial *f(x)* was chosen as the characteristic equation of the `magic(3)` matrix. Try:

```
A = magic(3)
s = poly(A)
roots(s)
eig(A)
f = poly(sym(A))
solve(f)
eig(sym(A))
```

17.2 Evaluating polynomials

You can evaluate a polynomial at one or more points with the polyval function.

```
x = -1:2 ;
y = polyval(p,x)
```

Compare y with x.^3-15*x.^2-24*x+360. You can construct a symbolic polynomial from the coefficient vector p and back again:

```
syms x
f = poly2sym(p)
sym2poly(f)
```

17.3 Polynomial interpolation

Polynomials are useful as easier-to-compute approximations of more complicated functions, via a Taylor series expansion or by a low-degree best-fit polynomial using the polyfit function. The statement:

```
p = polyfit(x, y, n)
```

finds the best-fit n-degree polynomial that approximates the data points x and y. Try this example:

```
x = 0:.1:pi ;
y = sin(x) ;
p = polyfit(x, y, 5)
figure(1) ; clf
ezplot(@sin, [0 pi])
hold on
xx = 0:.001:pi ;
plot(xx, polyval(p,xx), 'r-')
```

Piecewise-polynomial interpolation is typically better than a single high-degree polynomial. Try this example:

```
n = 10
x = -5:.1:5 ;
y = 1 ./ (x.^2+1) ;
p = polyfit(x, y, n)
figure(2) ; clf
ezplot(@(x) 1/(x^2+1))
hold on
xx = -5:.01:5 ;
plot(xx, polyval(p,xx), 'r-')
```

As `n` increases, the error in the center improves but increases dramatically near the endpoints. The `spline` and `pchip` functions compute piecewise-cubic polynomials which are better for this problem. Try:

```
figure(3) ; clf
yy = spline(x, y, xx) ;
plot(xx, yy, 'g')
```

Alternatively, with two inputs, `spline` and `pchip` return a `struct` that contains the piecewise polynomial, which can be later evaluated with `ppval`. Try:

```
figure(4) ; clf
pp = spline(x, y)
yy = ppval(pp, xx) ;
plot(xx, yy, 'c')
```

The `spline` function computes the conventional cubic spline, with a continuous second derivative. In contrast, `pchip` returns a piecewise polynomial with a discontinuous second derivative, but it preserves the shape of the function better than `spline`.

Polynomial multiplication and division (convolution and deconvolution) are performed by the `conv` and `deconv` functions. MATLAB also has a built-in fast Fourier transform function, `fft`.

17.4 Numeric integration (quadrature)

The `quad` and `quadl` functions are the numeric equivalent of the symbolic `int` function, for computing a definite integral. Both rely on polynomial approximations of subintervals of the function being integrated. `quadl` is a higher-order method that can be more accurate. The syntax `quad(@f,a,b)` computes an approximate of the definite integral,

$$\int_a^b f(x)dx$$

Compare these examples:

```
quad(@(x) x.^5, 1, 2)
quad(@log, 1, 4)
quad(@(x) x .* exp(x), 0, 2)
quad(@(x) exp(-x.^2), 0, 1e6)
quad(@(x) sqrt(1 + x.^3), -1, 2)
quad(@(x) real(airy(x)), -3, 3)
```

with the same results from the Symbolic Toolbox:

```
int('x^5', 1, 2)
int('log(x)', 1, 4)
int('x * exp(x)', 0, 2)
int('exp(-x^2)', 0, inf)
int('sqrt(1 + x^3)', -1, 2)
int('real(airy(x))', -3, 3)
```

Symbolic integration (`int`) can find a simple closed-form solution to the first four examples, above. The next is not in closed form, and the last example cannot be solved by `int` at all. It can only be computed numerically, with `quad`.

The function `f` provided to `quad` and `quadl` must operate on a vector `x` and return `f(x)` for each component of the vector. An optional fourth argument to `quad` and `quadl` modifies the error tolerance. Double and triple integrals are evaluated by `dblquad` and `triplequad`. Array-valued functions are integrated with `quadv`.

18. Solving Equations

Solving equations is at the core of what MATLAB does. Let us look back at what kinds of equations you have seen so far in the book. Next, in this chapter you will learn how MATLAB finds numerical solutions to nonlinear equations and systems of differential equations.

18.1 Symbolic equations

The Symbolic Toolbox can solve symbolic linear systems of equations using backslash (Section 16.9), nonlinear systems of equations using the `solve` function (Section 16.11), and systems of differential equations using `dsolve` (Section 16.12). The rest of MATLAB focuses on finding numeric solutions to equations, not symbolic.

18.2 Linear systems of equations

The pervasive and powerful backslash operator solves linear systems of equations of the form `A*x=b` (Sections 3.3, 15.3, and 16.9). The expression `x=A\b` handles the case when `A` is square or rectangular (under- or over-determined), full-rank or rank-deficient, full or sparse, numeric or symbolic, symmetric or unsymmetric, real or complex, and all but one reasonable combination of this extensive list (backslash does not work with complex rectangular sparse matrices). It efficiently handles triangular, permuted triangular, symmetric positive-definite, and Hessenberg matrices. Further details for the case when `A` is sparse are discussed in Chapter 15. When the matrix has specific known properties, the `linsolve` function can be faster (see Section 5.5, and a related Fortran code in Chapter 10).

18.3 Polynomial roots

Solving the function $f(x)=0$ for the special case when f is a polynomial and x is a scalar is discussed in Section 17.1. The more general case is discussed below.

18.4 Nonlinear equations

The `fzero` function finds a numerical solution to $f(x)=0$ when f is a real function over the real domain (both x and $f(x)$ must be real scalars). This is useful when an analytic solution is not possible. You must supply either an initial guess, or two values of x for which the function differs in sign. Here is a simple example that computes $\sqrt{2}$.

```
fzero(@(x) x^2-2, 1)
```

The `fzero` function can only find an x for which $f(x)$ crosses the x-axis. If the sign of $f(x)$ does not differ on either side of x, the zero point x will not be found. Try this example. Create two anonymous functions (regular M-files can also be used):

```
fa = @(x) (x-2)^2
fb = @(x) (x-2)^2 - 1e-12
```

The zero of `fa` cannot be found, and neither can a zero of `fb` be found if your initial guess is too far from the solution. Both of these examples will fail:

```
fzero(fa, 1)
fzero(fb, 3)
```

Both functions can be easily solved with the Symbolic Toolbox. Note that `solve` correctly reports that 2 is a double root of `(x-2)^2`. Try:

```
syms x
solve((x-2)^2)
s = solve((x-2)^2-1e-12)
fb(s(1))
fb(s(2))
```

The zeros of `fb` can be found numerically only if you guess close enough, or if you provide two initial values of `x` for which `fb` differs in sign:

```
fzero(fb, 2)
format long
fzero(fb, [2 3])
fzero(fb, [1 2])
```

All of the functions used in the examples so far can be solved analytically. Here is one that cannot (also plot the function so that you can see where it crosses the *x*-axis):

```
f = @(x) real(airy(x))
figure(1) ; clf
ezplot(f)
solve('real(airy(x))')
```

The first zero is easy to compute numerically:

```
s = fzero(f, 0)
hold on
plot(s, f(s), 'ro')
```

The fminbnd function finds a local minimum of a function, given a fixed interval. This example looks for a minimum in the range -4 to 0.

```
xmin = fminbnd(f, -4, 0)
plot(xmin, f(xmin), 'ko')
```

To find a local maximum, simply find the minimum of *-f*.

```
g = @(x) -real(airy(x))
xmax = fminbnd(g, -5, -4)
plot(xmax, f(xmax), 'ko')
```

Now find the zero between these two values of x:

```
s = fzero(f, [xmax xmin])
plot(s, f(s), 'ro')
```

The fminbnd function can only find minima of real-valued functions of a real scalar. To find a local minimum of a scalar function of a real vector x, use fminsearch instead. It takes an initial guess for x rather than an interval.

18.5 Ordinary differential equations

The symbolic solution to the ordinary differential equation $y'=t^2y$ appears in Section 16.12. Here is the same ODE, with a specific initial value of $y(0)=1$, along with its symbolic solution.

```
syms t y
Y = dsolve('Dy = t^2*y', 'y(0)=1', 't')
```

Not all ODEs can be solved analytically, so MATLAB provides a suite of numerical methods. The primary method for initial value problems is ode45. For an ODE of the form $y' = f(t,y)$, the basic usage is:

```
[tt,yy] = ode45(@f, tspan, y0)
```

where `@f` is a handle for a function `yprime=f(t,y)` that computes the derivative of `y`, `tspan` is the time span to compute the solution (a 2-element vector), and `y0` is the initial value of *y*. The variable `t` is a scalar, but `y` can be a vector. The solution is a column vector `tt` and a matrix `yy`. At time `tt(i)` the numerical approximation to *y* is `yy(i,:)`.

To solve this ODE numerically, create an anonymous function:

```
f1 = @(t,y) t^2 * y
```

Now you can compute the numeric solution:

```
[tr,yr] = ode45(f1, [0 2], 1) ;
```

Compare it with the symbolic solution:

```
ts = 0:.05:2 ;
ys = subs(Y, t, ts) ;
figure(2) ; clf
plot(ts,ys, 'r-', tr,yr, 'bx') ;
legend('symbolic', 'numeric')
ys = subs(Y, t, tr) ;
[tr ys yr ys-yr]
err = norm(ys-yr) / norm(ys)
```

To solve higher-order ODEs, you need to convert your ODE into a first-order system of ODEs. Let us start with the ODE $y''+y=t^2$ with initial values $y(0)=1$ and $y'(1)=0$. The symbolic solution to this ODE appears in Section 16.12, but here is the solution with initial values specified:

```
Y = dsolve('D2y + y = t^2', ...
    'y(0)=1', 'Dy(0)=0', 't')
```

Define $y_1=y$ and $y_2=y'$. The new system is $y_2'=t^2-y_1$ and $y_1'=y_2$. Create an anonymous function:

```
f2 = @(t,y) [y(2) ; t^2-y(1)]
```

The function `f2` returns a 2-element column vector. The first entry is y_1' and the second is y_2'. We can now solve this ODE numerically:

```
[tr,yy] = ode45(f2, [0 2], [1 0]') ;
yr = yy(:,1) ;
```

Note that `ode45` returns a 61-by-2 solution `yy`. Row `i` of `yy` contains the numerical approximation to y_1 and y_2 at time `tr(i)`. Compare the symbolic and numeric solutions using the same code for the previous ODE.

MATLAB's `ode45` can return a structure `s=ode45(...)` which can be used by `deval` to evaluate the numerical solution at any time `t` that you specify. There are seven other ODE solvers, able to handle stiff ODEs and for differential algebraic equations. Some can be more efficient, depending on the type of ODE you are trying to solve. Type `doc ode45` for more information.

18.6 Other differential equations

Delay differential equations (DDEs) are solved by `dde23`. The function `bvp4c` solves boundary value ODE problems. Finally, partial differential equations are solved with `pdepe` and `pdeval`. See the online help facility for more information on these ODE, DDE, and PDE solvers.

19. Displaying Results

The format command provides basic control over how your results are printed in the Command window. For example, if you want a trigonometric table with just a few digits of precision, you could do:

```
warning('off','MATLAB:divideByZero')
format short
x = [0:.1:pi]' ;
f = {@sin, @cos, @tan, @cot} ;
y = x ;
for i = 1:length(f)
    y = [y f{i}(x)] ;
end
disp(y)
```

The cell array f is used in the next example; otherwise a simpler way to construct y would be:

```
y = [x sin(x) cos(x) tan(x) cot(x)] ;
```

You can increase the number of digits printed with format long, but that does not allow you to define how many digits are printed. If you tried to add pi/2 to the table, the tan column would contain a huge (erroneous) value causes the rest of the digits in the table to be obscured. Try adding the statement x=[x ; pi/2] after x is first defined.

This problem is where fprintf is useful. If you know C, it acts just like the standard C fprintf, except that the reference to the file is optional in the MATLAB fprintf, and MATLAB's fprintf can print arrays.

The basic syntax (like printf in C) is:

```
fprintf(format_string, arg1, arg2, ...)
```

The format string tells MATLAB how to print each argument (*arg1*, *arg2*, ...). It contains plain text, which is printed verbatim, plus special conversion codes that start with '%' (to print an argument) or '\' (to print a special character such as a newline, tab, or backslash).

The basic syntax for a conversion code is *%W.PC*, where *W* is the optional field width (the total number of characters used to represent the number), *P* is the optional precision (the number of digits to the right of the decimal point), and *C* is the conversion type. Both *W* and *P* are fixed integers. The dot before the *P* field is required only if *P* is specified. The most common conversion types are:

`d`	decimal (integer)
`e`	exponential notation (as in `2.3e+002`)
`f`	fixed-point notation
`g`	`e` or `f`, whichever is more compact
`s`	string

Special characters include `\n` for newline, `\t` for tab, and `\\` for backslash itself. A single quote is either `\''` or two single quotes (`''`).

Here is a simple example that prints `pi` with 8 digits past the decimal point, in a space of 12 characters:

```
fprintf('pi is %12.8f\n', pi)
```

Try changing the `12` to `14`, and you will see how fprintf pads the string for `pi` to make it 14 characters wide. Note the last character is `'\n'`, which is a newline. If this were excluded, the next line of output would start at the end of this line. Sometimes that is what you want (see below for an example).

Unlike `printf` or `fprintf` in the C language, MATLAB's `fprintf` can print arrays. It accesses an array column by column, and reuses the format string as needed. This simple example prints the `magic(3)` array. It also gives you an example of how to print a backslash and a single quote:

```
A = magic(3)
fprintf('%4.2f %4.2f %4.2f\n', A')
b = (1:3)' ;
fprintf('A\\b is [%g %g %g]''\n', A\b);
```

The array `A` is transposed in the first `fprintf`, because `fprintf` cycles through its data column by column, but each use of the format string prints a single line of text as one row of characters on the Command window. Fortunately it makes no difference for vectors:

```
fprintf('x is %d\n', 1:5)
fprintf('x is %d\n', (1:5)')
```

Here is a way of adding extra information to your display:

```
fprintf( ...
'row %d is %4.2f %4.2f %4.2f\n', ...
[(1:3)' A]')
```

Here is a revised trigonometric table using `fprintf` instead. A header has been added as well:

```
x = [0:.1:pi]' ;
f = {@sin, @cos, @tan, @cot} ;
y = x ;
fprintf('   x') ;
for i = 1:length(f)
```

```
        fprintf('    %s(x)',func2str(f{i}));
        y = [y f{i}(x)] ;
    end
    fprintf('\n') ;
    fprintf( ...
    '%3.2f %9.4f %9.4f %9.4f %9.4f\n',y');
```

fprintf, by default, prints to the Command window. You can instead open a file, write to it with fprintf, and close the file. Add:

```
    fid = fopen('mytable.txt', 'w') ;
```

to the beginning of the example. Add fid as the first argument to each fprintf. Finally, close the file at the end with the statement:

```
    fclose(fid) ;
```

Your table is now in the file mytable.txt.

The sprintf function is just like fprintf, except that it sends its output to a string instead of the Command window or a file. It is useful for plot titles and other annotation, as in:

```
    title(sprintf('The result is %g', pi))
```

You cannot control the field width or precision with a variable as you can in the C printf or fprintf, but string concatenation along with sprintf or num2str can help here. Try:

```
    for n = 1:16
        s = num2str(n) ;
        s = ['%2d digits: %.' s 'g\n'] ;
        fprintf(s, n, pi) ;
    end
```

20. Cell Publishing

Cell publishing creates nicely formatted reports of MATLAB code, command window text output, figures, and graphics in HTML, LaTeX, XML, Microsoft Word, or Microsoft Powerpoint.

The term *cell publishing* has nothing to do with the cell array data type. In this context, a cell is a section of an M-file that corresponds to a section of your report. A cell starts with a cell divider, which is a comment with two percent signs at the beginning of a line, and ends either at the start of the next cell, or the end of the M-file. Cell publishing is normally done via scripts, not functions.

Create a new M-file, and select the Editor menu item `Cell ▶ Enable Cell Mode`. Try this 2-cell example:

```
%% Integrate a function
syms x
f = x^2
e = int(f)

%% Plot the results
figure(1)
ezplot(e)
```

Now publish the report to HTML, by selecting `File ▶ Save and Publish to HMTL` (or just `File ▶ Publish to HMTL` if you have already saved the M-file), or by clicking the publish button:

The M-file is evaluated and the report is presented in HTML form in a new window. The report is also saved to a file with the same name as your M-file but with an `html` file type. It includes the cell titles (the text after the double %%), the code itself, the output of the code, and any figures generated. You can change this default behavior in the `File ► Preferences` menu, under the `Editor/Debugger: Publishing` section.

To run the M-file without publishing the results, simply click the run button, as usual, or select `Cell ► Evaluate Entire Cell`. Individual cells can also be evaluated.

Additional descriptive text can be added as plain comments (one %) after the cell divider but before any commands. The text can be marked in various styles (bold, monospaced, TeX equations, and bullet lists, for example). See the `Cell ► Insert Text Markup ►` ... menu for a complete list.

To add descriptive text without starting a new report section, start with a cell divider that has no title (a line containing just %%). This creates a new cell, but it appears in the same section of the report as the cell before it.

21. Code Development Tools

The Current Directory window provides a pull-down menu with seven different reports that it can generate. These tools are described in the seven sections of this chapter, below.

The Current Directory window has two modes of display, the classic view and the visual directory view. In the visual directory view, you can click on a filename in the Current Directory window to edit it. If cell publishing has been used to publish the results of an M-file to an

HTML file, a link to the published report will appear next to the filename. A one-line description of each M-file is listed.

21.1 M-lint code check report

Navigate to the directory where you created the `ddomloops` M-file (see Chapter 8). On Microsoft Windows, this is your `work` directory by default. In the Current Directory window, select the M-Lint Code Check Report. The report examines all M-files in the directory and checks them for suspicious constructs. Scroll down to the report on `ddomloops.m`, and note that one warning is listed:

```
5:  The value assigned here to variable 'm'
is never used.
```

Click on the underlined `5:`. The Editor window opens the `ddomloops.m` file and highlights line 5:

```
[m n] = size(A) ;
```

The variable `m` is assigned by this statement, but not used. This is not an error, just a warning. It does remind you that `ddomloops` is only intended for square matrices, however. This is a good reminder, because no test is made to ensure the matrix is square. Try:

```
ddomloops(ones(2,3))
```

An obscure error occurs because the non-existent entry `A(3,3)` is referenced. This is not a reliable function.

Save a copy of your original `ddomloops.m` file, and call it `ddomloops_orig.m`. You will need it for the example in Section 21.6.

Add the following code to `ddomloops` just after line 5:

```
if (m ~= n)
    error('A must be square') ;
end
```

Rerun the M-lint report by clicking the Refresh button:

The warning has gone away, and your code is more reliable. Try `ddomloops(ones(2,3))` again. It correctly reports an error that `A` must be square.

21.2 TODO/FIXME report

The TODO/FIXME Report lists all lines in an M-file containing the words `TODO`, `FIXME`, or `NOTE`, along with the line numbers in which they appear. Clicking the line number brings up the editor at that line. This is useful during incremental development of a large project.

21.3 Help report

The Help Report examines each M-file in the current directory for the comment lines that appear when you type `help` or `doc` followed by the M-file name. Here is its report on `ddomloops`:

```
B = ddomloops(A) returns a diagonally

  B = ddomloops(A) returns a diagonally
  dominant matrix B by modifying the
  diagonal of A.
```

No example
No see-also line
No copyright line

The first line in the report is the description line, which is the first line after the `function` statement itself (if the line is a comment line). The MATLAB convention is for the first comment line to be a stand-alone one-line description of the function, starting with the name of the function in all capital letters. Edit `ddomloops` and add a new description line, as the second line in the file:

```
%DDOMLOOPS make matrix diagonally dominant
```

The Help Report also complains that there is no example, no see-also line, and no copyright line. An example starts with a comment line that starts with the word `example` or `Example` and ends at the next blank comment line. The see-also line is a comment line that starts with the words `See also`. The copyright line is a comment that starts with the word `Copyright`. All of these constructs are optional, of course, but adding them to the M-file makes the code easier to use. After the last comment line, add the following comments:

```
%
% Example
%     A = [1 0 ; 4 1]
%     B = ddomloops(A)
%     B is the same as A, except B(2,2)
%     is slightly greater than 4.
```

```
%
% See also DDOM, DIAGDOM.
```

Finally, add a blank line (not a comment), and then the line:

```
% Copyright 2004, Me.
```

The function names `DDOM` and `DIAGDOM` appear in upper case, so that they can be recognized as function names. Rerun the Help Report. You will see all of these constructs listed in the report. Type `help ddomloops` or `doc ddomloops` in the Command Window. You should see `ddom` and `diagdom` underlined and in blue as active links. Click on them, and you will see the corresponding `help` or `doc` for those functions (assuming you created them in Chapters 7 and 8).

21.4 Contents report

The Contents Report generates a special file called `Contents.m` that summarizes all of the M-files in the current directory. Select it from the menu, and scroll down until you see your modified `ddomloops` function. Its name is followed by its one-line description, generated automatically from the description line in `ddomloops.m`. You can edit the `Contents.m` file to add more description, and then click the refresh button to generate a new Contents Report. Any discrepancies are reported to you. For example, if you edit the one-line description in `Contents.m`, but not in the corresponding M-file, a warning will appear and you will have the opportunity to fix the discrepancy.

Type the command `help` *`directory`* where *`directory`* is the name of the current directory. This use of the `help` command prints the Contents.m listing, and highlights the name of each function. Click on ddomloops in the list, and the help ddomloops information will appear. Many of MATLAB's functions are implemented as M-files and are documented in the same way that you have documented your current directory. For example, help general lists the Contents.m file of the directory MATLAB/toolbox/matlab/general (where MATLAB is the directory in which MATLAB is installed).

Create a directory entitled diagonal_dominance and place all of the related M-files and mexFunctions in this directory. Add the diagonal_dominance directory to your path (see Section 7.7). Now, whatever your current directory is help diagonal_dominance will list these files, and the ddom, ddomloops, and diagdom functions will always be available to you.

21.5 Dependency report

For each M-file in the current directory, the Dependency Report lists the M-files and mexFunctions that it relies on, and which M-files rely on it. Create an M-file script in the diagonal_dominance directory called simple.m:

```
A = [1 2 ; 3 0]
B = ddomloops(A)
C = diagdom(A)
```

Run the dependency report. simple is listed as a parent of its child function ddomloops. The mexFunction diagdom is listed as a child of simple. diagdom itself does not appear in the list because it is not an M-file.

21.6 File comparison report

The File Comparison Report is very useful in tracking changes to your code as you develop it. Select this report, and scroll down until you see your original `ddomloops_orig` file. Click `<file 1>`. Next, find your new `ddomloops` and click `<file 2>`. A color-coded side-by-side display of these two functions is displayed. Plain gray text is code that is identical between the two files. Pink highlighting denotes lines that differ between the two files. Green highlighting denotes lines that appear in one file but not the other.

21.7 Profile and coverage report

MATLAB provides an M-file profiler that lets you see how much computation time each line of an M-file uses. Select `Desktop` ► `Profiler` or type `profile viewer`. Try this example. Type in a M-file script, `ddomtest.m`:

```
A = rand(1000) ;
B = ddomloops(A) ;
```

Type `ddomtest` in the text window entitled `Run this code` and hit enter. A short table appears with the number of calls and time spent in each function. Most of the time is spent in `ddomloops`. Click on the function name and you are provided a lengthy description of the time spent in `ddomloops`. This report is useful for improving code performance and for debugging. Untested lines of code could harbor a bug.

The Coverage Report provides a short overview of the profile coverage of each file in a directory. Selecting it shows that `ddomtest` was fully exercised (100% coverage), but a few lines of code in `ddomloops` were not tested. The code you added to check for rectangular matrices was not tested, and the case when the diagonal entry `A(i,i)` is negative was not tested.

22. Help Topics

There are many MATLAB functions and features that cannot be included in this Primer. Listed in the following tables are some of the MATLAB functions and operators, grouped by subject area. You can browse through these lists and use the online help facility, or consult the online documents for more detailed information on the functions, operators, and special characters. Open the Help Browser to `Help: MATLAB: Functions -- Categorical List`.

The `help` command lists help information in the MATLAB Command window. The tables are derived from the MATLAB 7 (R14) `help` command. Typing `help` alone will provide a listing of the major MATLAB directories, similar to the following table. Typing `help` *`topic`*, where *`topic`* is an entry in the left column of the table, will display a description of the topic. For example, `help general` will display on your Command window a plain text version of Section 22.1. Typing `help ops` will display Section 22.2, starting on page 144, and so on.

The `doc` command opens the MATLAB help browser. It display the M-file help, just as the help command, if the command has no HTML reference page. Try `doc general` or `doc ops`.

Each topic is discussed in a single subsection. The page number for each subsection is also listed in the following table.

Help topics		page
general	General purpose commands	142
ops	Operators and special characters	144
lang	Programming language constructs	147
elmat	Elementary matrices and matrix manipulation	149
elfun	Elementary math functions	151
specfun	Specialized math functions	153
matfun	Matrix functions - linear algebra	155
datafun	Data analysis & Fourier transforms	157
polyfun	Interpolation and polynomials	158
funfun	Function functions & ODE solvers	160
sparfun	Sparse matrices	162
scribe	Annotation and plot editing	164
graph2d	Two-dimensional graphs	164
graph3d	Three-dimensional graphs	165
specgraph	Specialized graphs	168
graphics	Handle Graphics	171
uitools	Graphical user interface tools	173
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imagesci	Image, scientific data input/output	178
iofun	File input/output	179
audiovideo	Audio and video support	182
timefun	Time and dates	183
datatypes	Data types and structures	183
verctrl	Version control	187
codetools	Creating and debugging code	187
helptools	Help commands	188
winfun	Microsoft Windows functions	189
demos	Examples and demonstrations	190
local	Preferences	190
symbolic	Symbolic Math Toolbox	191

22.1 General purpose commands

help general

General information	
syntax	Help on MATLAB command syntax
demo	Run demonstrations
ver	MATLAB, Simulink, & toolbox version
version	MATLAB version information

Managing the workspace	
who	List current variables
whos	List current variables, long form
clear	Clear variables, functions from memory
pack	Consolidate workspace memory
load	Load variables from MAT- or ASCII file
save	Save variables to MAT- or ASCII file
saveas	Save figure or model to file
memory	Help for memory limitations
recycle	Recycle folder option for deleted files
quit	Quit MATLAB session
exit	Exit from MATLAB

Managing commands and functions	
what	List MATLAB-specific files in directory
type	List M-file
open	Open files by extension
which	Locate functions and files
pcode	Create pre-parsed P-file
mex	Compile MEX-function
inmem	List functions in memory
namelengthmax	Max length of function or variable name

Managing the search path	
`path`	Get/set search path
`addpath`	Add directory to search path
`rmpath`	Remove directory from search path
`rehash`	Refresh function and file system caches
`import`	Import Java packages into current scope
`finfo`	Identify file type
`genpath`	Generate recursive toolbox path
`savepath`	Save MATLAB path in `pathdef.m` file

Managing the Java search path	
`javaaddpath`	Add directories to the dynamic Java path
`javaclasspath`	Get and set Java path
`javarmpath`	Remove dynamic Java path directory

Controlling the Command window	
`echo`	Echo commands in M-files
`more`	Paged output in command window
`diary`	Save text of MATLAB session
`format`	Set output format
`beep`	Produce beep sound
`desktop`	Start and query the MATLAB Desktop
`preferences`	MATLAB user preferences dialog

Debugging	
`debug`	List debugging commands

Locate dependent functions of an M-file	
`depfun`	Find dependent functions of M- or P-file
`depdir`	Find dependent directories of M or P-file

Operating system commands	
cd	Change current working directory
copyfile	Copy file or directory
movefile	Move file or directory
delete	Delete file or graphics object
pwd	Show (print) current working directory
dir	List directory
ls	List directory
fileattrib	Set/get attributes of files and directories
isdir	True if argument is a directory
mkdir	Make new directory
rmdir	Remove directory
getenv	Get environment variable
!	Execute operating system command
dos	Execute DOS command and return result
unix	Execute Unix command and return result
system	Execute system command, return result
perl	Execute Perl command and return result
computer	Computer type
isunix	True for Unix version of MATLAB
ispc	True for Windows version of MATLAB

Loading and calling shared libraries	
calllib	Call a function in an external library
libpointer	Create pointer for external libraries
libstruct	Create structure ptr. for external libraries
libisloaded	True if specified shared library is loaded
loadlibrary	Load a shared library into MATLAB
libfunctions	Info. on functions in external library
libfunctionsview	View functions in external library
unloadlibrary	Unload a shared library
java	Using Java from within MATLAB
usejava	True if Java feature supported

22.2 Operators and special characters

`help ops`

Arithmetic operators (help arith, help slash)		
`plus`	Plus	`+`
`uplus`	Unary plus	`+`
`minus`	Minus	`-`
`uminus`	Unary minus	`-`
`mtimes`	Matrix multiply	`*`
`times`	Array multiply	`.*`
`mpower`	Matrix power	`^`
`power`	Array power	`.^`
`mldivide`	Backslash or left matrix divide	`\`
`mrdivide`	Slash or right matrix divide	`/`
`ldivide`	Left array divide	`.\`
`rdivide`	Right array divide	`./`
`kron`	Kronecker tensor product	`kron`

Relational operators (help relop)		
`eq`	Equal	`==`
`ne`	Not equal	`~=`
`lt`	Less than	`<`
`gt`	Greater than	`>`
`le`	Less than or equal	`<=`
`ge`	Greater than or equal	`>=`

<table>
<tr><th colspan="3">Logical operators</th></tr>
<tr><td></td><td>Short-circuit logical AND</td><td>&&</td></tr>
<tr><td></td><td>Short-circuit logical OR</td><td>||</td></tr>
<tr><td>and</td><td>Logical AND</td><td>&</td></tr>
<tr><td>or</td><td>Logical OR</td><td>|</td></tr>
<tr><td>not</td><td>Logical NOT</td><td>~</td></tr>
<tr><td>xor</td><td colspan="2">Logical EXCLUSIVE OR</td></tr>
<tr><td>any</td><td colspan="2">True if any element of vector is nonzero</td></tr>
<tr><td>all</td><td colspan="2">True if all elements of vector are nonzero</td></tr>
</table>

Special characters		
colon	Colon	:
paren	Parentheses and subscripting	( )
paren	Brackets	[ ]
paren	Braces and subscripting	{ }
punct	Function handle creation	@
punct	Decimal point	.
punct	Structure field access	.
punct	Parent directory	..
punct	Continuation	...
punct	Separator	,
punct	Semicolon	;
punct	Comment	%
punct	Operating system command	!
punct	Assignment	=
punct	Quote	'
transpose	Transpose	.'
ctranspose	Complex conjugate transpose	'
horzcat	Horizontal concatenation	[,]
vertcat	Vertical concatenation	[;]
subsasgn	Subscripted assignment	( ) { }
subsref	Subscripted reference	( ) { }
subsindex	Subscript index	

Bitwise operators	
bitand	Bit-wise AND
bitcmp	Complement bits
bitor	Bit-wise OR
bitmax	Maximum floating-point integer
bitxor	Bit-wise EXCLUSIVE OR
bitset	Set bit
bitget	Get bit
bitshift	Bit-wise shift

Set operators	
`union`	Set union
`unique`	Set unique
`intersect`	Set intersection
`setdiff`	Set difference
`setxor`	Set exclusive-or
`ismember`	True for set member

22.3 Programming language constructs

`help lang`

Control flow	
`if`	Conditionally execute statements
`else`	When `if` condition fails
`elseif`	When `if` failed and condition is true
`end`	Scope of `for`, `while`, `switch`, `try`, `if`
`for`	Repeat specific number of times
`while`	Repeat an indefinite number of times
`break`	Terminate of `while` or `for` loop
`continue`	Pass control to next iteration of a loop
`switch`	Switch among several cases
`case`	`switch` statement case
`otherwise`	Default `switch` statement case
`try`	Begin `try` block
`catch`	Begin `catch` block
`return`	Return to invoking function
`error`	Display mesage and abort function
`rethrow`	Reissue error

Evaluation and execution	
`eval`	Execute MATLAB expression in string
`evalc`	`eval` with capture
`feval`	Execute function specified by string
`evalin`	Evaluate expression in workspace
`builtin`	Execute built-in function
`assignin`	Assign variable in workspace
`run`	Run script

Scripts, functions, and variables	
`script`	About MATLAB scripts and M-files
`function`	Add new function
`global`	Define global variable
`persistent`	Define persistent variable
`mfilename`	Name of currently executing M-file
`lists`	Comma separated lists
`exist`	Check if variables or functions defined
`isglobal`	True for global variables ***(obsolete)***
`mlock`	Prevent M-file from being cleared
`munlock`	Allow M-file to be cleared
`mislocked`	True if M-file cannot be cleared
`precedence`	Operator precedence in MATLAB
`isvarname`	Check for a valid variable name
`iskeyword`	Check if input is a keyword
`javachk`	Validate level of Java support
`genvarname`	MATLAB variable name from string

Argument handling	
`nargchk`	Validate number of input arguments
`nargoutchk`	Validate number of output arguments
`nargin`	Number of function input arguments
`nargout`	Number of function output arguments
`varargin`	Variable length input argument list
`varargout`	Variable length output argument list
`inputname`	Input argument name

Message display and interactive input	
`warning`	Display warning message
`lasterr`	Last error message
`lastwarn`	Last warning message
`disp`	Display array
`display`	Display array
`intwarning`	Controls state of the 4 integer warnings
`input`	Prompt for user input
`keyboard`	Invoke keyboard from M-file

22.4 Elementary matrices and matrix manipulation

`help elmat`

Elementary matrices	
`zeros`	Zeros array
`ones`	Ones array
`eye`	Identity matrix
`repmat`	Replicate and tile array
`rand`	Uniformly distributed random numbers
`randn`	Normally distributed random numbers
`linspace`	Linearly spaced vector
`logspace`	Logarithmically spaced vector
`freqspace`	Frequency spacing for frequency response
`meshgrid`	`x` and `y` arrays for 3-D plots
`accumarray`	Construct an array with accumulation
`:`	Regularly spaced vector and array index

Basic array information	
`size`	Size of matrix
`length`	Length of vector
`ndims`	Number of dimensions
`numel`	Number of elements
`disp`	Display matrix or text
`isempty`	True for empty matrix
`isequal`	True if arrays are numerically equal
`isequalwithequalnans`	True if arrays are numerically equal (assuming `nan==nan`)

Array utility functions	
`isscalar`	True for scalar
`isvector`	True for vector

Matrix manipulation	
`cat`	Concatenate arrays
`reshape`	Change size
`diag`	Diagonal matrices; diagonals of matrix
`blkdiag`	Block diagonal concatenation
`tril`	Extract lower triangular part
`triu`	Extract upper triangular part
`fliplr`	Flip matrix in left/right direction
`flipud`	Flip matrix in up/down direction
`flipdim`	Flip matrix along specified dimension
`rot90`	Rotate matrix 90 degrees
`:`	Regularly spaced vector and array index
`find`	Find indices of nonzero elements
`end`	Last index
`sub2ind`	Linear index from multiple subscripts
`ind2sub`	Multiple subscripts from linear index
`ndgrid`	Arrays of N-D functions & interpolation
`permute`	Permute array dimensions
`ipermute`	Inverse permute array dimensions
`shiftdim`	Shift dimensions
`circshift`	Shift array circularly
`squeeze`	Remove singleton dimensions

Special variables and constants	
`ans`	Most recent answer
`eps`	Floating-point relative accuracy
`realmax`	Largest positive floating-point number
`realmin`	Smallest positive floating-point number
`pi`	3.1415926535897...
`i, j`	Imaginary unit
`inf`	Infinity
`nan`	Not-a-Number
`isnan`	True for Not-a-Number
`isinf`	True for infinite elements
`isfinite`	True for finite elements

Specialized matrices	
`compan`	Companion matrix
`gallery`	Higham test matrices
`hadamard`	Hadamard matrix
`hankel`	Hankel matrix
`hilb`	Hilbert matrix
`invhilb`	Inverse Hilbert matrix
`magic`	Magic square
`pascal`	Pascal matrix
`rosser`	Symmetric eigenvalue test problem
`toeplitz`	Toeplitz matrix
`vander`	Vandermonde matrix
`wilkinson`	Wilkinson's eigenvalue test matrix

22.5 Elementary math functions

`help elfun`

Trigonometric (also continued on next page)	
`sin`	Sine
`sind`	Sine of argument in degrees
`sinh`	Hyperbolic sine
`asin`	Inverse sine
`asind`	Inverse sine, result in degrees
`asinh`	Inverse hyperbolic sine
`cos`	Cosine
`cosd`	Cosine of argument in degrees
`cosh`	Hyperbolic cosine
`acos`	Inverse cosine
`acosd`	Inverse cosine, result in degrees
`acosh`	Inverse hyperbolic cosine
`tan`	Tangent
`tand`	Tangent of argument in degrees
`tanh`	Hyperbolic tangent
`atan`	Inverse tangent
`atand`	Inverse tangent, result in degrees
`atan2`	Four quadrant inverse tangent

Trigonometric (continued)	
`atanh`	Inverse hyperbolic tangent
`sec`	Secant
`secd`	Secant of argument in degrees
`sech`	Hyperbolic secant
`asec`	Inverse secant
`asecd`	Inverse secant, result in degrees
`asech`	Inverse hyperbolic secant
`csc`	Cosecant
`cscd`	Cosecant of argument in degrees
`csch`	Hyperbolic cosecant
`acsc`	Inverse cosecant
`acscd`	Inverse cosecant, result in degrees
`acsch`	Inverse hyperbolic cosecant
`cot`	Cotangent
`cotd`	Cotangent of argument in degrees
`coth`	Hyperbolic cotangent
`acot`	Inverse cotangent
`acotd`	Inverse cotangent, result in degrees
`acoth`	Inverse hyperbolic cotangent

Exponential	
`exp`	Exponential
`expm1`	Compute `exp(x)-1` accurately
`log`	Natural logarithm
`log1p`	Compute `log(1+x)` accurately
`log10`	Common (base 10) logarithm
`log2`	Base 2 logarithm, dissect floating-point
`pow2`	Base 2 power, scale floating-point
`realpow`	Array power with real result (or error)
`reallog`	Natural logarithm of real number
`realsqrt`	Square root of number ≥ 0
`sqrt`	Square root
`nthroot`	Real n^{th} root of real numbers
`nextpow2`	Next higher power of 2

Complex	
`abs`	Absolute value
`angle`	Phase angle
`complex`	Complex from real and imaginary parts
`conj`	Complex conjugate
`imag`	Complex imaginary part
`real`	Complex real part
`unwrap`	Unwrap phase angle
`isreal`	True for real array
`cplxpair`	Sort into complex conjugate pairs

Rounding and remainder	
`fix`	Round towards zero
`floor`	Round towards minus infinity
`ceil`	Round towards plus infinity
`round`	Round towards nearest integer
`mod`	Modulus (remainder after division)
`rem`	Remainder after division
`sign`	Signum

22.6 Specialized math functions

`help specfun`

Number theoretic functions	
`factor`	Prime factors
`isprime`	True for prime numbers
`primes`	Generate list of prime numbers
`gcd`	Greatest common divisor
`lcm`	Least common multiple
`rat`	Rational approximation
`rats`	Rational output
`perms`	All possible permutations
`nchoosek`	All combinations of N choose K
`factorial`	Factorial function

Specialized math functions	
airy	Airy functions
besselj	Bessel function of the first kind
bessely	Bessel function of the second kind
besselh	Bessel function of 3rd kind (Hankel function)
besseli	Modified Bessel function of the 1st kind
besselk	Modified Bessel function of the 2nd kind
beta	Beta function
betainc	Incomplete beta function
betaln	Logarithm of beta function
ellipj	Jacobi elliptic functions
ellipke	Complete elliptic integral
erf	Error function
erfc	Complementary error function
erfcx	Scaled complementary error function
erfinv	Inverse error function
expint	Exponential integral function
gamma	Gamma function
gammainc	Incomplete gamma function
gammaln	Logarithm of gamma function
psi	Psi (polygamma) function
legendre	Associated Legendre function
cross	Vector cross product
dot	Vector dot product

Coordinate transforms	
cart2sph	Cartesian to spherical coordinates
cart2pol	Cartesian to polar coordinates
pol2cart	Polar to Cartesian coordinates
sph2cart	Spherical to Cartesian coordinates
hsv2rgb	Convert HSV colors to RGB
rgb2hsv	Convert RGB colors to HSV

22.7 Matrix functions — numerical linear algebra

`help matfun`

Matrix analysis	
`norm`	Matrix or vector norm
`normest`	Estimate the matrix 2-norm
`rank`	Matrix rank
`det`	Determinant
`trace`	Sum of diagonal elements
`null`	Null space
`orth`	Orthogonalization
`rref`	Reduced row echelon form
`subspace`	Angle between two subspaces

Linear equations	
`\` and `/`	Linear equation solution (`help slash`)
`linsolve`	Linear equation solution, extra control
`inv`	Matrix inverse
`rcond`	LAPACK reciprocal condition estimator
`cond`	Condition number
`condest`	1-norm condition number estimate
`normest1`	1-norm estimate
`chol`	Cholesky factorization
`cholinc`	Incomplete Cholesky factorization
`lu`	LU factorization
`luinc`	Incomplete LU factorization
`qr`	Orthogonal-triangular decomposition
`lsqnonneg`	Linear least squares (≥ 0 constraints)
`pinv`	Pseudoinverse
`lscov`	Least squares with known covariance

Eigenvalues and singular values	
`eig`	Eigenvalues and eigenvectors
`svd`	Singular value decomposition
`gsvd`	Generalized singular value decomp.
`eigs`	A few eigenvalues
`svds`	A few singular values
`poly`	Characteristic polynomial
`polyeig`	Polynomial eigenvalue problem
`condeig`	Condition number of eigenvalues
`hess`	Hessenberg form
`qz`	QZ factoriz. for generalized eigenvalues
`ordqz`	Reordering of eigenvalues in QZ
`schur`	Schur decomposition
`ordschur`	Sort eigenvalues in Schur decomposition

Matrix functions	
`expm`	Matrix exponential
`logm`	Matrix logarithm
`sqrtm`	Matrix square root
`funm`	Evaluate general matrix function

Factorization utilities	
`qrdelete`	Delete column from QR factorization
`qrinsert`	Insert column in QR factorization
`rsf2csf`	Real block diagonal to complex diagonal
`cdf2rdf`	Complex diagonal to real block diagonal
`balance`	Diagonal scaling for eigenvalue accuracy
`planerot`	Givens plane rotation
`cholupdate`	rank 1 update to Cholesky factorization
`qrupdate`	rank 1 update to QR factorization

22.8 Data analysis, Fourier transforms

`help datafun`

Basic operations	
`max`	Largest component
`min`	Smallest component
`mean`	Average or mean value
`median`	Median value
`std`	Standard deviation
`var`	Variance
`sort`	Sort in ascending order
`sortrows`	Sort rows in ascending order
`sum`	Sum of elements
`prod`	Product of elements
`hist`	Histogram
`histc`	Histogram count
`trapz`	Trapezoidal numerical integration
`cumsum`	Cumulative sum of elements
`cumprod`	Cumulative product of elements
`cumtrapz`	Cumulative trapezoidal num. integration

Finite differences	
`diff`	Difference and approximate derivative
`gradient`	Approximate gradient
`del2`	Discrete Laplacian

Correlation	
`corrcoef`	Correlation coefficients
`cov`	Covariance matrix
`subspace`	Angle between subspaces

Filtering and convolution	
filter	One-dimensional digital filter
filter2	Two-dimensional digital filter
conv	Convolution, polynomial multiplication
conv2	Two-dimensional convolution
convn	N-dimensional convolution
deconv	Deconvolution and polynomial division
detrend	Linear trend removal

Fourier transforms	
fft	Discrete Fourier transform
fft2	2-D discrete Fourier transform
fftn	N-D discrete Fourier transform
ifft	Inverse discrete Fourier transform
ifft2	2-D inverse discrete Fourier transform
ifftn	N-D inverse discrete Fourier transform
fftshift	Shift zero-freq. component to center
ifftshift	Inverse `fftshift`

22.9 Interpolation and polynomials

`help polyfun`

Data interpolation	
pchip	Piecewise cubic Hermite interpol. poly.
interp1	1-D interpolation (table lookup)
interp1q	Quick 1-D linear interpolation
interpft	1-D interpolation using FFT method
interp2	2-D interpolation (table lookup)
interp3	3-D interpolation (table lookup)
interpn	N-D interpolation (table lookup)
griddata	2-D data gridding and surface fitting
griddata3	3-D data gridding & hypersurface fitting
griddatan	N-D data gridding &hypersurface fitting

Spline interpolation	
spline	Cubic spline interpolation
ppval	Evaluate piecewise polynomial

Geometric analysis	
delaunay	Delaunay triangulation
delaunay3	3-D Delaunay tessellation
delaunayn	N-D Delaunay tessellation
dsearch	Search Delaunay triangulation
dsearchn	Search N-D Delaunay tessellation
tsearch	Closest triangle search
tsearchn	N-D closest triangle search
convhull	Convex hull
convhulln	N-D convex hull
voronoi	Voronoi diagram
voronoin	N-D Voronoi diagram
inpolygon	True for points inside polygonal region
rectint	Rectangle intersection area
polyarea	Area of polygon

Polynomials	
roots	Find polynomial roots
poly	Convert roots to polynomial
polyval	Evaluate polynomial
polyvalm	Evaluate polynomial (matrix argument)
residue	Partial-fraction expansion (residues)
polyfit	Fit polynomial to data
polyder	Differentiate polynomial
polyint	Integrate polynomial analytically
conv	Multiply polynomials
deconv	Divide polynomials

22.10 Function functions and ODEs

`help funfun`

Optimization and root finding	
`fminbnd`	Scalar bounded nonlinear minimization
`fminsearch`	Multidimensional unconstrained nonlinear minimization (Nelder-Mead)
`fzero`	Scalar nonlinear zero finding

Optimization option handling	
`optimset`	Set optimization `options` structure
`optimget`	Get optimization parameters

Numerical integration (quadrature)	
`quad`	Numerical integration, low order method
`quadl`	Numerical integration, high order method
`dblquad`	Numerically evaluate double integral
`triplequad`	Numerically evaluate triple integral
`quadv`	Vectorized `quad`

Plotting	
`ezplot`	Easy-to-use function plotter
`ezplot3`	Easy-to-use 3-D parametric curve plotter
`ezpolar`	Easy-to-use polar coordinate plotter
`ezcontour`	Easy-to-use contour plotter
`ezcontourf`	Easy-to-use filled contour plotter
`ezmesh`	Easy-to-use 3-D mesh plotter
`ezmeshc`	Easy-to-use mesh/contour plotter
`ezsurf`	Easy-to-use 3-D colored surface plotter
`ezsurfc`	Easy-to-use surf/contour plotter
`fplot`	Plot function

Inline function object	
`inline`	Construct `inline` function object
`argnames`	Argument names
`formula`	Function formula
`char`	Convert `inline` object to `char` array

Initial value problem solvers for ODEs	
`ode45`	Solve non-stiff differential equations, medium order method (Try this first)
`ode23`	Solve non-stiff ODEs low order method
`ode113`	Solve non-stiff ODEs, variable order
`ode23t`	Solve moderately stiff ODEs and DAEs Index 1, trapezoidal rule
`ode15s`	Solve stiff ODEs and DAEs Index 1, variable order method
`ode23s`	Solve stiff ODEs, low order method
`ode23tb`	Solve stiff ODEs, low order method

Initial value problem, fully implicit ODEs/DAEs	
`decic`	Compute consistent initial conditions
`ode15i`	Solve implicit ODEs or DAEs Index 1

Initial value problem solvers for DDEs	
`dde23`	Solve delay differential equations

Boundary value problem solver for ODEs	
`bvp4c`	Solve two-point boundary value ODEs

1-D Partial differential equation solver	
`pdepe`	Solve initial-boundary value PDEs

ODE, DDE, BVP option handling	
`odeset`	Create/alter ODE `options` structure
`odeget`	Get ODE `options` parameters
`ddeset`	Create/alter DDE `options` structure
`ddeget`	Get DDE `options` parameters
`bvpset`	Create/alter BVP `options` structure
`bvpget`	Get BVP `options` parameters

ODE, DAE, DDE, PDE input & output functions	
`deval`	Evaluate solution of differential equation
`odextend`	Extend solutions of differential equation
`odeplot`	Time series ODE output function
`odephas2`	2-D phase plane ODE output function
`odephas3`	3-D phase plane ODE output function
`odeprint`	ODE output function
`bvpinit`	Forms the initial guess for `bvp4c`
`pdeval`	Evaluates solution computed by `pdepe`

22.11 Sparse matrices

`help sparfun`

Elementary sparse matrices	
`speye`	Sparse identity matrix
`sprand`	Uniformly distributed random matrix
`sprandn`	Normally distributed random matrix
`sprandsym`	Sparse random symmetric matrix
`spdiags`	Sparse matrix formed from diagonals

Full to sparse conversion	
`sparse`	Create sparse matrix
`full`	Convert sparse matrix to full matrix
`find`	Find indices of nonzero elements
`spconvert`	Create sparse matrix from triplets

Working with sparse matrices	
`nnz`	Number of nonzero matrix elements
`nonzeros`	Nonzero matrix elements
`nzmax`	Space allocated for nonzero elements
`spones`	Replace nonzero elements with ones
`spalloc`	Allocate space for sparse matrix
`issparse`	True for sparse matrix
`spfun`	Apply function to nonzero elements
`spy`	Visualize sparsity pattern

Reordering algorithms	
colamd	Column approximate minimum degree
symamd	Approximate minimum degree
symrcm	Symmetric reverse Cuthill-McKee
colperm	Column permutation
randperm	Random permutation
dmperm	Dulmage-Mendelsohn permutation
lu	UMFPACK reordering (with 4 outputs)

Linear algebra	
eigs	A few eigenvalues, using ARPACK
svds	A few singular values, using eigs
luinc	Incomplete LU factorization
cholinc	Incomplete Cholesky factorization
normest	Estimate the matrix 2-norm
condest	1-norm condition number estimate
sprank	Structural rank

Linear equations (iterative methods)	
pcg	Preconditioned conjugate gradients
bicg	Biconjugate gradients method
bicgstab	Biconjugate gradients stabilized method
cgs	Conjugate gradients squared method
gmres	Generalized minimum residual method
lsqr	Conjugate gradients on normal equations
minres	Minimum residual method
qmr	Quasi-minimal residual method
symmlq	Symmetric LQ method

Operations on graphs (trees)	
treelayout	Lay out tree or forest
treeplot	Plot picture of tree
etree	Elimination tree
etreeplot	Plot elimination tree
gplot	Plot graph, as in “graph theory”

Miscellaneous	
`symbfact`	Symbolic factorization analysis
`spparms`	Set parameters for sparse matrix routines
`spaugment`	Form least squares augmented system

22.12 Annotation and plot editting

`help scribe`

Graph annotation	
`annotation`	Create annotation objects for figures
`colorbar`	Display coloar bar (color scale)
`legend`	Graph legend

22.13 Two-dimensional graphs

`help graph2d`

Elementary x-y graphs	
`plot`	Linear plot
`loglog`	Log-log scale plot
`semilogx`	Semi-log scale plot
`semilogy`	Semi-log scale plot
`polar`	Polar coordinate plot
`plotyy`	Graphs with y tick labels on left & right

Axis control	
`axis`	Control axis scaling and appearance
`zoom`	Zoom in and out on a 2-D plot
`grid`	Grid lines
`box`	Axis box
`hold`	Hold current graph
`axes`	Create axes in arbitrary positions
`subplot`	Create axes in tiled positions

Hard copy and printing	
`print`	Print graph, Simulink sys.; save to M-file
`printopt`	Printer defaults
`orient`	Set paper orientation

Graph annotation	
`plotedit`	Tools for editing and annotating plots
`title`	Graph title
`xlabel`	*x*-axis label
`ylabel`	*y*-axis label
`texlabel`	TeX format from string
`text`	Text annotation
`gtext`	Place text with mouse

22.14 Three-dimensional graphs

`help graph3d`

Elementary 3-D plots	
`plot3`	Plot lines and points in 3-D space
`mesh`	3-D mesh surface
`surf`	3-D colored surface
`fill3`	Filled 3-D polygons

Color control	
`colormap`	Color look-up table
`caxis`	Pseudocolor axis scaling
`shading`	Color shading mode
`hidden`	Mesh hidden line removal mode
`brighten`	Brighten or darken color map
`colordef`	Set color defaults
`graymon`	Graphics defaults for grayscale monitors

Lighting	
`surfl`	3-D shaded surface with lighting
`lighting`	Lighting mode
`material`	Material reflectance mode
`specular`	Specular reflectance
`diffuse`	Diffuse reflectance
`surfnorm`	Surface normals

Color maps	
`hsv`	Hue-saturation-value color map
`hot`	Black-red-yellow-white color map
`gray`	Linear grayscale color map
`bone`	Grayscale with tinge of blue color map
`copper`	Linear copper-tone color map
`pink`	Pastel shades of pink color map
`white`	All-white color map
`flag`	Alternating red, white, blue, and black
`lines`	Color map with the line colors
`colorcube`	Enhanced color-cube color map
`vga`	Windows colormap for 16 colors
`jet`	Variant of HSV
`prism`	Prism color map
`cool`	Shades of cyan and magenta color map
`autumn`	Shades of red and yellow color map
`spring`	Shades of magenta and yellow color map
`winter`	Shades of blue and green color map
`summer`	Shades of green and yellow color map

Axis control	
`axis`	Control axis scaling and appearance
`zoom`	Zoom in and out on a 2-D plot
`grid`	Grid lines
`box`	Axis box
`hold`	Hold current graph
`axes`	Create axes in arbitrary positions
`subplot`	Create axes in tiled positions
`daspect`	Data aspect ratio
`pbaspect`	Plot box aspect ratio
`xlim`	x limits
`ylim`	y limits
`zlim`	z limits

Transparency	
alpha	Transparency (alpha) mode
alphamap	Transparency (alpha) look-up table
alim	Transparency (alpha) scaling

Viewpoint control	
view	3-D graph viewpoint specification
viewmtx	View transformation matrix
rotate3d	Interactively rotate view of 3-D plot

Camera control	
campos	Camera position
camtarget	Camera target
camva	Camera view angle
camup	Camera up vector
camproj	Camera projection

High-level camera control	
camorbit	Orbit camera
campan	Pan camera
camdolly	Dolly camera
camzoom	Zoom camera
camroll	Roll camera
camlookat	Move camera and target to view objects
cameratoolbar	Interactively manipulate camera

High-level light control	
camlight	Creates or sets position of a light
lightangle	Spherical position of a light

Hard copy and printing	
print	Print graph, Simulink sys.; save to M-file
printopt	Printer defaults
orient	Set paper orientation
vrml	Save graphics to VRML 2.0 file

Graph annotation	
`title`	Graph title
`xlabel`	*x*-axis label
`ylabel`	*y*-axis label
`zlabel`	*z*-axis label
`text`	Text annotation
`gtext`	Mouse placement of text
`plotedit`	Graph editing and annotation tools

22.15 Specialized graphs

`help specgraph`

Specialized 2-D graphs	
`area`	Filled area plot
`bar`	Bar graph
`barh`	Horizontal bar graph
`comet`	Comet-like trajectory
`compass`	Compass plot
`errorbar`	Error bar plot
`ezplot`	Easy-to-use function plotter
`ezpolar`	Easy-to-use polar coordinate plotter
`feather`	Feather plot
`fill`	Filled 2-D polygons
`fplot`	Plot function
`hist`	Histogram
`pareto`	Pareto chart
`pie`	Pie chart
`plotmatrix`	Scatter plot matrix
`rose`	Angle histogram plot
`scatter`	Scatter plot
`stem`	Discrete sequence or “stem” plot
`stairs`	Stairstep plot

Contour and 2½-D graphs	
`contour`	Contour plot
`contourf`	Filled contour plot
`contour3`	3-D contour plot
`clabel`	Contour plot elevation labels
`ezcontour`	Easy-to-use contour plotter
`ezcontourf`	Easy-to-use filled contour plotter
`pcolor`	Pseudocolor (checkerboard) plot
`voronoi`	Voronoi diagram

Specialized 3-D graphs	
`bar3`	3-D bar graph
`bar3h`	Horizontal 3-D bar graph
`comet3`	3-D comet-like trajectories
`ezgraph3`	General-purpose surface plotter
`ezmesh`	Easy-to-use 3-D mesh plotter
`ezmeshc`	Easy-to-use mesh/contour plotter
`ezplot3`	Easy-to-use 3-D parametric curve plotter
`ezsurf`	Easy-to-use 3-D colored surface plotter
`ezsurfc`	Easy-to-use surf/contour plotter
`meshc`	Combination mesh/contour plot
`meshz`	3-D mesh with curtain
`pie3`	3-D pie chart
`ribbon`	Draw 2-D lines as ribbons in 3-D
`scatter3`	3-D scatter plot
`stem3`	3-D stem plot
`surfc`	Combination surf/contour plot
`trisurf`	Triangular surface plot
`trimesh`	Triangular mesh plot
`waterfall`	Waterfall plot

Color-related functions	
`spinmap`	Spin color map
`rgbplot`	Plot color map
`colstyle`	Parse color and style from string
`ind2rgb`	Convert indexed image to RGB image

Volume and vector visualization	
`vissuite`	Visualization suite
`isosurface`	Isosurface extractor
`isonormals`	Isosurface normals
`isocaps`	Isosurface end caps
`isocolors`	Isosurface and patch colors
`contourslice`	Contours in slice planes
`slice`	Volumetric slice plot
`streamline`	Streamlines from 2-D or 3-D vector data
`stream3`	3-D streamlines
`stream2`	2-D streamlines
`quiver3`	3-D quiver plot
`quiver`	2-D quiver plot
`divergence`	Divergence of a vector field
`curl`	Curl and angular velocity of vector field
`coneplot`	3-D cone plot
`streamtube`	3-D stream tube
`streamribbon`	3-D stream ribbon
`streamslice`	Streamlines in slice planes
`streamparticles`	Display stream particles
`interpstreamspeed`	Interpolate streamlines from speed
`subvolume`	Extract subset of volume dataset
`reducevolume`	Reduce volume dataset
`volumebounds`	Returns x,y,z, & color limits for volume
`smooth3`	Smooth 3-D data
`reducepatch`	Reduce number of patch faces
`shrinkfaces`	Reduce size of patch faces

Movies and animation	
`moviein`	Initialize movie frame memory
`getframe`	Get movie frame
`movie`	Play recorded movie frames
`rotate`	Rotate about specified orgin & direction
`frame2im`	Convert movie frame to indexed image
`im2frame`	Convert index image into movie format

Image display and file I/O	
`image`	Display image
`imagesc`	Scale data and display as image
`colormap`	Color look-up table
`gray`	Linear grayscale color map
`contrast`	Grayscale color map to enhance contrast
`brighten`	Brighten or darken color map
`colorbar`	Display color bar (color scale)
`imread`	Read image from graphics file
`imwrite`	Write image to graphics file
`imfinfo`	Information about graphics file
`im2java`	Convert image to Java image

Solid modeling	
`cylinder`	Generate cylinder
`sphere`	Generate sphere
`ellipsoid`	Generate ellipsoid
`patch`	Create patch
`surf2patch`	Convert surface data to patch data

22.16 Handle Graphics

`help graphics`

Figure window creation and control	
`figure`	Create figure window
`gcf`	Get handle to current figure
`clf`	Clear current figure
`shg`	Show graph window
`close`	Close figure
`refresh`	Refresh figure
`refreshdata`	Refresh data plotted in figure
`openfig`	Open new or raise copy of saved figure

Axis creation and control	
`subplot`	Create axes in tiled positions
`axes`	Create axes in arbitrary positions
`gca`	Get handle to current axes
`cla`	Clear current axes
`axis`	Control axis scaling and appearance
`box`	Axis box
`caxis`	Control pseudocolor axis scaling
`hold`	Hold current graph
`ishold`	Return hold state

Handle Graphics objects	
`figure`	Create figure window
`axes`	Create axes
`line`	Create line
`text`	Create text
`patch`	Create patch
`rectangle`	Create rectangle or ellipse
`surface`	Create surface
`image`	Create image
`light`	Create light
`uicontrol`	Create user interface control
`uimenu`	Create user interface menu
`uicontextmenu`	Create user interface context menu

Hard copy and printing	
`print`	Print graph, Simulink sys.; save to M-file
`printopt`	Printer defaults
`orient`	Set paper orientation

Utilities	
`closereq`	Figure close request function
`newplot`	M-file preamble for NextPlot property
`ishandle`	True for graphics handles

Handle Graphics operations	
set	Set object properties
get	Get object properties
reset	Reset object properties
delete	Delete object
gco	Get handle to current object
gcbo	Get handle to current callback object
gcbf	Get handle to current callback figure
drawnow	Flush pending graphics events
findobj	Find objects w/ specified property values
copyobj	Copy graphics object and its children
isappdata	Check if application-defined data exists
getappdata	Get value of application-defined data
setappdata	Set application-defined data
rmappdata	Remove application-defined data

22.17 Graphical user interface tools

`help uitools`

GUI functions	
uicontrol	Create user interface control
uimenu	Create user interface menu
ginput	Graphical input from mouse
dragrect	Drag XOR rectangles with mouse
rbbox	Rubberband box
selectmoveresize	Select, move, resize, copy objects
waitforbuttonpress	Wait for key/buttonpress
waitfor	Block execution and wait for event
uiwait	Block execution and wait for resume
uiresume	Resume execution of blocked M-file
uistack	Control stacking order of objects
uisuspend	Suspend the interactive state of a figure
uirestore	Restore the interactive state of a figure

GUI design tools	
guide	Design GUI
inspect	Inspect object properties
align	Align uicontrols and axes
propedit	Edit property

Dialog boxes	
axlimdlg	Axes limits dialog box
dialog	Create dialog figure
errordlg	Error dialog box
helpdlg	Help dialog box
imageview	Show image preview in a figure window
inputdlg	Input dialog box
listdlg	List selection dialog box
menu	Generate menu of choices for user input
movieview	Show movie in figure with replay button
msgbox	Message box
pagedlg	Page position dialog box
pagesetupdlg	Page setup dialog
printdlg	Print dialog box
printpreview	Display preview of figure to be printed
questdlg	Question dialog box
soundview	Show sound in figure and play
uigetpref	Question dialog box with preference
uigetfile	Standard open file dialog box
uiputfile	Standard save file dialog box
uigetdir	Standard open directory dialog box
uisetcolor	Color selection dialog box
uisetfont	Font selection dialog box
uiopen	Show open file dialog and call `open`
uisave	Show open file dialog and call `save`
uiload	Show open file dialog and call `load`
waitbar	Display wait bar
warndlg	Warning dialog box

Menu utilities	
makemenu	Create menu structure
menubar	Default setting for MenuBar property
umtoggle	Toggle checked status of uimenu object
winmenu	Create submenu for Window menu item

Toolbar button group utilities	
btngroup	Create toolbar button group
btnresize	Resize button group
btnstate	Query state of toolbar button group
btnpress	Button press manager
btndown	Depress button in toolbar button group
btnup	Raise button in toolbar button group

Miscellaneous utilities	
allchild	Get all object children
clipboard	Copy/paste to/from system clipboard
edtext	Interactive editing of axes text objects
findall	Find all objects
findfigs	Find figures positioned off screen
getptr	Get figure pointer
getstatus	Get status text string in figure
hidegui	Hide/unhide GUI
listfonts	Get list of available system fonts
movegui	Move GUI to specified part of screen
guihandles	Return a structure of handles
guidata	Store or retrieve application data
overobj	Get handle of object the pointer is over
popupstr	Get popup menu selection string
remapfig	Transform figure objects' positions
setptr	Set figure pointer
setstatus	Set status text string in figure
uiclearmode	Clears currently active interactive mode

Preferences	
addpref	Add preference
getpref	Get preference
rmpref	Remove preference
setpref	Set preference
ispref	Test for existence of preference

22.18 Character strings

help strfun

General	
char	Create character array (string)
strings	Help for strings
cellstr	Cell array of strings from char array
blanks	String of blanks
deblank	Remove trailing blanks

String tests	
iscellstr	True for cell array of strings
ischar	True for character array (string)
isspace	True for white space characters
isstrprop	Check category of string elements

Character set conversion	
native2unicode	Convert bytes to Unicode characters
unicode2native	Convert Unicode characters to bytes

String to number conversion	
num2str	Convert number to string
int2str	Convert integer to string
mat2str	Convert matrix to eval'able string
str2double	Convert string to double-precision value
str2num	Convert string matrix to numeric array
sprintf	Write formatted data to string
sscanf	Read string under format control

String operations	
regexp	Match regular expression
regexpi	Match regular expression, ignoring case
regexprep	Replace string using regular expression
strcat	Concatenate strings
strvcat	Vertically concatenate strings
strcmp	Compare strings
strncmp	Compare first N characters of strings
strcmpi	Compare strings ignoring case
strncmpi	Compare first N characters, ignore case
strread	Read formatted data from string
strtrim	Remove insignificant whitespace
findstr	Find one string within another
strfind	Find one string within another
strjust	Justify character array
strmatch	Find possible matches for string
strrep	Replace string with another
strtok	Find token in string
upper	Convert string to uppercase
lower	Convert string to lowercase

Base number conversion	
hex2num	IEEE hexadecimal to double-precision
hex2dec	hexadecimal string to decimal integer
dec2hex	decimal integer to hexadecimal string
bin2dec	Convert binary string to decimal integer
dec2bin	Convert decimal integer to binary string
base2dec	Convert base B string to decimal integer
dec2base	Convert decimal integer to base B string
num2hex	single and double to IEEE hexadecimal

22.19 Image and scientific data

`help imagesci`

Image file import/export	
`imformats`	List details about supported file formats
`imfinfo`	Return information about graphics file
`imread`	Read image from graphics file
`imwrite`	Write image to graphics file
`im2java`	Convert image to Java image
`multibandread`	Read band-interleaved data from a file
`multibandwrite`	Write multiband data to a file

CDF file handling	
`cdfread`	Read data from a CDF file
`cdfinfo`	Get information from a CDF file
`cdfwrite`	Write data to a CDF file
`cdfepoch`	Construct `cdfepoch` object

FITS file handling	
`fitsinfo`	Get information from a FITS file
`fitsread`	Read data from a FITS file

HDF version 4 file handling	
`hdfinfo`	Get information about an HDF4 file
`hdfread`	Read HDF4 file
`hdftool`	Browse/import HDF4 or HDF-EOS files

HDF version 5 file handling	
`hdf5info`	Get information about an HDF5 file
`hdf5read`	Read data and attributes from HDF5 file
`hdf5write`	Write data and attributes to HDF5 file

HDF version 5 data objects	
`hdf5.h5array`	Construct HDF5 array
`hdf5.h5compound`	Construct HDF5 compound object
`hdf5.h5enum`	Construct HDF5 enumeration object
`hdf5.h5string`	Construct HDF5 string
`hdf5.h5vlen`	Construct HDF5 variable length array

HDF version 4 library interface	
hdf	MEX-file interface to the HDF library
hdfan	HDF multifile annotation interface
hdfdf24	HDF raster image interface
hdfdfr8	HDF 8-bit raster image interface
hdfh	HDF H interface
hdfhe	HDF HE interface
hdfhx	HDF HX interface
hdfml	MATLAB-HDF gateway utilities
hdfsd	HDF multifile scientific dataset interface
hdfv	HDF V (Vgroup) interface
hdfvf	HDF VF (Vdata) interface
hdfvh	HDF VH (Vdata) interface
hdfvs	HDF VS (Vdata) interface

HDF-EOS library interface help	
hdfgd	HDF-EOS grid interface
hdfpt	HDF-EOS point interface
hdfsw	HDF-EOS swath interface

22.20 File input/output

`help iofun`

File import/export functions	
dlmread	Read ASCII delimited text file
dlmwrite	Write ASCII delimited text file
importdata	Load data from a file into MATLAB
daqread	Read Data Acquisition Toolbox `daq` file
matfinfo	Text description of MAT-file contents

Internet resource	
urlread	Read URL contents as a string
urlwrite	Save URL contents to a file
ftp	Create an `ftp` object
sendmail	Send e-mail

Spreadsheet support	
xlsread	Read Excel (xls) workbook
xlswrite	Write to Excel (xls) workbook
xlsfinfo	Check if file contains Excel workbook
wk1read	Read Lotus spreadsheet (wk1) file
wk1write	Write Lotus spreadsheet (wk1) file
wk1finfo	Check if file contains Lotus worksheet
str2rng	Convert range string to numeric array
wk1wrec	Write a Lotus worksheet record header

Zip file access	
zip	Compress files in a zip file
unzip	Extract contents of a zip file

Formatted file I/O	
fgetl	Read line from file, discard newline char
fgets	Read line from file, keep newline char.
fprintf	Write formatted data to file
fscanf	Read formatted data from text file
textscan	Read formatted data from text file
textread	Read formatted data from text file

File opening and closing	
fopen	Open file
fclose	Close file

Binary file I/O	
fread	Read binary data from file
fwrite	Write binary data to file

File positioning	
feof	Test for end-of-file
ferror	Inquire file error status
frewind	Rewind file
fseek	Set file position indicator
ftell	Get file position indicator

File name handling	
fileparts	Filename parts
filesep	Directory separator for this platform
fullfile	Build full filename from parts
matlabroot	Root directory of MATLAB installation
mexext	MEX filename extension
partialpath	Partial pathnames
pathsep	Path separator for this platform
prefdir	Preference directory name
tempdir	Get temporary directory
tempname	Get temporary file

XML file handling	
xmlread	Parse an XML document
xmlwrite	Serialize XML Document Object Model
xslt	Transform XML document via XSLT

Serial port support	
serial	Construct serial port object
instrfindall	Find all serial port objects
freeserial	Release serial port
instrfind	Find serial port objects

Timer support	
timer	Construct timer object
timerfindall	Find all timer objects
timerfind	Find visible timer objects

Command window I/O	
clc	Clear Command window
home	Send cursor home

SOAP support	
callSoapService	Send a SOAP message
createSoapMessage	Create a SOAP message
parseSoapResponse	Convert SOAP message response

22.21 Audio and video support

`help audiovideo`

Audio input/output objects	
audioplayer	Audio player object
audiorecorder	Audio recorder object

Audio hardware drivers	
sound	Play vector as sound
soundsc	Autoscale and play vector as sound
wavplay	Play on Windows audio output device
wavrecord	Record from Windows audio input

Audio file import and export	
aufinfo	Return information about au file
auread	Read NeXT/SUN (.au) sound file
auwrite	Write NeXT/SUN (.au) sound file
wavfinfo	Return information about wav file
wavread	Read Microsoft (.wav) sound file
wavwrite	Write Microsoft (.wav) sound file

Video file import/export	
aviread	Read movie (.avi) file
aviinfo	Return information about avi file
avifile	Create a new avi file
movie2avi	Make avi movie from MATLAB movie

Utilities	
lin2mu	Convert linear signal to mu-law encoding
mu2lin	Convert mu-law encoding to linear signal

Example audio data (MAT files)	
chirp	Frequency sweeps
gong	Gong
handel	Hallelujah chorus
laughter	Laughter from a crowd
splat	Chirp followed by a splat
train	Train whistle

22.22 Time and dates

`help timefun`

Current date and time	
`now`	Current date and time as date number
`date`	Current date as date string
`clock`	Current date and time as date vector

Basic functions	
`datenum`	Serial date number
`datestr`	String representation of date
`datevec`	Date components

Date functions	
`calendar`	Calendar
`weekday`	Day of week
`eomday`	End of month
`datetick`	Date formatted tick labels

Timing functions	
`cputime`	CPU time in seconds
`tic`	Start stopwatch timer
`toc`	Stop stopwatch timer
`etime`	Elapsed time
`pause`	Wait in seconds

22.23 Data types and structures

`help datatypes`

Class determination functions	
`isnumeric`	True for numeric arrays
`isfloat`	True for `single` and `double` arrays
`isinteger`	True for integer arrays
`islogical`	True for `logical` arrays
`ischar`	True for `char` arrays (string)

Data types (classes)	
double	Convert to double precision
char	Create character array (string)
logical	Convert numeric values to logical
cell	Create cell array
struct	Create or convert to structure array
single	Convert to single precision
int8	Convert to signed 8-bit integer
int16	Convert to signed 16-bit integer
int32	Convert to signed 32-bit integer
int64	Convert to signed 64-bit integer
uint8	Convert to unsigned 8-bit integer
uint16	Convert to unsigned 16-bit integer
uint32	Convert to unsigned 32-bit integer
uint64	Convert to unsigned 64-bit integer
inline	Construct `inline` object
function_handle	Function handle (@ operator)
javaArray	Construct a Java array
javaMethod	Invoke a Java method
javaObject	Invoke a Java object constructor

Multidimensional array functions	
cat	Concatenate arrays
ndims	Number of dimensions
ndgrid	Arrays for N-D functions & interpolation
permute	Permute array dimensions
ipermute	Inverse permute array dimensions
shiftdim	Shift dimensions
squeeze	Remove singleton dimensions

Function handle functions	
@	Create `function_handle`
func2str	`function_handle` array to string
str2func	String to `function_handle` array
functions	List functions of a `function_handle`

Cell array functions	
cell	Create cell array
cellfun	Functions on cell array contents
celldisp	Display cell array contents
cellplot	Display graphical depiction of cell array
cell2mat	Combine cell array of matrices
mat2cell	Break matrix into cell array of matrices
num2cell	Convert numeric array into cell array
deal	Deal inputs to outputs
cell2struct	Convert cell array into structure array
struct2cell	Convert structure array into cell array
iscell	True for cell array

Structure functions	
struct	Create or convert to structure array
fieldnames	Get structure field names
getfield	Get structure field contents
setfield	Set structure field contents
rmfield	Remove structure field
isfield	True if field is in structure array
isstruct	True for structures
orderfields	Order fields of a structure array

Object-oriented programming functions	
class	Create object or return object class
struct	Convert object to structure array
methods	List names & properties of class methods
methodsview	List names & properties of class methods
isa	True if object is a given class
isjava	True for Java objects
isobject	True for MATLAB objects
inferiorto	Inferior class relationship
superiorto	Superior class relationship
substruct	Create structure for subsref/subasgn

Overloadable operators	
minus	Overloadable method for a-b
plus	Overloadable method for a+b
times	Overloadable method for a.*b
mtimes	Overloadable method for a*b
mldivide	Overloadable method for a\b
mrdivide	Overloadable method for a/b
rdivide	Overloadable method for a./b
ldivide	Overloadable method for a.\b
power	Overloadable method for a.^b
mpower	Overloadable method for a^b
uminus	Overloadable method for -a
uplus	Overloadable method for +a
horzcat	Overloadable method for [a b]
vertcat	Overloadable method for [a;b]
le	Overloadable method for a<=b
lt	Overloadable method for a<b
gt	Overloadable method for a>b
ge	Overloadable method for a>=b
eq	Overloadable method for a==b
ne	Overloadable method for a~=b
not	Overloadable method for ~a
and	Overloadable method for a&b
or	Overloadable method for a|b
subsasgn	for a(i)=b, a{i}=b, and a.field=b
subsref	for a(i), a{i}, and a.field
colon	Overloadable method for a:b
end	Overloadable method for a(end)
transpose	Overloadable method for a.'
ctranspose	Overloadable method for a'
subsindex	Overloadable method for x(a)
loadobj	Called to load object from .mat file
saveobj	Called to save object to .mat file

22.24 Version control

`help verctrl`

Checkin/checkout	
`checkin`	checkin files to version control system
`checkout`	checkout files
`undocheckout`	undo checkout files

Specific version control	
`rcs`	Version control actions using RCS
`pvcs`	Version control actions using PVCS
`clearcase`	Version control actions using ClearCase
`sourcesafe`	Version control using Visual SourceSafe
`customverctrl`	Custom version control template
`verctrl`	Version control operations on Windows
`cmpopts`	Version control settings

22.25 Creating and debugging code

`help codetools`

Writing and managing M-files	
`edit`	Edit M-file
`notebook`	Open an M-book in Microsoft Word
`mlint`	List suspicious constructs in M-files

Directory tools	
`contentsrpt`	Audit `Contents.m` of a directory
`coveragerpt`	Scan directory for profiler line coverage
`deprept`	Scan file or directory for dependencies
`diffrpt`	Directory browser and file comparitor
`dofixrpt`	Scan file or directory for `TODO`, ...
`helprpt`	Scan file or directory for help
`mlintrpt`	Scan file or directory for M-lint info.
`standardrpt`	Directory browser

Managing the file system and search patch	
`filebrowser`	Open Current Directory browser
`pathtool`	View, modify, & save MATLAB `path`

Profiling M-files	
`profile`	Profile function execution time
`profview`	Profile browser
`profsave`	Save static copy of profile report
`profreport`	Generate profile report
`profviewgateway`	Profiler HTML gateway function
`opentoline`	Start editting a file at a given line
`stripanchors`	Remove code evaluation anchors

Debugging M-files	
`debug`	`help debug` lists debugging commands
`dbstop`	Set breakpoint
`dbclear`	Remove breakpoint
`dbcont`	Continue execution
`dbdown`	Change local workspace context
`dbstack`	Display function call stack
`dbstatus`	List all breakpoints
`dbstep`	Execute one or more lines
`dbtype`	List M-file with line numbers
`dbup`	Change local workspace context
`dbquit`	Quit debug mode
`dbmex`	Debug MEX-files (Unix only)

Managing, watching, and editting variables	
`openvar`	Open workspace for graphical editting
`workspace`	View contents of a workspace

22.26 Help commands

`help helptools`

Accessing on-line HTML help	
`doc`	Bring up Help Browser to specific place
`helpbrowser`	Same as `doc`, to last place viewed
`helpdesk`	Same as `doc`, to help "Begin Here" page
`helpview`	Display HTML file in Help Browser
`docsearch`	Search in Help Browser

Accessing M-file help	
`help`	View M-file help in Command window
`helpwin`	View M-file help in Help Browser
`lookfor`	Search all M-files for keyword

MathWorks tech support, web access	
`info`	Info about MATLAB & The MathWorks
`support`	Open MathWorks tech support web page
`whatsnew`	View Release Notes in Help Browser
`web`	Open internal or system web browser

22.27 Microsoft Windows functions

`help winfun`

COM automation client functions	
`actxcontrol`	Create an ActiveX control
`actxserver`	Create an ActiveX server
`eventlisteners`	Lists all registered events
`isevent`	True if event of object
`registerevent`	Registers events
`unregisterallevents`	Unregister all events
`unregisterevent`	Unregister events
`iscom`	True if COM/ActiveX object
`isinterface`	True if COM interface
`COM/set`	Set COM object property
`COM/get`	Get COM object properties
`COM/invoke`	Invoke/display method
`COM/events`	List COM object events
`COM/interfaces`	List custom interfaces
`COM/addproperty`	Add custom property to object
`COM/deleteproperty`	Remove custom property
`COM/delete`	Delete COM object
`COM/release`	Release COM interface
`COM/move`	Move/resize ActiveX control
`COM/propedit`	Edit properties

COM automation client functions (continued)	
`COM/save`	Serialize COM object to file
`COM/load`	Initialize COM object from file

COM sample code	
`mwsamp`	ActiveX control creation
`sampev`	Event handler

DDE client functions	
`ddeadv`	Setup advisory link
`ddeexec`	Execute string
`ddeinit`	Initiate DDE conversation
`ddepoke`	Send data to application
`ddereq`	Request data from application
`ddeterm`	Terminate DDE conversation
`ddeunadv`	Release advisory link

General MS Windows functions	
`winopen`	Open file using Windows command
`winqueryreg`	Read Windows registry

22.28 Examples and demonstrations

Type `help demos` to see a list of MATLAB demos.

22.29 Preferences

`help local`

Saved preferences files	
`startup`	User startup M-file
`finish`	User finish M-file
`matlabrc`	Master startup M-file
`pathdef`	Search path defaults
`docopt`	Web browser defaults
`printopt`	Printer defaults

Configuration information	
`hostid`	MATLAB server host ID number
`license`	License number
`version`	MATLAB version number

22.30 Symbolic Math Toolbox

`help symbolic`

Demonstrations	
`symintro`	Introduction to Symbolic Math Toolbox
`symcalcdemo`	Calculus demonstration
`symlindemo`	Demonstrate symbolic linear algebra
`symvpademo`	Variable precision arithmetic demo
`symrotdemo`	Study plane rotations
`symeqndemo`	Demonstrate symbolic equation solving

Symbolic operations	
`sym`	Create symbolic object
`syms`	Create symbolic object (short-hand)
`findsym`	Determine symbolic variables
`pretty`	Pretty print a symbolic expression
`latex`	Symbolic expression in LaTeX
`texlabel`	Convert string to TeX
`ccode`	Symbolic expression in C code
`fortran`	Symbolic expression in Fortran code

Calculus	
`diff`	Differentiate
`int`	Integrate
`limit`	Limit
`taylor`	Taylor series
`jacobian`	Jacobian matrix
`symsum`	Summation of series

Linear algebra		
diag	Create or extract diagonals	
triu	Upper triangle	
tril	Lower triangle	
inv	Matrix inverse	
det	Determinant	
rank	Rank	
rref	Reduced row echelon form	
null	Basis for null space	
colspace	Basis for column space	
eig	Eigenvalues and eigenvectors	
svd	Singular values and singular vectors	
jordan	Jordan canonical (normal) form	
poly	Characteristic polynomial	
expm	Matrix exponential	
mldivide	Matrix left division (backslash)	a\b
mpower	Matrix power	a^b
mrdivide	Matrix right division (slash)	a/b
mrtimes	Matrix multiplication	a*b
transpose	Matrix transpose	a.'
ctranspose	Matrix complex conj. transpose	a'

Simplification	
simplify	Simplify
expand	Expand
factor	Factor
collect	Collect
simple	Search for shortest form
numden	Numerator and denominator
horner	Nested polynomial representation
subexpr	Rewrite in terms of subexpressions
coeffs	Coefficients of a multivariate polynomial
sort	Sort symbolic vectors or polynomials
subs	Symbolic substitution

Solution of equations	
`solve`	Solve algebraic (nonlinear) equations
`dsolve`	Solve differential equations
`finverse`	Functional inverse
`compose`	Functional composition

Variable precision arithmetic	
`vpa`	Variable precision arithmetic
`digits`	Set variable precision accuracy

Integral transforms	
`fourier`	Fourier transform
`laplace`	Laplace transform
`ztrans`	Z transform
`ifourier`	Inverse Fourier transform
`ilaplace`	Inverse Laplace transform
`iztrans`	Inverse Z transform

Conversions	
`double`	Convert symbolic matrix to `double`
`single`	Convert symbolic matrix to `single`
`poly2sym`	Coefficients to symbolic polynomial
`sym2poly`	Symbolic polynomial to coefficients
`char`	Convert sym object to string
`int8`	Convert to signed 8-bit integer
`int16`	Convert to signed 16-bit integer
`int32`	Convert to signed 32-bit integer
`int64`	Convert to signed 64-bit integer
`uint8`	Convert to unsigned 8-bit integer
`uint16`	Convert to unsigned 16-bit integer
`uint32`	Convert to unsigned 32-bit integer
`uint64`	Convert to unsigned 64-bit integer

Arithmetic and algebraic operations		
plus	Addition	a+b
minus	Subtraction	a-b
uminus	Negation	-a
times	Array multiplications	a.*b
ldivide	Left division (backslash)	a\b
rdivide	Right division (slash)	a/b
power	Array power	a.^b
abs	Absolute value	
ceil	Ceiling	
conj	Conjugate	
colon	Colon operator	
fix	Integer part	
floor	Floor	
frac	Fractional part	
mod	Modulus	
round	Round	
quorem	Quotient and remainder	
imag	Imaginary part	
real	Real part	
exp	Exponential	
log	Natural logarithm	
log10	Common (base-10) logarithm	
log2	Base-2 logarithm	
sqrt	Square root	
prod	Product of elements	
sum	Sum of elements	

Logical operations	
isreal	True for real array
eq	Equality test a==b
ne	Inequality test a~=b

Trigonometric functions	
`sin`	Sine
`sinh`	Hyperbolic sine
`asin`	Inverse sine
`asinh`	Inverse hyperbolic sine
`cos`	Cosine
`cosh`	Hyperbolic cosine
`acos`	Inverse cosine
`acosh`	Inverse hyperbolic cosine
`tan`	Tangent
`tanh`	Hyperbolic tangent
`atan`	Inverse tangent
`atanh`	Inverse hyperbolic tangent
`sec`	Secant
`sech`	Hyperbolic secant
`asec`	Inverse secant
`asech`	Inverse hyperbolic secant
`csc`	Cosecant
`csch`	Hyperbolic cosecant
`acsc`	Inverse cosecant
`acsch`	Inverse hyperbolic cosecant
`cot`	Cotangent
`coth`	Hyperbolic cotangent
`acot`	Inverse cotangent
`acoth`	Inverse hyperbolic cotangent

String handling utilities	
`isvarname`	Check for a valid variable name
`vectorize`	Vectorize a symbolic expression
`disp`	Display symbolic expression as text
`display`	Display function for symbolic statements
`eval`	Evaluate a symbolic expression

Special functions	
besselj	Bessel function of the first kind
bessely	Bessel function of the second kind
besseli	Modified Bessel function of the 1st kind
besselk	Modified Bessel function of the 2nd kind
erf	Error function
sinint	Sine integral
cosint	Cosine integral
zeta	Riemann zeta function
gamma	Symbolic gamma function
gcd	Greatest common divisor
lcm	Least common multiple
hypergeom	Generalized hypergeometric function
lambertw	Lambert W function
dirac	Delta function
heaviside	Step function

Pedagogical and graphical applications	
rsums	Riemann sums
ezcontour	Easy-to-use contour plotter
ezcontourf	Easy-to-use filled contour plotter
ezmesh	Easy-to-use mesh (surface) plotter
ezmeshc	Easy-to-use mesh/contour plotter
ezplot	Easy-to-use function plotter
ezplot3	Easy-to-use spatial curve plotter
ezpolar	Easy-to-use polar coordinates plotter
ezsurf	Easy-to-use surface plotter
ezsurfc	Easy-to-use surface/contour plotter
funtool	Function calculator
taylortool	Taylor series calculator

Access to Maple (not in Student Version)	
maple	Access Maple kernel
mfun	Numeric evaluation of Maple functions
mfunlist	List of functions for mfun
mhelp	Maple help

23. Additional Resources

The MathWorks, Inc., and others provide a wide range of products that extend MATLAB's capabilities. Some are collections of M-files called toolboxes. One of these has already been introduced (the Symbolic Math Toolbox). Also available is Simulink, an interactive graphical system for modeling and simulating dynamic nonlinear systems. The `ver` command lists the toolboxes and Simulink components included in your installation, as does the Help Browser (`doc`). Similar to MATLAB toolboxes, Simulink has domain-specific add-ons called blocksets.

MATLAB:

MATLAB®
Database Toolbox
MATLAB Report Generator

Math and Optimization:
Optimization Toolbox
Symbolic Toolbox
Extended Symbolic Math Toolbox
Partial Differential Equation Toolbox
Genetic Algorithm and Direct Search Toolbox

Statistics and Data Analysis:
Statistics Toolbox
Neural Network Toolbox
Curve Fitting Toolbox
Spline Toolbox
Model-Based Calibration Toolbox
Bioinformatics Toolbox

Control System Design and Analysis:
Control System Toolbox
System Identification Toolbox
Fuzzy Logic Toolbox
Robust Control Toolbox
μ-Analysis and Synthesis Toolbox
LMI Control Toolbox
Model Predictive Control Toolbox

Signal Process and Communications:
Signal Processing Toolbox
Communications Toolbox
Filter Design Toolbox
Filter Design HDL Coder
System Identification Toolbox
Wavelet Toolbox
Fixed-Point Toolbox
RF Toolbox
Link for Code Composer Studio™
Link for ModelSim®

Image Processing:
Image Processing Toolbox
Image Acquisition Toolbox
Mapping Toolbox

Test and Measurement:
Data Acquisition Toolbox
Instrument Control Toolbox
Image Acquisition Toolbox
OPC Toolbox

Financial Modeling and Analysis:
Financial Toolbox

Financial Derivatives Toolbox
GARCH Toolbox
Financial Time Series Toolbox
Datafeed Toolbox
Fixed-Income Toolbox

Application Deployment:
MATLAB Compiler
Excel Link
MATLAB Web Server

Application Deployment Targets:
MATLAB Builder for COM
MATLAB Builder for Excel

Simulink:

Simulink®
Stateflow®
Simulink Fixed Point
Simulink Accelerator
Simulink Report Generator

Physical Modeling:
SimMechanics
SimPowerSystems

Simulation Graphics:
Virtual Reality Toolbox
Dials and Gauges Blockset

Control System Design and Analysis:
Simulink Control Design
Simulink Response Optimization

Simulink Parameter Estimation
Aerospace Blockset

Signal Processing and Communications:
Signal Processing Blockset
Communications Blockset
CDMA Reference Blockset
RF Blockset

Code Generation:
Real-Time Workshop®
Real-Time Workshop Embedded Coder
Stateflow Coder

PC-Based Rapid Control Prototyping and HIL:
xPC Target
xPC Target Embedded Option
xPC TargetBox™
Real-Time Windows Target

Embedded Targets:
Embedded Target for TI C6000™ DSP
Embedded Target for Motorola® MPC555
Embedded Target for OSEK/VDX®
Embedded Target for Infineon C166® Microcontrollers
Embedded Target for Motorola® HC12
Embedded Target for TI C2000™ DSP

Verification, Validation, and Testing:
Link for Code Composer Studio™
Link for ModelSim®
Simulink Verification and Validation

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