

## Preface

This book is intended to supplement Ken Rosen's *Discrete Mathematics and Its Applications*, Eighth Edition, published by McGraw-Hill. It was developed with Maple 2018, created by Waterloo Maple Inc. This is intended to be a guide as you explore concepts in discrete mathematics and to provide you with tools you can use to investigate further on your own. This text can significantly enhance a traditional course in discrete mathematics in several ways. First, it makes a plethora of examples readily available that you can interact with easily. Second, it makes the notion of algorithm, which is central in discrete mathematics, concrete by giving you the opportunity to actually implement algorithms rather than only analyze them in the abstract. Finally, and most significantly, it provides you greater freedom to make conjectures and experiment without getting bogged down in repetitive calculation.

The focus of this manual is on Maple code and does not attempt to explain discrete mathematics. It is expected that you are taking, or have taken, a course in discrete mathematics. Ideally, you have access to Ken Rosen's *Discrete Mathematics and Its Applications*. It is not assumed that you have any prior experience with Maple. The introductory chapter that follows this preface is designed to introduce you to Maple. Likewise, it is not assumed that you have any experience with computer programming languages. Part of the Introduction is devoted to the basic concepts and techniques of computer programming. Subsequent chapters gradually introduce increasingly sophisticated programming ideas. While this is not a textbook on computer programming, you will likely find yourself fairly comfortable with the basics of programming by the end.

With the exception of the Introduction, the structure of this book follows that of *Discrete Mathematics and Its Applications*. For each section of each chapter in that text, this manual contains a corresponding section describing Maple commands and providing Maple procedures that are used to explore the mathematics topics in that section. Each chapter also contains solutions to some of the Computer Projects and Computations and Explorations exercises found at the end of the chapter of *Discrete Mathematics and Its Applications*. You will also find a number of exercises at the conclusion of each chapter designed to suggest additional questions that you can explore using Maple.

This manual strikes a balance between describing existing Maple commands and creating new procedures that extend Maple's capabilities for exploring discrete mathematics. For example, Maple does not currently include the capability of calculating with pseudographs. Therefore, in Chapter 10, in addition to describing Maple's capabilities for modeling graphs, we also write procedures relating to pseudographs. Some readers may not be interested in the detailed descriptions of how new procedures and programs like these are created. However, even if you are not interested in the programming aspect, the procedures we create are still available to you to explore those topics.

Much has happened since the first edition of this text was written. Rosen's text has undergone five revisions and there have been 18 major releases of Maple (it was at Release 4 when the first edition was published). As a result, this manual has undergone extensive revision, and has also been substantially expanded and reorganized. At the same time, this manual retains the spirit and goals of the original *Exploring Discrete Mathematics with Maple*. We therefore reproduce the preface of the original book below.

## ***Changes in the New Edition***

The previous version of this manual was written for the seventh edition of Ken Rosen's *Discrete Mathematics and Its Applications* and was developed with Maple Release 15. The current version includes significant revisions and updates to reflect the revisions in the eighth edition of the textbook and the improvements in the 2018 version of Maple. Some of the most notable revisions include:

- Exposition and programming examples have been improved, with a focus on simplifying and clarifying both to help you more easily understand connections to the mathematics content. Moreover, the Explore function is illustrated at multiple places in the text to illustrate how Maple can be used to easily create interactive elements for exploring concepts and making conjectures.
- Additional examples have been added to reflect new content in the eighth edition of *Discrete Mathematics and Its Applications*, including solving the  $n$ -Queens problem via satisfiability, implementing the naive string matching algorithm, and illustrating homomorphic encryption.
- Maple commands that have been improved or added to the system since the last version of the manual have been incorporated. In some cases, the improvements to the built-in functions have made it no longer necessary to develop functions within this manual to fill gaps in Maple's capabilities. For example, Maple's built-in function for finding graph isomorphisms can now handle directed graphs, making the procedure provided in the previous version of this manual unnecessary and making room for procedures for visualizing the isomorphisms instead. Several "from scratch" procedures duplicating built-in capabilities remain when doing so illustrates important mathematics content or programming techniques.
- Data structures introduced since the last version of the manual, including the DataFrame object and MultiSet structure, are discussed in relation to appropriate content. In particular, the built-in function for producing truth tables produces a DataFrame by default, and the MultiSet structure can be used to represent both multi- and fuzzy-sets. Generally speaking, however, preference is given to more fundamental data structures more universally present across computer algebra system and programming languages.
- Deprecated commands and packages have been replaced by their newer equivalents; most notably the numtheory package has been replaced by NumberTheory.

## ***Acknowledgments***

I am deeply grateful to Ken Rosen for having trusted me with this work and for his wisdom and guidance. I am indebted to the authors of the original *Exploring Discrete Mathematics with Maple* for providing an excellent foundation on which to build.

I also wish to thank Nora Devlin, the Product Developer at McGraw-Hill Higher Education for *Discrete Mathematics and Its Applications*, eighth edition, for her patience and confidence.

Thanks also to those who have provided feedback on the previous version.

I am grateful to Martin Erickson for his mentorship. To Daniel Baack, Jason Beckfield, Elizabeth Davis-Berg, Julie Minbiole, Christopher Shaw, Michael Welsh, and Heather Minges Wols for their constant support and encouragement. Finally, I am always grateful to my parents for all they have done.

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## Preface to the First Edition

This book is a supplement to Ken Rosen's text *Discrete Mathematics and Its Applications, Third Edition*, published by McGraw-Hill. It is unique as an ancillary to a discrete mathematics text in that its entire focus is on the computational aspects of the subject. This focus has allowed us to cover extensively and comprehensively how computations in the different areas of discrete mathematics can be performed, as well as how results of these computations can be used in explorations. This book provides a new perspective and a set of tools for exploring concepts in discrete mathematics, complementing the traditional aspects of an introductory course. We hope the users of this book will enjoy working with it as much as the authors have enjoyed putting this book together.

This book was written by a team of people, including Stan Devitt, one of the principle authors of the Maple system and Eithne Murray who has developed code for certain Maple packages. Two other authors, Troy Vasiga and James McCarron, have mastered discrete mathematics and Maple through their studies at the University of Waterloo, a key center of discrete mathematics research and the birthplace of Waterloo Maple Inc.

To effectively use this book, a student should be taking, or have taken, a course in discrete mathematics. For maximum effectiveness, the text used should be Ken Rosen's *Discrete Mathematics and Its Applications*, although this volume will be useful even if this is not the case. We assume that the student has access to Maple, Release 3 or later. We have included material based on Maple shareware and on Release 4 with explicit indication of where this is done. (Where to obtain Maple shareware is described in the Introduction.) We do not assume that the student has previously used Maple. In fact, working through the book can teach students Maple while they are learning discrete mathematics. Of course, the level of sophistication of students with respect to programming will determine their ability to write their own Maple routines. We make peripheral use of calculus in this book. Although all places where calculus is used can be omitted, students who have studied calculus will find this material of interest.

This volume contains a great deal of Maple code, much based on existing Maple functions. But substantial extensions to Maple can be found throughout the book; new Maple routines have been added in key places, extending the capabilities of what is currently part of Maple. An excellent example is new Maple code for displaying trees, providing functionality not currently part of the network package of Maple. All the Maple code in this book is available over the Internet; see the Introduction for details.

This volume contains an Introduction and 10 chapters. The Introduction describes the philosophy and contents of the chapters and provides an introduction to the use of Maple, both for computation and for programming. This chapter is especially important to students who have not used Maple before. (More material on programming with Maple is found throughout the text, especially in Chapters 1 and 2.) Chapters 1 to 10 correspond to the respective chapters of *Discrete Mathematics and Its Applications*. Each chapter contains a discussion of how to use Maple to carry out computation on the subject of that chapter. Each chapter also contains a discussion of the Computations and Explorations found at the end of the corresponding chapter of *Discrete Mathematics and Its Applications*, along with a set of exercises and projects designed for further work.

Users of this book are encouraged to provide feedback, either via the postal service or the Internet. We expect that students and faculty members using this book will develop material that they want to share with others. Consult the Introduction for details about how to download Maple software

associated with this book and for information about how to upload your own Maple code and worksheets.

## ***Acknowledgments***

Thanks go to the staff of the College Division of McGraw-Hill for providing us with the flexibility and support to put together something new and innovative. In particular, thanks go to Jack Shira, Senior Sponsoring Editor, and Maggie Rogers, Senior Associate Editor, for their strong interest, enthusiasm, and frequent inquiries into the status of this volume, and to Denise Schanck, Publisher, for her overall support. Thanks also goes to the production department of McGraw-Hill for their able work.

We would also like to express thanks to the staff of Waterloo Maple Inc. for their support of this project. In particular, we would like to thank Benton Leong and Ha Quang Le for their suggestions. Furthermore, we offer our appreciation to Charlie Colbourn of the University of Waterloo for helping bring this working team together as well as for his contributions as one of the authors of Maple's networks package which is heavily used in parts of this book.

As always, one of the authors, Ken Rosen, would like to thank his management at AT&T Bell Laboratories, including Steve Nurenberg, Ashok Kuthyar, Hrair Aldermishian, and Jim Day, for providing the environment and the resources that have made this book possible. Another author, Troy Vasiga, would like to thank his wife for her encouragement and support during the preparation of this book.

## **Introduction**

Modern mathematical computation software, such as Maple, allow us to carry out complicated computations quickly and easily. As a supplement to traditional exercises solved by hand, having computational tools available while learning discrete mathematics provides a new dimension to the learning experience. Specifically, Maple supports an enquiry and experimental approach to learning. This book is designed to connect the traditional approach to learning discrete mathematics with this experimental approach.

Using computational software, students can experiment directly with many objects that are important in discrete mathematics. These include sets, large integers, combinatorial objects, graphs, and trees. Furthermore, by using interactive computational software to do this, students can explore these examples more thoroughly, fostering a deeper understanding of concepts, applications, and problem-solving techniques.

This supplement has two main goals. The first is to help students learn how to carry out computations in discrete mathematics using Maple. The second is to be a guide and a model as students discover mathematics with the use of computational tools.

This book is intended for use by any student of discrete mathematics. No previous familiarity with Maple is required. Likewise, we do not assume any previous experience with computer programming. The fundamentals of Maple and the basic concepts of computer programming will be thoroughly explained as they are needed.

## **Structure of This Manual**

This supplement begins with a brief introduction to Maple, its capabilities, and its use. The material in this introductory chapter explains the philosophy behind working with Maple, how to use Maple

to carry out computations, and its basic structure. This introduction continues by explaining the basic concepts and syntax for programming with Maple. This will provide those who are new to Maple and programming languages the background they will need in the rest of the book.

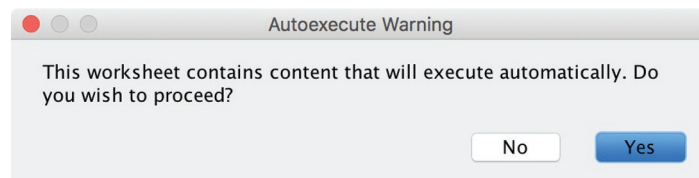
Following the introduction, the main body of this book contains 13 chapters. Each chapter parallels a chapter of *Discrete Mathematics and Its Applications, Eighth Edition*, by Kenneth H. Rosen (henceforth referred to as the text or the textbook). Each chapter includes comprehensive coverage explaining how Maple can be used to explore the topics of the corresponding chapter of the text. This includes a discussion of relevant Maple commands, many new procedures written expressly for this book, and examples illustrating how to use Maple to explore topics in the text.

Additionally, we discuss selected *Computer Projects* and *Computations and Explorations* from the corresponding chapter of the text. We provide guidance, partial solutions, or complete solutions to these exercises. A similar philosophy governs the inclusion of these solutions as does the inclusion of answers to selected exercises in the back of most mathematics textbooks. You should attempt the problem on your own first. The solutions in this manual are intended to be referred to: after you have succeeded in solving a problem to see a (potentially) different approach, when you have stopped making progress on your own and need a slight boost to continue, or when you are trying to solve a similar problem.

Finally, each chapter concludes with a set of additional questions for you to explore. Some of these are straightforward computational exercises, while others are more accurately described as projects requiring substantial additional work, including programming.

The chapters of this manual are available in two formats: as a PDF document and as a Maple Worksheet. The PDF format contains all of the text and Maple commands and other information that you need. The Maple Worksheet version of the chapter includes additional features, specifically active Maple code and links to Maple help pages. It is recommended that you primarily work with the Maple Worksheet version of this manual, and use the PDF version for when you do not have access to Maple.

When you first open the Maple Worksheet version of a chapter, a dialog box should pop up telling you that the worksheet contains content that will automatically execute (see image below). It asks whether you want to proceed. We recommend that you choose yes.



This way, the vital commands within the chapter, those that define variables and procedures, are executed for you right when you open the document. If you do not allow the automatic execution to happen, you may run into errors if you try to execute commands that require other statements to have been executed first. Of course, some groups of commands must be executed in order to produce the correct output, so if you encounter errors, you may need to backtrack and execute commands in order.

The main benefit of the Maple Worksheet version of this book is that it is interactive. That is, you can execute the Maple commands demonstrated in the chapter. Even better, you can modify the

example commands so that you can experiment right within the body of the chapter. Additionally, you have immediate access to Maple's help system. Within the text of this manual, Maple commands appear in red and are underlined indicating that clicking on them will open the corresponding Maple help page.

This book has been designed to help students achieve the main goals of a course in discrete mathematics. These goals, as described in the preface of the textbook, are the mastery of mathematical thinking, combinatorial analysis, discrete structures, algorithmic thinking, and applications and modeling. This supplement demonstrates how to use the interactive computational environment of Maple to enhance and accelerate the achievement of these goals.

## Interactive Maple

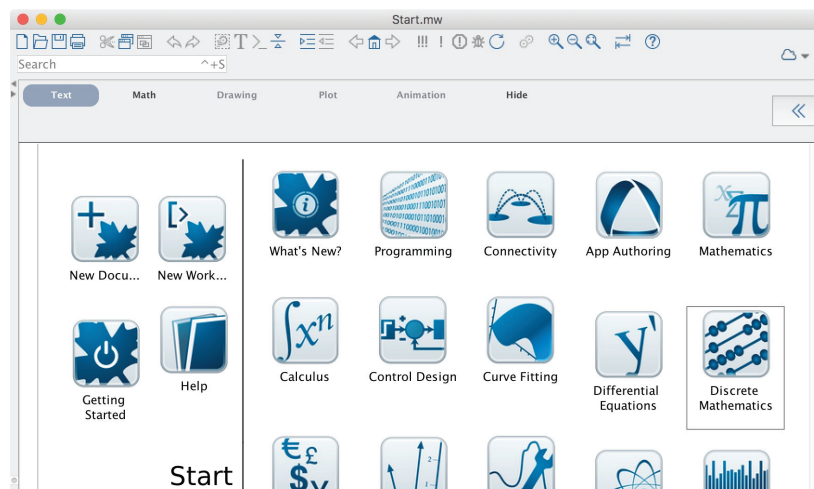
Exploring discrete mathematics with Maple is like exploring a mathematical topic with an expert assistant at your side. As you investigate a topic, you should always be asking questions. In many cases, the answer to your question can be found by experimenting. Maple, your highly trained mathematical assistant, can often carry out these directed experiments quickly and accurately, often with only a few simple instructions.

By hand, the magnitude and quantity of work required to investigate even one reasonable test case may be prohibitive. By delegating the details to Maple, your efforts can be much more focused on choosing the right mathematical questions and on interpreting results. Moreover, with a system such as Maple, the types of objects you are investigating, and tools for manipulating them, already exist as part of the basic infrastructure provided by the system. This includes sets, lists, variables, polynomials, graphs, arbitrarily large integers, rational numbers, and most important, support for exact and fast computations.

The use of Maple is merely a means to the end of achieving the goals of a course in discrete mathematics. As with any tool, to use it effectively you must have some basic understanding of the tool and its capabilities. In this section, we introduce Maple by working through a sample interactive session.

### Starting Maple

A new Maple session begins when you start the Maple software. When you start Maple, you generally will see the Maple startup worksheet, which will look something like the window shown below.



The main portion of the startup worksheet displays icons referring to various topics. The left side of the window consists of four useful icons. The lower two are links to a worksheet that itself links to a variety of resources that can help you get started using Maple and a link to the Maple help system.

The top two icons on the left-hand side of the window are the new document options. Selecting one of those icons will create either a new Document or Worksheet. The difference between these is discussed below. To open an existing file, perhaps a file that you created or one of the chapters of this manual, you can select **Open** from the **File** menu or click on the open icon, which is typically the second icon in the toolbar along the top of the Maple window. A standard file selection dialog will open that allows you to select the file you want.

### *Documents versus Worksheets*

This Introduction and, in fact, all the chapters of this manual were created in Document mode. In Document mode, you interact with Maple in similar ways to how you edit a document in a word processing program. You can type text, change the font, insert images, and complete other typical word processing tasks. However, you also have a powerful mathematical engine at your fingertips.

A file in Worksheet mode is more focused on executing Maple commands. When you start a Maple file in Worksheet mode, you immediately see a command prompt. The goal of this manual is to help you explore and learn discrete mathematics, so the execution of Maple commands is the focus. For this reason, it is likely to be more natural to interact with Maple in Worksheet mode. From the start-up worksheet, you can click on “New Worksheet” or select “Worksheet Mode” from the **New** submenu of the main **File** menu. Note that Document mode is the default, so if you click on the new document icon (the first icon in the toolbar at the top of the Maple window), you will be presented with a blank file in Document mode.

However, the difference between Worksheet mode and Document mode is mostly a matter of focus and style. Text blocks can be added in Worksheet mode and command prompts can be added in Document mode. In the toolbar at the top of the Maple window you should see icons like the ones shown below.

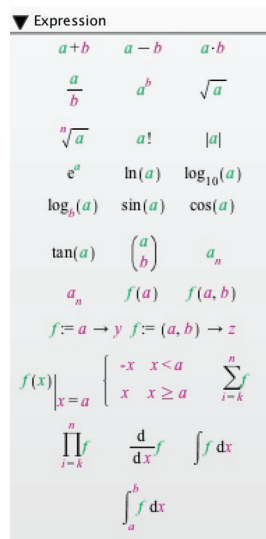


These icons should be about a third of the way along the toolbar, which begins with icons for a new file, open, save, and print. If you do not see them, click on the **View** menu and make sure that a checkmark appears next to **Toolbar**. When you are working in Maple, whether in a Worksheet or a Document, clicking on the capital T icon (or selecting **Text** from the **Insert** menu) will insert a text block immediately after your cursor. Clicking on the icon that looks like a greater than symbol followed by an underline (or selecting one of the **Execution Group** options in the **Insert** menu) will create a command prompt.

The first of the four icons displayed above inserts a Code Edit Region, which is useful when you are writing procedures, as opposed to executing an individual command. In a Code Edit Region, Maple will highlight syntax errors and warn you about other possible issues with your code as you type. In addition, a fixed-width font is used which makes careful checking of syntax easier. The procedures in this manual are entered in Code Edit Regions. The final icon is for entering a new Document Block. These, like the Document mode, are used for mixing text with results of computations to produce the kinds of polished documents and final reports you might see in a business context.

## Maple Notation Versus 2-D Math Mode

Along the left side of the main window you may see palettes. If they are not already visible, they can be controlled by the **Expand Dock** or **Collapse Dock** options in the **Palettes** submenu of the **View** menu. Shown below is the Expression palette.



Palettes can be used to insert mathematical formulae and symbols within text blocks. They can also be used to make expressions in 2-D math mode. By default, for both Documents and Worksheets, math is input and output in 2-D math notation. The 2-D notation allows you to use, for example, the integral symbol as part of an expression that you have Maple evaluate. With 2-D notation, you can also access context menus by right-clicking on an expression to instruct Maple to perform certain operations on the expression.

These are nice features, but it is not required to use them. Everything you can do in Maple can be accomplished with plain keyboard input, and all of the commands demonstrated in this manual are presented in the form obtained by simple typing. Indeed, that is how all the commands were entered during the creation of the manual. There are several reasons we chose to use this approach for command entry, but the primary reason is that it is much easier to explain what to do when you just need to type what you see.

However, when working in 2-D input mode, Maple will automatically do some formatting as you type. You will most often notice this when typing exponents (obtained by a caret, or Shift+6) and arrows (obtained from a hyphen followed by a greater-than). For example, consider the input below.

$$\begin{aligned} > f := x \rightarrow x^3 + 4 \cdot x - 7 \\ f &:= x \mapsto x^3 + 4x - 7 \end{aligned} \tag{0.1}$$

Contrast that with the following in 1-D input mode.

$$\begin{aligned} > f := x -> x^3 + 4*x - 7; \\ f &:= x \mapsto x^3 + 4x - 7 \end{aligned} \tag{0.2}$$

Do not worry about what these commands do right now. The point is that their output is exactly the same. And, in fact, they are entered in nearly the same way. The only significant differences are the semicolon and the fact that when entering the command in 2-D mode, you need to press the right



arrow key after entering the 3 to exit the exponent. We also added spaces to make the 1-D input a bit more readable, but they are unnecessary.

In this manual, input is almost always given in 2-D mode, but entered entirely from the keyboard. On those few occasions where Maple's automatic transformation of 2-D input obscures how to enter the command, it is provided in 1-D mode. That said, you can have Maple translate from 2-D mode to 1-D mode for you. Right-click on a 2-D input and in the pop-up menu, select the **2-D Math** menu, then the **Convert To** submenu and then choose **1-D Math Input**. If you do that to the 2-D command above, you will get a bit more than you bargained for, as the conversion will also reveals what the arrow is a shorthand for.

In traditional Maple notation, complete commands end in semicolons (;) or colons (:). In 2-D input mode, these are not usually required, unless you are entering a sequence of commands in the same input. More will be said about the use of semicolons and colons below, but know that including a semicolon at the end of a command will not produce an error so you can safely include one if you are unsure.

### *Executing Commands*

To execute a command, make sure that the cursor is somewhere on the line containing the command and press the Enter or Return key to execute the command and display the result. It is time to execute your first Maple command. Let us start simple and add two plus three. To do this, make sure your cursor is on a command line and type **2+3** and then press Enter or Return.

$$\begin{array}{l} > \text{2 + 3} \\ \quad \quad 5 \end{array} \qquad (0.3)$$

Here are a few more commands. Try entering them on your computer.

$$\begin{array}{l} > \text{add}(i^2, i = 1..10) \\ \quad \quad 385 \end{array} \qquad (0.4)$$

$$\begin{array}{l} > \text{int}((x-1)^3, x) \\ \quad \quad \frac{(x-1)^4}{4} \end{array} \qquad (0.5)$$

$$\begin{array}{l} > \text{expand}(\%) \\ \quad \quad \frac{1}{4}x^4 - x^3 + \frac{3}{2}x^2 - x + \frac{1}{4} \end{array} \qquad (0.6)$$

The percent symbol (%) is used to refer to the result of the most recently executed statement. The percent does not always refer to the value immediately above it, as commands can be executed out of order.

In addition, the line numbers that automatically appear next to the results can be used in commands to refer to specific results. To use a result, it is not enough to type (0.5) in a statement. Instead, you must select **Label...** from the **Insert** menu and enter the number of the label in the dialog box that opens. You can also use the shortcut Control+L (or Command+L on a Mac) to open the dialog. If equation numbers are not appearing when you execute commands, you should turn them

on. In the **Tools** menu, select **Options** (or **Preferences** from the **Maple** menu on a Mac). On the **Display** tab, make sure that the **Show Equation Labels** box is checked.

Try entering the following command.

$$\begin{array}{l} > \text{subs}(x = 3, (0.5)) \\ 4 \end{array} \quad (0.7)$$

## A First Encounter with Maple

As already indicated, working with Maple is like working with an expert mathematical assistant. This requires a subtle change in the way you think about a problem. When working on an exercise by hand, your attention is focused on the details and quite often you can lose sight of the “big picture.” Maple takes care of the details for you and frees you to focus on deciding what needs to be done next. This is not to say that the details are not important nor does it imply that you should forgo learning how to solve the problems by hand.

Much of discrete mathematics is about understanding the relationships between objects or sets of objects and using mathematical models to capture some property of these objects. Understanding these relationships often requires that you view either the objects or the associated mathematical model in different ways.

Maple allows you to manipulate the mathematical models almost casually. For example, the polynomial  $(x + (x + z)y)^3$  can be entered into Maple as:

$$\begin{array}{l} > (x + (x + z) \cdot y)^3 \\ (x + (x + z)y)^3 \end{array} \quad (0.8)$$

The result of executing this statement is displayed immediately. In this case, Maple simply echoes the polynomial as no special computations were requested.

The power of having a computational tool like Maple is that a wide range of standard operations become immediately available. For example, you can expand, differentiate, and integrate just by telling Maple to do so. Suppose you decided that it would be useful to see the full expansion of the polynomial above. All you need to do is issue the appropriate command to Maple. In this case, the command you would want is the **expand** command, which tells Maple to expand the polynomial.

$$\begin{array}{l} > \text{expand}(\%) \\ x^3y^3 + 3x^2y^3z + 3xy^3z^2 + y^3z^3 + 3x^3y^2 + 6x^2y^2z + 3xy^2z^2 + \\ 3x^3y + 3x^2yz + x^3 \end{array} \quad (0.9)$$

(Recall that Maple uses the percent sign (%) to refer to the output from the previous command.)

Perhaps you decide it would be useful to look at this as a polynomial in the variable  $x$ , with the variables  $y$  and  $z$  placed in the coefficients of  $x$ . Then, you would use the **collect** command.

$$\begin{array}{l} > \text{collect}(\%, x) \\ (y^3 + 3y^2 + 3y + 1)x^3 + (3y^3z + 6y^2z + 3yz)x^2 + \\ (3y^3z^2 + 3y^2z^2)x + y^3z^3 \end{array} \quad (0.10)$$

To return to a factored form, simply ask Maple to **factor** the previous result.

```
> factor(%)  
(yx + yz + x)3 (0.11)
```

We used several commands without explanation in the above. Rest assured that in the body of this manual we will always provide detailed explanations of the usage and syntax of new commands when we first encounter them. The purpose of the last several paragraphs was not to introduce the commands, but to illustrate how easy it is to quickly move between different representations of the same object. Having these kinds of routine tasks performed quickly and accurately means that you are freer to experiment and explore.

A second very important benefit is that the particular computations that you choose to have Maple execute are performed accurately. Thus, the results you get from your experiments are much more likely to be feedback on the model you had chosen rather than nonsense arising from arithmetic errors.

Finally, the sheer computational power of Maple allows you to run much more extensive experiments and many more of them. This can be important when trying to establish or identify a relationship between a mathematical model and a collection of discrete objects.

It is worth making some comments about terminology and syntax. First, in this manual, we will use the term *command* to refer to **expand**, **collect**, **factor**, and the like. Maple's help documents refer to them as commands or functions, but we will avoid the use of function because of its mathematical meaning. Maple commands will appear in the red Maple notation font and will be underlined indicating that it links to the Maple help documents. On the other hand, programs that we write will be referred to as procedures.

Second, when you use a command on one or more objects, the objects are referred to as arguments. To execute a command, you type its name followed by a pair of parentheses. Inside the parentheses you list the arguments, separated by commas.

```
> max(9, 2, 12, 14, 7, 11)  
14 (0.12)
```

Even commands that do not need any arguments require the parentheses. For example, the **time** command returns the total amount of computer time that the current Maple session has used.

```
> time()  
3.894 (0.13)
```

## The Basics

This section and the next are devoted to introducing you to the most essential Maple commands and concepts that will be used throughout this manual. Some of this material will be repeated, often in more depth, in the first few chapters when the topics arise naturally in conjunction with the content of the textbook. This section is focused on basic commands and the next focuses on programming.

## Help

The most important command is the help command. Maple includes extensive documentation on all of its commands, including examples of the how the command is used. There are two primary ways to access Maple's help documents. First, you can select **Maple Help** from the **Help** menu or click on the circled question mark in the toolbar. The Maple Help window will open and from there you can browse the table of contents or search for the topic or command you are interested in.

The more typical way to access Maple's help pages is by entering a question mark (?) on a command line. For example, if you need to know the command for computing the square root of a number, you could enter the following.

> ?square root

The Help window will open to the help page for the **sqrt** command, which computes the principle square root of a number or an algebraic expression. Note that you do not need to know the name of the command you are looking for help on. Following the ? with "square root" finds the **sqrt** command. You should try to make your query as simple as possible, though. Often, taking a guess at the name of the command works well. Remember that when commands are discussed in this manual, they appear in red and underlined. These are links to the Maple help documents and clicking on them will open the relevant help page.

Each help page on a Maple command provides several examples of how to use that command. Open the **sqrt** help page now and take a look. If you wish, you can open help pages as interactive worksheets. To do this, from the help system's **View** menu, select **Open Page as Worksheet**, or click on the next-to-last icon on the help system toolbar.

## Arithmetic

Maple uses the typical notation for arithmetic. For addition and subtraction, Maples uses **+** and **-** just as you would expect. The **-** symbol is used for negation as well. Multiplication and division are performed with **\*** and **/**, and **^** is used for exponentiation. Note that in 2-D input mode, typing the caret or slash will move the cursor to an exponent or denominator position and you will need to use the right-arrow key to input the next part of the expression.

Maple obeys the usual order of precedence for arithmetic operators, and parentheses serve as grouping symbols. However, brackets, braces, and angle brackets all have different meanings in Maple and cannot be used as grouping symbols in arithmetic expressions. Therefore, to compute the expression

$$7 + 2 \cdot \left[ 5 - \left( \frac{2}{3} \pi \right)^2 \right],$$

you would enter the following, using **Pi** for  $\pi$  and parentheses in place of the brackets.

$$\begin{aligned} > 7 + 2 \cdot \left( 5 - \left( \frac{2}{3} \text{Pi} \right)^2 \right) \\ 17 - \frac{8 \pi^2}{9} \end{aligned} \tag{0.14}$$

In 1-D mode, this looks like:

$$\begin{aligned} &> 7+2*(5-(2/3*Pi)^2); \\ &17 - \frac{8\pi^2}{9} \end{aligned} \tag{0.15}$$

Notice that Maple automatically simplifies the expression, but as an exact value in terms of  $\pi$ . If you prefer a decimal approximation, you can use the **evalf** command (for evaluate floating-point). This command takes one argument, an expression, and evaluates it with floating-point arithmetic.

$$\begin{aligned} &> \text{evalf}(\%) \\ &8.227018307 \end{aligned} \tag{0.16}$$

By default, **evalf** computes with 10 significant figures. If you prefer more or fewer significant digits, you can specify the number of digits to use as shown below.

$$\begin{aligned} &> \text{evalf}[3]((0.14)) \\ &8.23 \end{aligned} \tag{0.17}$$

$$\begin{aligned} &> \text{evalf}[15]((0.14)) \\ &8.22701831014281 \end{aligned} \tag{0.18}$$

Recall that the **%** symbol is used to refer to the previous computation and references to specific output lines can be inserted by clicking on the **Label** item in the **Insert** menu or with the shortcut **Ctrl+L** (**Command+L** on a Mac).

Maple considers integers, fractions, and floating-point numbers to be different and it works with them differently. In expression (0.14), we used only integers and the constant **Pi**. If we had used a floating-point number, Maple would have computed with floating-point arithmetic.

$$\begin{aligned} &> \frac{2}{3} + \frac{3.1}{2} \\ &2.216666667 \end{aligned} \tag{0.19}$$

The presence of 3.1 caused Maple to evaluate the entire expression with floating-point arithmetic. You can use this fact to cause Maple to evaluate with floating-point arithmetic even when only integers are involved. Mathematically, there is no difference between 3 and 3.0. Maple treats them differently, however.

$$\begin{aligned} &> \frac{3}{5} \\ &\frac{3}{5} \end{aligned} \tag{0.20}$$

$$\begin{aligned} &> \frac{3.0}{5} \\ &0.6000000000 \end{aligned} \tag{0.21}$$

In fact, the trailing 0 is not required.

$$\begin{array}{ll} > \frac{3.}{5} \\ & 0.6000000000 \end{array} \quad (0.22)$$

This discussion illustrates the concept of a *type*. A computer can be much more efficient if it knows what kinds of things it will be working with. If the computer knows that one object is going to be a floating-point number while another is going to be a string, it will allocate memory differently for the two objects, for instance.

Types also allows programs such as Maple and programming languages to make use of operator overloading. This means that the symbol  $+$  means one thing when applied to two integers, something else when applied to floating-point numbers, and something completely different when applied to matrices. The concept of type is what makes it possible for Maple to figure out which version of  $+$  is called for at the time. Maple recognizes over 200 different predefined types and users are free to create more. We will see much more of types as we go forward.

### ***Names, Assignment, and Equality***

In mathematics, we talk about variables as symbols that stand in for something else. In Maple, this role is filled by *names*. The simplest definition of a name in Maple is that a name must begin with a letter and may be followed by letters, digits, or the underscore character. The following are all valid Maple names: **evalf**, **name**, **x**, **a15**, **B\_5x\_**.

Names can be used as a variable in an algebraic expression as in the following.

$$\begin{array}{ll} > 3x^2 + 5x - 7 \\ & 3x^2 + 5x - 7 \end{array} \quad (0.23)$$

Names can also be used to store particular values using the assignment operator. The assignment operator consists of a colon followed by an equals sign ( $:=$ ). To assign a value to a name, you begin with the name, followed by the assignment operator and then the expression that you want stored in the name. For example, to assign the value 12 to the name **twelve**, you type the statement below.

$$\begin{array}{ll} > \text{twelve} := 12 \\ & \text{twelve} := 12 \end{array} \quad (0.24)$$

When a value or other object has been assigned to a name, then any time that name appears in a statement, it is “resolved” to the expression stored in it.

$$\begin{array}{ll} > \text{twelve} + 5x \\ & 12 + 5x \end{array} \quad (0.25)$$

When Maple encounters an assignment statement, it first evaluates the right-hand side of the statement and then makes the assignment. You can use this fact to modify values as follows.

$$\begin{array}{ll} > \text{twelve} := 2 \cdot \text{twelve} + 1 \\ & \text{twelve} := 25 \end{array} \quad (0.26)$$

In the statement above, the right-hand side is evaluated first, meaning that the **twelve** on the right is resolved to its “old” value of 12. Maple then computes  $2 \cdot 12 + 1 = 25$  and assigns the value 25 to the name **twelve**, overwriting the value stored earlier.

In Maple parlance, **twelve** is referred to an assigned name, as opposed to an unassigned name. An assigned name, that is a name that has been assigned a value, can be used as an unassigned name by enclosing it in right single quotes. For example,

$$\begin{array}{ll} > 2 \cdot 'twelve' + 5x \\ & 2 \text{ twelve} + 5x \end{array} \quad (0.27)$$

Right single quotes are used by Maple to delay evaluation of whatever expression they enclose. One important use of this is to unassign a name, as shown below.

$$\begin{array}{ll} > \text{twelve} := 'twelve' \\ & \text{twelve} := \text{twelve} \end{array} \quad (0.28)$$

After this statement, **twelve** is no longer assigned a value.

$$\begin{array}{ll} > \text{twelve} \\ & \text{twelve} \end{array} \quad (0.29)$$

It is important to note that Maple distinguishes between the right and left single quote.

Practically any expression can be assigned to a name, not just numbers. For example, we can assign the algebraic expression  $2y + 5x$  to the name **f**.

$$\begin{array}{ll} > f := 2y + 5x \\ & f := 2y + 5x \end{array} \quad (0.30)$$

Now, every time **f** appears in a statement, it is resolved to this expression.

$$\begin{array}{ll} > \text{sqrt}(f) \\ & \sqrt{2y + 5x} \end{array} \quad (0.31)$$

Even an equation can be assigned to a name.

$$\begin{array}{ll} > \text{eqn} := F = \frac{9}{5}C + 32 \\ & \text{eqn} := F = \frac{9C}{5} + 32 \end{array} \quad (0.32)$$

Observe in the last example the different uses of the assignment operator and the equals sign. Some programming languages use the equals sign for assignment, but Maple reserves the equals sign for mathematical equality. The previous statement assigns the name **eqn** to the mathematical equation  $F = \frac{9}{5}C + 32$ . Since Maple understands this to be an equation, we can, for instance, solve

it. Given an equation and a name appearing in the equation, the **solve** command solves the equation for the given name. Therefore, we can solve for  $C$  as follows.

$$\begin{aligned} &> \text{solve}(\text{eqn}, C) \\ &\quad -\frac{160}{9} + \frac{5F}{9} \end{aligned} \tag{0.33}$$

When you execute the statement above, Maple first resolves **eqn** to the equation  $F = \frac{9}{5}C + 32$ . It also attempts to resolve **C**, but **C** is an unassigned name. (If **C** were not unassigned, an error would result.) Once the arguments have been evaluated, Maple applies the **solve** command to them.

## Basic Types

We mentioned above that Maple recognizes many different types of objects. In this subsection, we will discuss some of the most fundamental types. We will not go into all the details of what it means to be a type in Maple. Our goal in this section is to introduce you to the kinds of objects you will be using and the use of the **type** command.

We have already seen numeric types, such as integers, fractions, and floating-point numbers. Maple has a host of names for numeric types, such as **integer**, **fraction**, **float**, **posint**, **realcons**, and **imaginary**, to name a few.

You can test whether a Maple expression is of a specific type by using the **type** command. This command requires two arguments. The first is the expression you want to test and the second is the type. For example, to see whether or not 2 is a positive integer, a fraction, and a float, you enter the following statements.

$$\begin{aligned} &> \text{type}(2, \text{posint}) \\ &\quad \text{true} \end{aligned} \tag{0.34}$$

$$\begin{aligned} &> \text{type}(2, \text{fraction}) \\ &\quad \text{false} \end{aligned} \tag{0.35}$$

$$\begin{aligned} &> \text{type}(2, \text{float}) \\ &\quad \text{false} \end{aligned} \tag{0.36}$$

In addition to numeric types, Maple has a **string** type for strings of characters. You form a string by enclosing any sequence of characters within a pair of double quotes. For example, Einstein wrote:

$$\begin{aligned} &> \text{quotation} := \text{"Pure mathematics is, in its way, the poetry of logical ideas."} \\ &\quad \text{quotation} := \text{"Pure mathematics is, in its way, the poetry of logical ideas."} \end{aligned} \tag{0.37}$$

Strings may be combined with the concatenation operator, **||**, or with the command **cat**, as demonstrated below.

$$\begin{aligned} &> \text{cat}(\text{quotation}, \text{" - Einstein"}) \\ &\quad \text{"Pure mathematics is, in its way, the poetry of logical ideas. - Einstein"} \end{aligned} \tag{0.38}$$

$$\begin{aligned} &> \text{"abc"} || \text{"def"} \\ &\quad \text{"abcdef"} \end{aligned} \tag{0.39}$$



You can ask Maple what the type of an object is with the **whattype** command. Since many objects satisfy the definitions of multiple types, this command returns the object's basic type.

```
> whattype(2)
integer
```

(0.40)

We will see why types are important in the next section when we discuss basic programming concepts.

### ***Expression Sequences***

An expression sequence, or simply sequence, is the fundamental Maple data structure. An expression sequence is formed using commas to separate expressions. For example, the following assigns the expression sequence 7, 8, 9, 10, 11 to the name **S**.

```
> S := 7, 8, 9, 10, 11
S := 7, 8, 9, 10, 11
```

(0.41)

To lengthen a sequence, you use a comma.

```
> S := S, 12
S := 7, 8, 9, 10, 11, 12
```

(0.42)

### **Selection**

The *selection operation* is used to access members of a sequence and subsequences. The first element of the sequence can be obtained by typing the name assigned to the sequence followed by a pair of brackets enclosing the number 1.

```
> S[1]
7
```

(0.43)

You would use 2 to obtain the second element, 3 for the third, and so on.

```
> S[2]
8
```

(0.44)

```
> S[3]
9
```

(0.45)

You may also use negative integers to count from the right. Therefore,  $-1$  refers to the last element of the sequence,  $-2$  to the next to last, and so on.

```
> S[-1]
12
```

(0.46)

```
> S[-2]
11
```

(0.47)

Any expression can be placed inside the brackets, provided it evaluates to an integer that is not 0 and does not exceed the bounds of the sequence (for example, 7 or higher and  $-7$  or lower, in this case).

$$\begin{array}{l} > S[2 \cdot 3 - 2^2] \\ 8 \end{array} \quad (0.48)$$

### Ranges

A **range** is a Maple type consisting of two expressions connected by two periods. A common use of a range is in conjunction with the selection operation to extract a subsequence from a sequence. For example, to extract the subsequence consisting of the third through the fifth elements of  $S$ , you use the range **3..5** within the brackets.

$$\begin{array}{l} > S[3..5] \\ 9, 10, 11 \end{array} \quad (0.49)$$

$$\begin{array}{l} > S[-5..-3] \\ 8, 9, 10 \end{array} \quad (0.50)$$

Note that the left side of the range must be less than or equal to the right side. However, either or both sides may be omitted. If both are omitted, it is interpreted as the entire sequence.

$$\begin{array}{l} > S[..] \\ 7, 8, 9, 10, 11, 12 \end{array} \quad (0.51)$$

If only one side is given, it is interpreted either as the sequence from the given location onwards,

$$\begin{array}{l} > S[3..] \\ 9, 10, 11, 12 \end{array} \quad (0.52)$$

or as the sequence up to the given location.

$$\begin{array}{l} > S[..5] \\ 7, 8, 9, 10, 11 \end{array} \quad (0.53)$$

### The seq Command and Final Comments about Sequences

The **seq** command is often used to create sequences using a formula. Here we only discuss the most typical way to use **seq**. The command will be discussed more thoroughly in Section 2.4 of this manual.

You should first choose a name, which is referred to as the index variable. The letter **i** is a typical choice. In the simplest form, **seq** requires two arguments. The first argument is any expression, typically one that involves the index variable in its computation. The second argument is an equation with the index variable on the left-hand side and a range on the right-hand side, for example, **i=3..7**. The result of executing the **seq** command is the sequence obtained by evaluating the first argument at each value of the index variable determined by the range in the second argument. For example, we can obtain the squares of the integers between 5 and 11 as follows.

$$\begin{array}{l} > seq(i^2, i = 5..11) \\ 25, 36, 49, 64, 81, 100, 121 \end{array} \quad (0.54)$$

Expression sequences are an important Maple data structure and form the basis for several types including lists and sets, to be discussed below. However, you should be aware that sequences generally cannot be given as the argument to a command or procedure. To understand why, suppose that **ACommand** were a command that accepted only one argument. If you try to execute this command with a sequence, such as **S**, as the argument, Maple first resolves the expression sequence.

```
> ACommand(S)
      ACommand(7, 8, 9, 10, 11, 12) (0.55)
```

It looks to Maple like you were passing six arguments to **ACommand** instead of one. That would generate an error if **ACommand** were actually a command. In order to pass a collection of values to a procedure or command, they must be enclosed in a list or a set.

Finally, the empty expression sequence is referred to as **NULL**. A command that results in **NULL** displays no output.

```
> NULL
```

## Lists

In Maple, a list is an ordered sequence of expressions. The name of the type in Maple is **list**. You create a list by enclosing an expression sequence, that is, values separated by commas, in brackets.

```
> L := [6, 7, 8, 9, 10, 11]
      L := [6, 7, 8, 9, 10, 11] (0.56)
```

Note that the **seq** command can be used to create a list by enclosing it in brackets. Maple computes the sequence and then forms the list based on that sequence.

```
> L2 := [seq(4 i + 3, i = 1 .. 10)]
      L2 := [7, 11, 15, 19, 23, 27, 31, 35, 39, 43] (0.57)
```

At first glance, it may appear that the only difference between a list and the expression sequence that defines it is the brackets. Conceptually, the actual difference is that a list can be thought of as a single object. Therefore, unlike a sequence, a list can be passed as an argument to a procedure or command.

## Selection

Selection works essentially the same with lists as with sequences. To access a single element of the list, you follow the name of the list with a pair of brackets containing the integer indicating the position of the element. Remember that the first element is 1 and that negative numbers count from the end.

```
> L2[3]
      15 (0.58)
```

```
> L2[-2]
      39 (0.59)
```

As with sequences, you can select a range as well. The difference is that when used with a list, the result will be a list.

```
> L2[3 .. - 2]
[15, 19, 23, 27, 31, 35, 39] (0.60)
```

### The **op** Command

It is sometimes necessary to extract the underlying sequence from a list. This can be done with the **op** (short for operands) command. The most basic form of the **op** command takes one argument, which can be any expression. For lists, this will return the sequence of elements in the list.

```
> op(L2)
7, 11, 15, 19, 23, 27, 31, 35, 39, 43 (0.61)
```

The **op** command can also accept either an integer or a range as its first argument with the list as the second. In this case, it behaves similar to selection, except **op** returns a sequence while selection returns a list.

```
> op(5, L2)
23 (0.62)
```

```
> op(..5, L2)
7, 11, 15, 19, 23 (0.63)
```

With objects other than lists, **op** has a slightly different behavior. For example, for polynomials, **op** will extract the terms.

```
> op(3x2 - 5x + 7)
3x2, -5x, 7 (0.64)
```

We will discuss other uses of **op** in later chapters as they are needed.

Related to **op** is the **nops** (number of operands) command. For lists, **nops** returns the number of elements in the list.

```
> nops(L)
6 (0.65)
```

```
> nops(L2)
10 (0.66)
```

We saw that extending a sequence is just a matter of using a comma to continue the sequence. Adding elements to a list is a bit more complicated. Suppose you want to add 47 to the end of **L2**. To do this, you use **op** to extract the sequence of elements from **L2**. Then, add 47 to the sequence with a comma. Turn the extended sequence back into a list by surrounding it with brackets. Finally, reassign the result to the name **L2**.

```
> L2 := [op(L2), 47]
L2 := [7, 11, 15, 19, 23, 27, 31, 35, 39, 43, 47] (0.67)
```

Adding to the beginning of the list is done in essentially the same way.

$$\begin{aligned} &> L2 := [3, op(L2)] \\ &L2 := [3, 7, 11, 15, 19, 23, 27, 31, 35, 39, 43, 47] \end{aligned} \quad (0.68)$$

If you want to insert an element in the middle of a list, say after the 5th member of **L2**, you would use **op** with ranges in order to separate the front and back ends of the existing list as follows.

$$\begin{aligned} &> L2 := [op(..5, L2), 21, op(6 .., L2)] \\ &L2 := [3, 7, 11, 15, 19, 21, 23, 27, 31, 35, 39, 43, 47] \end{aligned} \quad (0.69)$$

### The map Command

We discuss one last command related to lists: the **map** command. This command requires two arguments. The first argument is the name of a command or procedure. The second argument is a list. (Technically, the second argument can be any expression, but we will typically use **map** with a list as the second argument.) The result is the list obtained by applying the command to each element of the list. For example, the statement below produces the list of square roots of the given list.

$$\begin{aligned} &> map(sqrt, [3, 6, 9]) \\ &[\sqrt{3}, \sqrt{6}, 3] \end{aligned} \quad (0.70)$$

Note that when **map** is applied to a name that has been assigned to a list, the named list is not modified.

$$\begin{aligned} &> map(sqrt, L) \\ &[\sqrt{6}, \sqrt{7}, 2\sqrt{2}, 3, \sqrt{10}, \sqrt{11}] \end{aligned} \quad (0.71)$$

$$\begin{aligned} &> L \\ &[6, 7, 8, 9, 10, 11] \end{aligned} \quad (0.72)$$

If you want the original list to be updated, you should reassign it.

$$\begin{aligned} &> L := map(sqrt, L) \\ &L := [\sqrt{6}, \sqrt{7}, 2\sqrt{2}, 3, \sqrt{10}, \sqrt{11}] \end{aligned} \quad (0.73)$$

$$\begin{aligned} &> L \\ &[\sqrt{6}, \sqrt{7}, 2\sqrt{2}, 3, \sqrt{10}, \sqrt{11}] \end{aligned} \quad (0.74)$$

Note that it is typical for Maple commands to *not* modify their arguments.

For commands that require more than one argument, **map** can accept optional arguments following the list that are then passed to the command. There are also variants such as **map2** and **zip**. The use of additional arguments and these other commands will be discussed as they are needed.

### Sets

In mathematics, a set is a collection of objects that is unordered and without repetition. Maple's **set** type models the mathematical notion. To form a set, you enclose a sequence in braces.

```
> {1,2,3}
      {1,2,3}
(0.75)
```

```
> S := {seq(i^2,i = 1..10)}
      S := {1,4,9,16,25,36,49,64,81,100}
(0.76)
```

Note that repeated elements in a set are automatically removed by Maple.

```
> {1,2,3,2,1}
      {1,2,3}
(0.77)
```

This is a useful feature that we will make use of quite often to avoid redundancy.

The **op** command works on sets in the same way as lists to return the sequence that underlies the set, and the **nops** command applied to a set returns the number of elements.

```
> op(S)
      1, 4, 9, 16, 25, 36, 49, 64, 81, 100
(0.78)
```

```
> nops(S)
      10
(0.79)
```

Note that, while sets are technically unordered, Maple actually imposes an order on them. This is done to improve efficiency. Rest assured that the implementation of sets and the commands related to them is done in such a way as to ensure that they behave as mathematical sets should. However, selection works with sets in the same way as lists, as does the **op** command with an integer or range as the first argument.

```
> S[3..7]
      {9,16,25,36,49}
(0.80)
```

```
> op(7,S)
      49
(0.81)
```

Sets will be explored in more detail in Chapter 2.

## Printing

There are three main ways to have Maple display the result of a computation. First, of course, is to execute a command that displays a result.

```
> 2 + 3
      5
(0.82)
```

On the other hand, sometimes you may wish for a result to not be displayed. In this case, you end the statement with a colon instead of a semicolon.

```
> 2 + 3:
```

The second way to get Maple to display information is the **print** command. This is often used within a procedure to display the results of intermediate calculations before the final result is computed and displayed. The **print** command accepts as its input a sequence of expressions and displays them on a line. For example,

```
> print(L)
[ $\sqrt{6}$ ,  $\sqrt{7}$ ,  $2\sqrt{2}$ , 3,  $\sqrt{10}$ ,  $\sqrt{11}$ ] (0.83)
```

```
> print(S, L2)
{1, 4, 9, 16, 25, 36, 49, 64, 81, 100}, [3, 7, 11, 15, 19, 21, 23, 27, 31, 35, 39, 43, 47] (0.84)
```

The third way to have Maple display output is **printf**. (There are three related commands that work in similar ways with slightly different purposes, but we will only discuss **printf**.)

The purpose of **printf** is to print expressions using a particular format (hence the f) that you specify. The first argument to the command is a string that details the format in which the information is to be displayed. The remaining arguments are the information to be displayed. Here is an example of using **printf** to display a number and its square with each number displayed with room for at least 5 digits.

```
> printf("The square of %5a is %5a.\n", 7, 7^2)
The square of 7 is 49.
```

The **%** symbol is used to indicate the beginning of the formatting specification **%5a**. The 5, which is optional, specifies that the width of that field is to be at least 5 characters. This is a useful option for displaying a table or otherwise ensuring that displayed values are aligned. Finally, the **a**, for anything, tells Maple to display the corresponding object in whatever format it normally would. Other letters can be used that are specific to different types of objects to display, such as integers and strings. The **\n** at the end of the formatting string indicates that a new line should be inserted at that point. Following the formatting string, are the two values **7** and **7<sup>2</sup>**. Notice that the first value is put in place of the first formatting specification (the first **%5a**) and the second goes in place of the second.

The **printf** command is very flexible with a great many options. The interested reader should refer to the Maple help page for further information. In this manual, we will use **printf** rarely and we will not discuss it further here.

## Programming Preliminaries

This section is intended for those readers who have little or no previous exposure to programming. We will endeavor to provide you with enough information to get you started so that you can work productively with Maple. For further information, you are encouraged to consult the Maple manuals, which will provide you with further examples of the use of Maple's programming facilities.

All programming languages provide a few basic means for the construction of algorithms. On the most basic level, a computer program is a sequence of instructions that the computer executes one after the other. Programs become more sophisticated when you start changing the flow of execution. Maple provides the same sort of mechanisms for flow control as is found in traditional programming

languages such as C. While the syntax varies from one computer language to the next, there are two primary kinds of control structures used: branching and iteration.

## ***Branching***

We will first discuss the concept of branching and its implementation in Maple. Branching is a mechanism that allows you to choose between statements based on conditions that can only be determined during a program's execution. This is also called a selection or conditional statement.

### **if-then**

As an example, suppose that you want to display a message based on whether a particular value is positive. First, we assign a value to the name **z**.

```
> z := 5  
z := 5 (0.85)
```

The following code will display the message "That's positive" if the value stored in **z** is greater than zero.

```
> if z > 0 then  
    print("That's positive")  
end if  
"That's positive" (0.86)
```

Note that, in order to begin a new line within a single command prompt, you press Shift+Enter or Shift+Return. The line breaks and extra spaces are not required, in fact Maple ignores them, but they often make programs easier to read and understand.

Typically, the condition in an if statement depends on a value input to a program or some intermediary calculation or a value that changes during the execution of a procedure. In these examples, think about the name **z** as storing some value that varies based on some other computations. For instance, **z** could be the value of some function at a particular point. Then, the value of **z** would depend on which point was chosen.

Let us dissect the code above. The if statement begins with the keyword **if**. This is immediately followed by a conditional expression, that is, an expression that Maple can evaluate to true or false. Conditional expressions may include expressions that include relational operators (**<**, **<=**, **=**, **>**, **>=**, **<>**), logical operators (**and**, **or**, **not**), or procedures and commands that return logical values (**true**, **false**, or **FAIL**). We will see many examples of conditional expressions in Chapter 1. Note that the nonstrict inequalities and not-equals are automatically transformed to the symbols  $\leq$ ,  $\geq$ , and  $\neq$  in 2-D input mode.

Following the conditional expression, you must include the keyword **then**. Following the **then** keyword is a statement sequence, one or more statements that are to be executed in the event that the conditional expression is true. In our example above, the **then** keyword was followed by the statement sequence consisting of a single statement, the **print** command.

Finally, the phrase **end if** is used to indicate the end of the conditional statement.

When you execute the statement above, Maple evaluates the conditional expression **z > 0**. Since this is a true statement (because **z** happened to be 5), Maple executes the **print** command in the



statement sequence following the **then** keyword. If the conditional expression had been found to be false, then Maple would not execute the **print** command.

Below is another example, in which the conditional statement is false.

```
> if  $z \geq 10$  then
    print("That has at least two digits")
end if
```

Notice that in this case, nothing is displayed. Once Maple determines that the condition is false, it skips past the statement sequence following the **then** keyword.

### else

Often, you will want to take one action if a condition is true and a different action if a condition is false. The **else** keyword allows you to extend a conditional statement to contain a second statement sequence to be executed if the condition is false.

```
> if  $z < 0$  then
    print("It's negative")
else
    print("It's not negative")
end if
    "It's not negative" (0.87)
```

The **then** keyword separates the conditional expression from the statement sequence that is executed when the condition is true. The **else** keyword indicates the beginning of the statement sequence that is to be executed when the condition is not true.

In the example, Maple first tests to see if  $z < 0$ . Since this is false, Maple skips to the **else** clause and executes the second **print** command.

### elif

You can also extend the if statement to a multiway branching structure for when there are more than two options. To do this, you use the **elif** keyword to introduce additional conditions that may be true when the initial **if** condition fails.

```
> if  $z \geq 10$  then
    print("That has at least two digits")
elif  $z > 0$  then
    print("It's positive")
elif  $z \geq 0$  then
    print("It's zero")
else
    print("It's negative")
end if
    "It's positive" (0.88)
```

The statement above works as follows. First, Maple checks the condition  $z \geq 10$ . If this were true, it would execute the first **print** statement. However, since it is false, Maple moves on to the

first **elif** condition,  $z > 0$ . This condition is true, so Maple executes the **print**("It's positive.") command.

Look at the next condition:  $z \geq 0$ . This condition is also true, but Maple does not execute the corresponding **print** command. In an **if-elif-else** structure, once the first conditional expression is found to be true, the statement sequence following that condition is executed and any conditions that follow the first are skipped. Likewise, the **else** statement sequence is only executed in case all the conditional expressions were false. In other words, only one of the statement sequences is ever executed.

That is why we can say that the number is 0 if the test  $z \geq 0$  is true. This condition is only checked if all the previous conditions failed. Thus, if the  $z \geq 0$  test is evaluated true, we know that  $z > 0$  was false, and hence  $z$  is 0.

## Iteration

The previous subsection showed how to use branching in Maple to execute different blocks of code depending on whether or not a specified condition was met. In this subsection, we look at ways to repeat a block of code. Iteration is the mechanism for doing a given task repeatedly and is typically accomplished by a loop structure.

### for Loops

The most common type of iteration is the **for** loop. The most basic kind of for loop executes a statement for each integer in a particular range. The example below computes the squares of the integers from 3 to 5.

```
> for i from 3 to 5 do
    i^2
end do
9
16
25
```

(0.89)

The statement begins with the **for** keyword, indicating the type of loop. After the **for** keyword is a variable name, called the loop variable. The letter **i** is a typical choice. Then, the **from** keyword is followed by the initial value of the loop variable. The **to** keyword is followed by the maximum value for the loop. After that, the **do** keyword precedes the body of the loop, which is terminated by the **end do** phrase.

The statement(s) in between **do** and **end do** form the body of the loop. That is, those are the statements that are executed repeatedly. When Maple executes this loop, here is what happens. First, Maple assigns the starting value, specified by the **from** clause, to the loop variable **i**. Then, the statement sequence is executed and the loop variable is squared. Once the statement sequence is completed, Maple increments the loop variable by 1 and checks to see whether its new value exceeds the value specified by the **to** clause. If not, the statement sequence is executed again with the new value of the loop variable before incrementing it again. Once the loop variable exceeds the maximum value, the loop terminates.

In other words, **i** is assigned to **3**, and  $3^2$  is computed. Then **i** is incremented to **4** and  $4^2$  is computed. Then **i** is incremented to **5** and  $5^2$  is computed. Then **i** is incremented to **6**, which exceeds the maximum so the loop ends.

There is actually an extra step that we did not mention. Immediately after assigning the starting value to the loop variable, the loop variable is tested against the maximum value. This means that it is possible to create loops that never execute their statement sequence.

```
> for i from 7 to 2 do  
    print("Execute")  
end do
```

Maple also includes the option for a **by** clause if you would like to increment the loop variable by a value other than 1.

```
> for i from 3 by 2 to 11 do  
     $i^2$   
end do
```

9

25

49

81

121

(0.90)

In this example, the **by 2** clause indicates that the loop variable is incremented by 2. The value 2 is referred to as the *step*.

The **by** clause also provides a way to loop from high to low by using a negative step.

```
> for i from 10 by - 1 to 5 do  
     $i^2$   
end do
```

100

81

64

49

36

25

(0.91)

Any of the clauses shown above can be omitted, under certain circumstances. If the **from** clause is omitted, Maple will assume the starting value is 1. If the **to** clause is omitted, the loop will execute forever, unless interrupted by another command. (You should take great care to avoid so-called infinite loops unless it is what you intend, and even then, save your work before executing the loop!) If the loop variable is not actually needed as part of the statement sequence, then the **for** clause can be omitted. For example, the following prints "Hello world" three times.

```
> to 3 do  
    print("Hello world")  
end do
```

"Hello world"

"Hello world"

"Hello world"

(0.92)

## while Loops

Somewhat more general than a **for** loop is the **while** loop, which is another method for iteration available in Maple. In a while loop, execution continues as long as a conditional statement remains true.

```
> i := 2 :  
  while i < 107 do  
    print(i);  
    i := i2 + 2  
  end do :  
  2  
  6  
  38  
  1446  
  2090918
```

(0.93)

Note that loops, like other statements, can be ended with a colon. For loops, this suppresses the automatic printing of all the statements in the loop. Then, you can use the **print** command to print only the information that you want displayed.

Look at the previous example carefully. First, we assigned the value 2 to the name **i**. This initialization step is done automatically for us in a for loop but was made explicit in this while loop. The **while** keyword indicates that the loop is a while loop and is immediately followed by the conditional statement that controls the loop. This can be any condition you want. The condition is followed by the **do** keyword. Between the **do** keyword and the **end do** phrase is the statement sequence. The statement sequence is executed repeatedly until the condition is false.

In our example, there are two statements in the statement sequence. First, the current value of **i** is printed. Then, the value of **i** is changed to the result of squaring it and adding 2. This continues as long as the value of **i** is less than  $10^7$ . Note that the first semicolon is required in order to separate the two statements in the statement sequence.

It is very important in a while loop to be sure that the body of the loop will eventually have the effect of making the controlling condition false. Think about what would happen if the second command in the body of the previous loop had been **i := i - 2**. In that case, **i** would have started out equal to 2. Then, it would become 0, then -2, then -4, then -6, etc, and it would never exceed  $10^7$ , so it would never cease.

## Mixing for and while

The for loops and while loops we have demonstrated in this section are the most common kinds of loops. However, Maple has a feature that allows you to combine the for and while loop semantics into a single loop construction. Here is an example of how this is done.

```
> for i from 3 to 44 while i2 < 50 do  
  i, i2  
end do  
  3, 9  
  4, 16
```

5, 25  
6, 36  
7, 49

(0.94)

In fact, in Maple, there is only one kind of loop, and the **for** clause and **while** clause are considered optional statements that control the looping behavior in specific ways.

### Looping Over a List or Set

There is one additional clause that can appear in a loop, the **in** clause. Given a list or a set, the **in** clause allows you to define a loop that executes once for each element of the list or set. In the example below, the loop squares each element of the list.

```
> for i in [2, 5, 6, 11, 8] do
    printf("The square of %2a is %3a.\n", i, i^2)
end do
The square of 2 is 4.
The square of 5 is 25.
The square of 6 is 36.
The square of 11 is 121.
The square of 8 is 64.
```

The **for** clause indicates that the name of the loop variable is **i**. The **in** clause specifies that the loop variable should be assigned to each element of the given list in turn. The **while** clause can also appear in conjunction with the **in** clause. However, none of **from**, **by**, or **to** can appear when **in** is used.

### Premature Loop Exit

Sometimes it is necessary to terminate a loop prematurely. This may be in order to prevent an error or because the logic of a particular problem dictates that it must. In these cases, the **break** keyword is used to transfer control out of a loop. Consider the example below. Note that **even** and **odd** are considered types in Maple and so can be used as the second argument to the **type** command. (The reader is encouraged to research the Collatz conjecture, which forms the basis of this example.)

```
> n := 27 :
   count := 0 :
   while n ≠ 1 do
       if type(n, odd) then
           n := 3 n + 1
       else
           n :=  $\frac{n}{2}$ 
       end if;
       count := count + 1;
       if count > 50 then
           break
       end if
   end do :
   count
51
```

(0.95)

In the above, the **break** statement is executed if the number of iterations of the loop exceeds a specified threshold. This example is meant to illustrate how you can use **break** to place limits on the number of iterations in a while loop.

Related to **break** is the **next** command. Instead of terminating a loop entirely, the **next** command causes the rest of the statements in the body of the loop to be skipped, but the loop continues. In a for loop, this means that it moves on to the next value of the loop variable. The example below computes the value of the rational expression  $\frac{x^2 + 3}{x - 1}$  for the integers between  $-3$  and  $3$ . A **next** statement is used to avoid a division by zero error.

```
> for x from -3 to 3 do
    if x = 1 then
        next
    end if;
    x,  $\frac{x^2 + 3}{x - 1}$ 
end do
-3, -3
-2, -7/3
-1, -2
0, -3
2, 7
3, 6
```

(0.96)

## Procedures

A Maple procedure is very much like a function in mathematics. It is an object that is capable of receiving data as input and producing output.

A Maple procedure is created using the **proc** keyword. Ordinarily, procedures are assigned to a name. Consider the simple example below. Observe that we have entered the procedure in a Code Edit Region. You can add a Code Edit Region to your worksheet by selecting **Code Edit Region** from the **Insert** menu or by clicking on the icon shown below in the toolbar.



The Code Edit Regions in this manual are all set to autoexecute, so if you allow Maple to execute the autoexecutable code when you open the file, those procedures will all be prepared for you to experiment with. To manually execute code in a Code Edit Region, you can right-click on it and use the pop-up menu item Execute Code, or you can click anywhere in the region and type either Control+E or Control+= in Windows or Unix, or type Command+E or Command+= on a Mac.

```
1 MySum := proc (a, b)
2   a + b;
3 end proc;
```

*MySum* := proc(*a*, *b*)    *a* + *b*    end proc

This creates a procedure and assigns it to the name **MySum**. Note that assignment of procedures to names via the **:=** assignment operator is identical to assignment of any other Maple object. Also note that the output of this assignment is merely a repetition of the procedure definition. In the future, we will terminate procedure definitions with a colon rather than a semicolon as it is not necessary to see the procedure definition repeated.

Following the assignment operator, the procedure definition begins with the keyword **proc**. Immediately following the **proc** keyword is a matched pair of parentheses enclosing a sequence of names. These names are called the parameters to the procedure. When the procedure is called, for instance as below,

```
> MySum(2, 3)
5 (0.97)
```

the arguments **2** and **3** are assigned to the parameters **a** and **b**. Parameters are names used in the definition of the procedure to hold the place of input values, while arguments are the particular input values used in a particular execution of a procedure. (Note that this distinction is sometimes blurred and some programming languages use different terminology.) It is possible to define a procedure that requires no parameters, but even in this case the parentheses are required both in the procedure definition and when executing the procedure.

Following the parameter declaration is the statement sequence. This is the body of the procedure, consisting of all the commands that the procedure needs to perform to compute its output value. In this example only one command is used, the two parameters are added. Note that the output of a procedure is the result of the last statement that is executed. In the example above, 5 is output by the procedure because the final (and only) statement is the sum of **a** and **b**.

### Declaring Parameter Types

Within the parameter declaration, it is common, and very useful, to declare the types of the parameters. Consider the following procedure.

```
1 newMySum := proc (a : integer, b : integer)
2     a + b;
3 end proc;
```

In this **newMySum** procedure, the double colons followed by the Maple type name **integer** tells Maple that we expect the parameters **a** and **b** to be integers. If we try to execute this procedure with noninteger arguments, Maple will prevent the statement sequence from being executed and will report an error.

```
> newMySum(3, 2.5)
```

Error, invalid input: newMySum expects its 2nd argument, b, to be of type integer, but received 2.5

Declaring the types of parameters is good programming practice and very useful, and we will often include parameter types in the procedures we create in this manual.

### Return Statements and Global and Local Variables

Consider the procedure below.

```

1 Alg1 := proc (a : numeric)
2   global w;
3   local x;
4   if a < 1 then
5     x := 1;
6   else
7     x := 2;
8   end if;
9   w := x + 10;
10  return w;
11 end proc;

```

This procedure introduces a few more concepts. The first line assigns the procedure to the name **Alg1** and specifies that it takes one **numeric** argument (**numeric** is a broadly defined type for integers, rational numbers, and floating-point values).

Note the use of the **return** command in the final line of the procedure body. We have mentioned that the output of a procedure is, by default, the final computed value. The keyword **return** can be used, as it is here, to make explicit what is being output. It can also be used to cause a procedure to stop execution and immediately output a particular result. In this manual, we will usually use **return** statements, even when they are not required, so that it is clear what the output of a procedure is.

The second and third lines in **Alg1** use the **global** and **local** keywords followed by variable names. In any procedure, all of the names used in the procedure fall into one of three kinds: parameters, global variables, and local variables.

A variable is called local when it is only used within the procedure. Local variables exist only within the procedure and have no meaning outside of it.

To see what this means, we will assign the value 4 to the name **x**.

```

> x := 4
   x := 4

```

(0.98)

If we apply the **Alg1** procedure to a value smaller than 1, within the body of the procedure, **x** will be assigned the value 1.

```

> Alg1(0.5)
   11

```

(0.99)

However, if we check the value of **x**,

```

> x
   4

```

(0.100)

it has remained 4. This is because the **x** inside the procedure is declared local. You can think about the local **x** in the procedure as different than and isolated from the **x** that stores 4.

Global variables are the opposite. A variable is global when it is accessible and has the same value both inside and outside the procedure. In our example, the name **w** is declared global. If you look at



its value before and after the execution of the procedure, you will see that, unlike **x**, the value of **w** is changed.

```
> w := 76
    w := 76
```

(0.101)

```
> Alg1(3)
    12
```

(0.102)

```
> w
    12
```

(0.103)

Use of global variables in procedures is generally discouraged in most programming languages. There are a variety of reasons to avoid global variables, not least of which is that they can cause unpredictable results, especially in larger projects. In this manual, we will have cause to use global variables on occasion, but generally we will declare variables to be local.

Parameters to a Maple procedure are considered local automatically, in the sense that previous values of those names are not affected by the execution of the procedure. In fact, parameters are subject to the additional restriction that they cannot normally be modified during execution. In particular, they cannot be assigned to. For example, the procedure below causes an error to be generated when we execute it. It also illustrates how you declare more than one variable.

```
1 Alg2 := proc (a : numeric)
2     local x, y;
3     if a > 0 then
4         x := sqrt(a);
5         y := a^2;
6     else
7         x := sqrt(-a);
8         y := -a^2;
9     end if;
10    a := x + y;
11    return (a);
12 end proc;
```

```
> Alg2(5)
```

Error, (in Alg2) illegal use of a formal parameter

The “illegal use” described in the error message is the assignment **a := x + y**;

### A Final Example

We give one final example of a procedure.

```
1 Alg3 := proc (a : numeric)
2     # This procedure does nothing
3     if a > 0 then
4         return NULL;
5     else
```

```

6      return FAIL;
7  end if;
8      a := sqrt(a);
9  end proc;

```

First, note the line that begins with a pound symbol (also called hash or sharp or number symbol). This is Maple's syntax for commenting code. Anything following a # in a line is ignored by Maple. You can use comments to provide explanation, within your procedure's code, of what it does and how it works. Commenting can also be useful in debugging procedures because it allows you to temporarily deactivate lines of code without deleting them. In this manual, explanation of code will generally be given within the exposition rather than as comments within the code itself.

Second, this example has two **return** statements. In the case that the argument is positive, the procedure returns the value **NULL**. Recall from earlier that **NULL** is Maple's name for the empty sequence. Returning **NULL** is how you can cause a Maple procedure to have no output.

```
> Alg3(5)
```

The other **return** statement returns the value **FAIL**. It is typical to have a procedure return **FAIL** to indicate that the procedure is unable to compute the desired output.

```
> Alg3(-2)
FAIL
```

(0.104)

Finally, notice that the two **return** statements block the final statement, **a := sqrt(a)**, from ever being encountered. Despite the statement being illegal (it assigns to a parameter), errors were not generated because the illegal assignment is never reached.

## Functional Operators

We conclude this section with a brief discussion of functional operators. In Maple, a functional operator is a particular kind of procedure. Functional operators are often used to model simple mathematical functions.

The following defines a functional operator that models the function

$$f(x, y) = 2x^2 + 5y^2 + 3xy.$$

```
> f := (x, y) → 2x^2 + 3xy + 5y^2
f := (x, y) ↦ 2x^2 + 3yx + 5y^2
```

(0.105)

Let us look at the example above piece by piece. First is the name **f** followed by the assignment operator indicating that we are assigning the functional operator to the name **f**. Following the assignment operator is the list of parameters enclosed in parentheses. In the example above, there are two parameters, **x** and **y**. (If a functional operator only requires one parameter, then the parentheses are optional.) After the parameter list is the "arrow," typed as a hyphen followed by a greater than sign. The definition concludes with the expression, which may use other Maple commands, that defines the operator.

Applying a functional operator is the same as applying a procedure. To calculate  $f(2, -3)$ , you enter **f(2,-3)**.

```
> f(2, -3)
35
```

(0.106)

Functional operators are particularly useful in conjunction with other commands that expect Maple commands or procedures as one of the arguments. For example, with the **map** command. Recall that the first argument of the **map** command must be a procedure. If a list is given as the second argument, then **map** returns the list obtained by applying the procedure to each element of the list. The following demonstrates how to use a functional operator together with **map** in order to square all of the elements of a list.

```
> square := x → x2
square := x ↦ x2
```

(0.107)

```
> map(square, [-7, -3, -1, 0, 2, 3, 5])
[49, 9, 1, 0, 4, 9, 25]
```

(0.108)

The functional operator **square** could also have been created using **proc**, but for such a simple procedure, the functional operator definition is easier. Functional operators also allow you to include the definition of the procedure as the argument. For instance, to cube the elements of a list, you could do the following.

```
> map(x → x3, [-7, -3, -1, 0, 2, 3, 5])
[-343, -27, -1, 0, 8, 27, 125]
```

(0.109)

Functional operators will be discussed in more detail in Chapter 2.

## System Architecture and Packages

This section briefly explains the overall structure of the Maple system. It is intended to help you better understand how Maple works and why some things work the way that they do.

Maple uses an innovative system architecture to achieve ambitious design goals. The Maple kernel implements the basic interpreter of the Maple programming language, the interface with the host computer's operating system, and certain time-critical services.

However, nearly all of Maple's mathematical power dwells in the extensive Maple library. Consisting of thousands of lines of code, the Maple library is written in the Maple programming language itself. The advantages of this design include: portability, extensibility, and openness.

Portability refers to the ability to quickly and easily modify a program to run on a different computer system or a different operating system. With Maple, only the relatively small kernel needs to be ported between systems while nothing needs to be done to the library.

Extensibility is the ability of users, like yourself, to add capabilities and features to Maple. You can even redefine existing Maple library routines to extend or modify their behavior. You will see extensibility throughout this manual as we guide you through the process of writing procedures for exploring discrete mathematics that Maple does not already include.

Openness, in Maple, means that you can examine the source code for many of the library functions, thereby gaining greater understanding of the algorithms used by Maple.

Because of its size, much of the Maple library is organized into packages. A package is a collection of Maple library routines that offer related functionality. Since these are not normally loaded when you start Maple, you must request the services localized in each package by telling Maple explicitly that you want to load them. For this purpose, Maple provides the **with** command.

For example, the **combinat** package provides routines related to combinatorics. To use procedures from the **combinat** package, you would first load the package by typing

```
> with(combinat)
[Chi, bell, binomial, cartprod, character, choose, composition, conjpart,
 decodepart, encodepart, eulerian1, eulerian2, fibonacci, firstcomb,
 firstpart, firstperm, graycode, inttovec, lastcomb, lastpart, lastperm,
 multinomial, nextcomb, nextpart, nextperm, numbbcomb, numbbcomp,
 numbbpart, numbbperm, partition, permute, powerset, prevcomb,
 prevpart, prevperm, randcomb, randpart, randperm, rankcomb,
 rankperm, setpartition, stirling1, stirling2, subsets, unrankcomb,
 unrankperm, vectoint]
```

(0.110)

All the names of the newly loaded library routines are listed. Of course, you can suppress this list by terminating the statement with a colon.

You can access commands in a package without loading the whole package by using the long form of the command name. For example, Maple includes a command, **Mean**, for computing the arithmetic mean, or average, of a list of numbers. This command is located within the **Statistics** package. We can use it as shown below.

```
> Statistics[Mean]([1, 2, 3, 4, 5, 6, 7])
4.
```

(0.111)

In the long form, the name of the package is followed by the name of the command in brackets. Alternately, for most packages used in this manual, you can use the **:-** operator.

```
> Statistics:-Mean([1, 2, 3, 4, 5, 6, 7])
4.
```

(0.112)

In order to use the short form of the command name, that is, just **Mean**, you would first have to load the package.

```
> with(Statistics):
> Mean([5, 7, 12, 21])
11.250000000000000
```

(0.113)

Within a procedure definition, you have the option of specifying packages that the procedure requires by means of the **uses** keyword, as in the example below.

```

1 Avg3 := proc (a : numeric, b : numeric, c : numeric)
2     local m;
3     uses Statistics;
4     m := Mean ([a, b, c]);
5     return m;
6 end proc:

```

```

> Avg3(9, 2, 11)
7.33333333333333

```

(0.114)

The purpose of the **uses** statement is to ensure that commands used in the procedure are available. This way, if you were to try to execute this procedure without first loading the **Statistics** package via the **with** command, Maple would still be able to execute it. In this manual, when writing procedures, we will either use the long form of the name or include a **uses** statement in the procedure definition.

## Maple Versions

The procedures and examples in this manual were developed and tested with Maple 2018.

## On-Line Material

The files for this manual, including both the PDF and Maple Worksheet versions of all chapters, are available at the website for the eighth edition of *Discrete Mathematics and Its Applications* by Kenneth Rosen: [www.mhhe.com/rosen](http://www.mhhe.com/rosen). This site includes many other kinds of supplementary material for students and instructors.

The website includes one file in particular to be aware of: `RosenMaplePackages.mla`. This file is a repository for Maple packages that include many of the commands developed in this manual. There are two ways in which you can make these packages available.

The recommended way is to install `RosenMaplePackages.mla` in a library directory. First, execute the following statement (shown here without output)

```
> libname
```

The name **libname** is a system variable that specifies where on your computer Maple looks for library files, such as those that define packages. When you execute the statement, Maple will display the current value of the variable, which should be one or more directories on your computer.

Choose one of the directories listed and copy `RosenMaplePackages.mla` into that directory.

Then, restart the Maple kernel by executing the **restart** command. Note that the execution group below has been set to be nonexecutable, so that if you have Maple execute the entire worksheet, it will not automatically restart the kernel. Either enter it on a new input line in your worksheet, or make it executable by right clicking to open the pop-up menu and select **Executable Math**.

```
> restart
```

The alternative, in case you are not able to copy files into the Maple directories, is to add a directory to **libname**. First, copy `RosenMaplePackages.mla` into a directory on your computer.

Suppose that the full path of the directory in which you copied RosenMaplePackages.mla is:

/Users/danieljordan/DiscreteMath/

Then, you would execute the following statement, replacing the directory shown with your directory.

```
> libname := libname, "/Users/danieljordan/DiscreteMath/"
```

As with the restart command, this has been made nonexecutable, since your directory will be different.

Note that if you must use this method, you will need to repeat it every time you start a new Maple session. The first approach needs to be done only once, however.

If you are not sure what the correct directory is, you can execute the command below. This will open a file selection dialog window; if you locate the file RosenMaplePackages.mla on your computer and click Open, the correct directory will be added to **libname**. This command has also be set to be nonexecutable.

```
> libname := libname, FileTools[ParentDirectory](  
    Maplets[Utilities][GetFile](  
        'title' = "Locate RosenMaplePackages.mla",  
        'directory' = currentdir(homedir), filefilter = "mla",  
        filterdescription = "Library Files"))
```

Once you have completed one of these methods, the following commands should execute without error.

```
> with(Chapter0):  
test()
```

Each chapter has an associated package, called “Chapter” followed by the number of the chapter. Each package contains the procedures defined in the respective chapter that may be of use to you as you explore discrete mathematics. All of these packages are defined in the RosenMaplePackages.mla repository.

## Exercises

**Exercise 1.** Compute  $17 \cdot (126^{34} - 93)$ .

**Exercise 2.** Form the **list** (in the Maple sense) of the first 100 positive numbers that are 3 greater than a multiple of 7, using the **seq** command.

**Exercise 3.** Insert the number 300 between the 42nd and 43rd entries in the list you created in the previous exercise.

**Exercise 4.** Use a for loop to print the string “Hello World!” 10 times.

**Exercise 5.** Use a while loop to print the string “Hello World!” 10 times.

**Exercise 6.** **even** is a Maple type and thus can be used with the **type** command. Loop over the list you created in Exercise 2, and within the loop, use an if-else statement to print “even” or “odd” for each element of the list.

**Exercise 7.** Use **map** and a functional operator to apply the formula  $x^2 + 3x - 2$  to the list  $[-5, -4.5, -4, \dots, 4, 4.5, 5]$ .

**Exercise 8.** Write a procedure (using **proc**) that has one parameter, a list, and outputs the list in reverse order. You should use only commands discussed in this Introduction.