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Learning to Program with F#

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Preface

This book has been written as an introduction to programming for novice programmers. It is used in the first programming course at the University of Copenhagen's bachelor in computer science program. It has been typeset in \LaTeX , and all programs have been developed and tested in Mono version 6.0.0.327.

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Chapter 1

Introduction

Programming is a creative process in which exciting problems may be solved and new tools and applications may be created. With programming skills, you can create high-level applications to run on a mobile device that interact with other users, databases, and artificial intelligence; you may create programs that run on supercomputers for simulating weather systems on alien planets or social phenomena in the internet economy; and you may create programs that run on small custom-made hardware for controlling your home appliances.

1.1 How to Learn to Solve Problems by Programming

In order to learn how to program, there are a couple of steps that are useful:

1. Choose a programming language: A programming language, such as F#, is a vocabulary and a set of grammatical rules for instructing a computer to perform a certain task. It is possible to program without a concrete language, but your ideas and thoughts must still be expressed in some fairly rigorous way. Theoretical computer scientists typically do not rely on computers nor programming languages but uses mathematics to prove properties of algorithms. However, most computer scientists program using a computer, and with a real language you have the added benefit of checking your algorithm, and hence your thoughts, rigorously on a real computer. This book teaches a subset of F#. The purpose is not to be a reference guide to this language but to use it as a vessel to teach you, the reader, how to convert your ideas into programs.
2. Learn the language: A computer language is a structure for thought, and it influences which thoughts you choose to express as a program, and how you

choose to do it. Any conversion requires you to acquire a sufficient level of fluency in order for you to be able to make programs. You do not need to be a master in F# nor to know every corner of the language, and you will expand your knowledge as you expose yourself to solving problems in the language, but you must invest an initial amount of time and energy in order to learn the basics of the language. This book aims at getting you started quickly, which is why we intentionally teach just a small subset of F#. On the internet and through other works you will be able to learn much more.

3. Practice: In order to be a good programmer, the most essential step is: practice, practice, practice! It has been estimated that to master anything, then you have to have spent at least 10000 hours practicing, so get started logging hours! It of course matters, how you practice. This book teaches a number of different programming themes. The point is that programming is thinking, and the scaffold you use shapes your thoughts. It is therefore important to recognize this scaffold and to have the ability to choose one which suits your ideas and your goals best. The best way to expand your abilities is to sharpen your present abilities, push yourself into new territory, and try something new. Do not be afraid to make errors or be frustrated at first. These are the experiences that make you grow.
4. Solve real problems: I have found that using my programming skills in real situations with customers demanding specific solutions, has forced me to put the programming tools and techniques that I use into perspective. Sometimes a task requires a cheap and fast solution, other times customers want a long-perspective solution with bug fixes, upgrades, and new features. Practicing solving real problems helps you strike a balance between the two when programming. It also allows makes you a more practical programmer, by allowing you to recognize its applications in your everyday experiences. Regardless, real problems create real programmers.

1.2 How to Solve Problems

Programming is the act of solving a problem by writing a program to be executed on a computer. A general method for solving problems, given by George Pólya [9] and adapted to programming, is:

Understand the problem: To solve any problem it is crucial that the problem formulation is understood. What is to be solved? Do you understand everything in the description of the problem? Is all information for finding the solution available or is something missing?

Design a plan: Good designs lead to programs are faster to implement, easier to find errors in, and easier to update in the future. Before you start typing a program consider things like: What are the requirements and constraints for the program? Which components should the program have? How are these components supposed to work together? Designing often involves drawing a diagram of the program and writing program sketches on paper.

Implement the plan: Implementation is the act of transforming a program design into code. A crucial part of any implementation is choosing which programming language to use. Furthermore, the solution to many problems will have a number of implementations which vary in how much code they require, to which degree they rely on external libraries, which programming style they are best suited for, what machine resources they require, and how long time they take to run on a computer. With a good design, the coding is usually easy, since the design will have uncovered the major issues and found solutions for these, but sometimes implementation reveals new problems, which require rethinking the design. Most often the implementation step also require a careful documentation of key aspects of the code, e.g., a user manual for the user, and internal notes for fellow programmers that are to maintain and update the code in the future.

Reflect on the result: A crucial part of any programming task is ensuring that the program solves the problem sufficiently. Ask yourself questions such as: What are the program's errors, is the documentation of the code sufficient and relevant for its intended use? Is the code easily maintainable and extendable by other programmers? Which parts of your method would you avoid or replicate in future programming sessions? Can you reuse some of the code you developed in other programs?

Programming is a very complicated process, and Pólya's list is a useful guide but not a fail-safe approach. Always approach problem-solving with an open mind.

1.3 Approaches to Programming

This book focuses on several fundamentally different approaches to programming:

Declarative programming emphasizes *what a program shall accomplish* but not *how*. We will consider Functional programming as an example of declarative programming. A *functional programming* language evaluates *functions* and avoids state changes. The program consists of *expressions* instead of statements. As an example, the function $f(x) = x^2$ takes a number x , evaluates the expression x^2 , and returns the resulting number. Everything about the function may be

characterized by the relation between the input and output values. Functional programming has its roots in lambda calculus [1]. The first language emphasizing functional programming was Lisp [7].

Imperative programming emphasizes *how a program shall accomplish a solution* and focusses less on *what the solution is*. A cooking recipe is an example of the spirit of imperative programming, where the recipe emphasizes what should be done in each step rather than describing the result. For example, a recipe for bread might tell you to first mix yeast and water, then add flour, etc. In imperative programming what should be done are called *statements* and in the recipe analogy, the steps are the statements. Statements influence the computer's *states*, in the same way that adding flour changes the state of our dough. Almost all computer hardware is designed to execute low-level programs written in imperative style. Imperative programming builds on the Turing machine [10]. As a historical note, the first major language was FORTRAN [6] which emphasized an imperative style of programming.

Structured programming emphasizes organization of programs in units of code and data. For example, a traffic light may consist of a state (red, yellow, green), and code for updating the state, i.e., switching from one color to the next. We will focus on Object-oriented programming as the example of structured programming. *Object-oriented programming* is a type of programming, where the code and data are structured into *objects*. E.g., a traffic light may be an object in a traffic-routing program. The first object-oriented programming language was Simula 67 developed by Dahl and Nygaard at the Norwegian Computing Center in Oslo [2].

Event-driven programming, which is often used when dynamically interacting with the real world. This is useful, for example, when programming graphical user interfaces, where programs will often need to react to a user clicking on the mouse or to text arriving from a web-server to be displayed on the screen. Event-driven programs are often programmed using *call-back functions*, which are small programs that are ready to run when events occur.

Most programs do not follow a single programming paradigm as, e.g., one of the above, but are a mix. Nevertheless, this book will treat each paradigm separately to emphasize its advantages and disadvantages.

1.4 Why Use F#

This book uses F#, also known as Fsharp, which is a functional first programming language, meaning that it is designed as a functional programming language that also

supports imperative and object-oriented programming. It was originally developed for Microsoft's .Net platform but is available as open source for many operating systems through Mono. As an introduction to programming, F# is a young programming language still under development, with syntax that at times is a bit complex. Still, it offers a number of advantages:

Interactive and compile mode: F# has an interactive and a compile mode of operation. In interactive mode you can write code that is executed immediately in a manner similar to working with a calculator, while in compile mode you combine many lines of code possibly in many files into a single application, which is easier to distribute to people who are not F# experts and is faster to execute.

Indentation for scope: F# uses indentation to indicate scope. Some lines of code belong together and should be executed in a certain order and may share data. Indentation helps in specifying this relationship.

Strongly typed: F# is strongly typed, reducing the number of runtime errors. That is, F# is picky, and will not allow the programmer to mix up types such as numbers and text. This is a great advantage for large programs.

Multi-platform: F# is available on Linux, Mac OS X, Android, iOS, Windows, GPUs, and browsers both via the public domain Mono platform and Microsoft's open source .Net system.

Free to use and open source: F# is supported by the Fsharp foundation (<http://fsharp.org>) and sponsored by Microsoft.

Assemblies: F# is designed to be able to easily communicate with other .Net and Mono programs through the language-independent, platform-independent byte-code called Common Intermediate Language (CIL) organized as assemblies. Thus, if you find that certain parts of a program are easy to express in F# and others in C++, then you will be able to combine these parts later into a single program.

Modern computing: F# supports all aspects of modern computing including Graphical User Interfaces, Web programming, Information rich programming, Parallel algorithms, . . .

Integrated development environments (IDE): F# is supported by IDEs such as Visual Studio (<https://www.visualstudio.com>) and Xamarin Studio (<https://www.xamarin.com>).

1.5 How to Read This Book

Learning to program requires mastering a programming language, however, most programming languages contain details that are rarely used or used in contexts far from a specific programming topic. Hence, this book only includes a subset of F# but focuses on language structures necessary to understand several common programming paradigms: Imperative programming mainly covered in Chapters 4 to 10, functional programming mainly covered in Chapters 8 to 9, object-oriented programming in Chapters 23 and 25, and event-driven programming in Chapter 15. A number of general topics are given in the appendix for reference. For further reading please consult <http://fsharp.org>.

Chapter 2

Solving problems by writing a program

Abstract In this chapter, you will find a quick introduction to several essential programming constructs with several examples that you can try on your computer using the `dotnet` command in your console. All constructs will be discussed in further detail in the following chapters. In this chapter, you will get a peek at:

- How to execute an F# program
- How to perform simple arithmetic using F#
- What types are and why they are important
- How to write to and obtain written input from the user
- How to perform conditional execution of code
- How to define functions
- How to repeat code without having to rewrite them
- How to add textual comments to help yourself and other programmers understand your programs.

Programming is the art of solving problems by writing a program to be executed by a computer. For example, to solve the following problem,

Problem 2.1

What is the sum of 357 and 864?

we have written the program shown in Listing 2.1. In this book, we will show many

Listing 2.1 quickStartSum.fsx:**A script to add 2 numbers and print the result to the console.**

```
1 let a = 357
2 let b = 864
3 let c = a + b
4 do printfn "%A" c

1 $ dotnet fsi quickStartSum.fsx
2 1221
```

programs, and for most, we will also show the result of executing the programs on a computer. Listing 2.1 shows both our program and how this program is executed on a computer. In the listing, we see our program was saved as a script in a file called `quickStartSum.fsx`, and in the console (also known as the terminal and the command-line) we executed the program by typing the command `dotnet fsi quickStartSum.fsx`. The result is then printed by the computer to the console as 1221. The colors are not part of the program but have been added to make it easier for us to identify different syntactical elements of the program.

The program consists of several lines. Our listing shows line numbers to the left. These are not part of the program but added for ease of discussion, since the order in which the lines appear the program matters. In this program, each line contains *expressions*, and this program has *let*-, *do*-expressions, and an addition. *let*-expressions defines aliases, and *do*-expressions defines computations. *let* and *do* are examples of *keywords*, and “+” is an example of an *operator*. Keywords, operators, and other sequences of characters, which F# recognizes are jointly called *lexemes*.

Reading the program from line 1, the first expression we encounter is `let a = 357`. This is known as a *let-binding* in F# and defines the equivalence between the name `a` and the value 357. F# does not accept a keyword as a name in a *let*-bindings. The consequence of this line is that in later lines there is no difference between writing the name `a` and the value 357. Similarly in line 2 the value 864 is bound to the name `b`. In contrast, line 3 contains an addition and a *let*-expression. It is at times useful to simulate the execution the computer does in a step-by-step manner by replacement:

$$\text{let } c = a + b \rightsquigarrow \text{let } c = 357 + 864 \rightsquigarrow \text{let } c = 1221$$

Thus, since the expression on the right-hand side of the equal sign is evaluated, the result of line 3 is that the name `c` is bound to the value 1221.

Line 4 has a *do*-expression is also called a *do-binding* or a *statements*. In this *do*-binding, the *printfn* function `printfn` is called with 2 arguments, “%A” and `c`. All functions return values, and `printfn` the value ‘nothing’, which is denoted “()”. This function is very commonly used but also very special since it can take any

number of arguments and produces output to the console. We say that “the output is printed to the screen”. The first argument is called the *formatting string* and describes, what should be printed and how the remaining arguments if any, should be formatted. In this case, the value `c` is printed as an integer followed by a newline. Notice that in contrast to many other languages, F# does not use parentheses to frame the list of function arguments, nor does it use commas to separate them.

2.1 Executing F# programs on a computer

The main purpose of writing programs is to make computers execute or run them. F# has two modes of execution, *interactive* and *compiled*. Interactive mode allows the user to interact with F# as a dialogue: The user writes statements, and F# responds immediately. If a program has been saved as a file as in Listing 2.1 we do not need to rewrite the complete program every time we wish to execute it but can give the file as input to the F#'s interactive mode as demonstrated in Listing 2.1. Interactive mode is well suited for small experiments or back-of-an-envelope calculations, but not for programming in general, since each line is interpreted anew every time the program is run. In contrast, in compile mode, dotnet interprets the content of a source file once, and writes the result to disk, such that every when the user wishes to run the program, the interpretation step is not performed. For large programs, this can save considerable time. In the first chapters of this book, we will use interactive mode, and compile mode will be discussed in further detail in Chapter 17.

An interactive session is obtained by starting the console, typing the `fsharp` command, typing the lines of the program, and ending the script-fragment with “`;;`”. The dialogue in Listing 2.2 demonstrates the workflow. What the user types has been highlighted by a box.

Listing 2.2: An interactive session.

```
1 $ dotnet fsi
2
3 Microsoft (R) F# Interactive version 12.0.0.0 for F# 6.0
4 Copyright (c) Microsoft Corporation. All Rights Reserved.
5
6 For help type #help;;
7
8 > let a = 3
9 - do printfn "%A" a;;
10 3
11 val a : int = 3
12 val it : unit = ()
13
14 > #quit;;
```

We see that after typing `fsharp`, the program starts by stating details about itself. Then F# writes `>` indicating that it is ready to receive commands. The user types `let a = 3` and presses `enter`, to which the interpreter responds with `-`. This indicates that the line has been received, that the script fragment is not yet completed, and that it is ready to receive more input. When the user types `do printfn "%A" a;;` followed by `enter`, then by `“;;”` the interpreter knows that the script-fragment is completed, it interprets the script-fragment, responds with `3` and some extra information about the entered code, and with `>` to indicate that it is ready for more script-fragments. The interpreter is stopped when the user types `#quit;;`. It is also possible to stop the interpreter by typing `ctrl-d`.

The interactive session results in extra output on the *type inference* performed. In Listing 2.2, F# states that the name `a` has *type* `int` and the value `3`. Likewise, the `do` statement F# refers to by the name `it`, and it has the type `unit` and value `“()”`. Types are very important to F# since they define how different program pieces fit together like lego bricks. They are a key ingredient for finding errors in programs, also known as *debugging*, and much of the rest of this book is concerned with types.

Instead of running `fsharp` interactively, we can write the script-fragment from Listing 2.2 into a file, here called `gettingStartedStump.fsx`. This file can be interpreted directly by `dotnet fsi` as shown in Listing 2.3.

Listing 2.3: Using the interpreter to execute a script.

```
1 $ dotnet fsi gettingStartedStump.fsx
2 3
```

Notice that in the file, `“;;”` is optional. In comparison to Listing 2.2, we see that the interpreter executes the code and prints the result on screen without the extra type information.

Files are important when programming, and F# and the console interprets files differently by the filename's suffix. A filename's suffix is the sequence of letters after the period in the filename. Generally, there are two types of files: *source code* and compiled programs. Until Chapter 17, we will concentrate on script files, which are source code, written in human-readable form using an editor, and has `.fsx` or `.fsscript` as suffix. In Table 2.1 is a complete list of possible suffixes used by F#.

Suffix	Human readable	Description
<code>.fs</code>	Yes	An <i>implementation file</i> , e.g., <code>myModule.fs</code>
<code>.fsi</code>	Yes	A <i>signature file</i> , e.g., <code>myModule.fsi</code>
<code>.fsx</code>	Yes	A <i>script file</i> , e.g., <code>gettingStartedStump.fsx</code>
<code>.fsscript</code>	Yes	Same as <code>.fsx</code> , e.g., <code>gettingStartedStump.fsscript</code>
<code>.dll</code>	No	A <i>library file</i> , e.g., <code>myModule.dll</code>
<code>.exe</code>	No	A stand-alone <i>executable file</i> , e.g., <code>gettingStartedStump.exe</code>

Table 2.1 Suffixes used, when programming F#.

2.2 Values have types and types reduce the risk of programming errors

Types are a central concept in F#. In the script 2.1 we bound values of integer type to names. There are several different integer types in F#, here we used the one called `[int]`. The values were not *declared* to have these types, instead the types were *inferred* by F#. Typing these bindings line by line in an interactive session, we see the inferred types as shown in Listing 2.4. The interactive session displays the type using the

Listing 2.4: Inferred types are given as part of the response from the interpreter.

```

1 > let a = 357;;
2 val a: int = 357
3
4 > let b = 864;;
5 val b: int = 864
6
7 > let c = a + b;;
8 val c: int = 1221
9
10 > do printfn "%A" c;;
11 1221
12 val it: unit = ()
```

`val` keyword followed by the name used in the binding, its type, and its value. Since the value is also returned, the last `printfn` statement is superfluous. Notice that `printfn` is automatically bound to the name `it` of type `unit` and value `()`. F# insists on binding all statements to values, and in lack of an explicit name, it will use `it`. Rumor has it that `it` is an abbreviation for "irrelevant".

In mathematics, types are also an important concept. For example, a number may belong to the set of natural \mathbb{N} , integer \mathbb{Z} , or real numbers, where all 3 sets are infinitely large and $\mathbb{N} \subset \mathbb{Z} \subset \mathbb{R}$ as illustrated in Figure 2.1. For many problems,

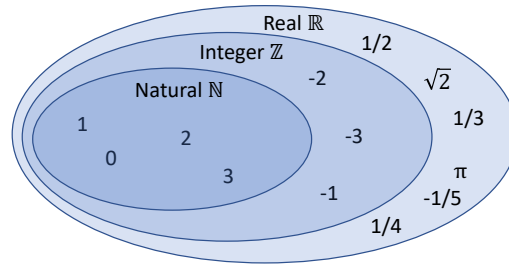


Fig. 2.1 In mathematics, the sets of natural, integer, and real numbers are each infinitely large, and real contains integers which in turn contains the set of natural numbers.

working with infinite sets is impractical, and instead, a lot of work in the early days of the computer's history was spent on designing finite sets of numbers, which have many of the properties of their mathematical equivalent, but which also are efficient for performing calculations on a computer. For example, the set of integers in F# is called `int` and is the set $\{-2\,147\,483\,648 \dots 2\,147\,483\,647\}$.

Types are also important when programming. For example, a the string `"863"` and the `int 863` may conceptually be identical but they are very different in the computer. F# is very picky about types, and generally does not allow types to be mixed, as demonstrated in the interactive session in Listing 2.5. In this ex-

Listing 2.5: Mixing types is often not allowed.

```

1 > let a = 357;;
2 val a: int = 357
3
4 > let b = "863";;
5 val b: string = "863"
6
7 > let c = a + b;;
8
9     let c = a + b;;
10     -----^
11
12 /Users/jrh630/repositories/fsharp-book/src/stdin(3,13): error
    FS0001: The type 'string' does not match the type 'int'
```

ample, we see that adding a string to an integer results in an error. The *error message* contains much information. First, it illustrates where dotnet could not understand the input by `-----^`. Then it repeats where the error is found as `/User/.../src/stdin(3,13)`, which means that dotnet was started in the directory `/User/.../src/`, the input was given on the standard-input meaning the keyboard, and the error was detected on line 3, column 13. Then F# gives the error number and a description of the error. Error numbers are an underdeveloped feature

in F# and should be ignored. However, the verbal description often contains useful information for correcting the program. Here, we are informed that there is a type mismatch in the expression. The reason for the mismatch is that since *a* is an integer, then the “+” operator must be integer addition, and thus for the expression to be executable, *b* can only be an integer.

2.3 Organizing often used code in functions

`printfn` is an example of a built-in function, and very often we wish to define our own. For example, in longer programs, some code needs to be used in several places and defining functions to *encapsulate* such code can be a great advantage for reducing the length of code, debugging, and writing code, which is easier to understand by other programmers. A function is defined using a `let`-binding. For example, to define a function, which takes two integers as input and returns their sum, we write

Listing 2.6: Defining the function `sum`

```
1 let sum x y =  
2   x + y
```

What this means is that we bind the name `sum` as a function, which takes two arguments and adds them. Further, in the function, the arguments are locally referred to by the names `x` and `y`. Indentation determines which lines should be evaluated when the function is called, and in this case, there is only one. The value of the last expression evaluated in a function is its return value. Here there is only one expression `x+y`, and thus, this function returns the value of the addition. This program does not do anything, since the function is neither called nor is its output used. However, we can modify Listing 2.1 to include it as shown in Listing 2.7. The output is the

Listing 2.7 `quickStartSumFct.fsx`:

Adding two integers with the use of a in-code defined function.

```
1 let sum x y =  
2   x + y  
3 let c = sum 357 864  
4 do printfn "%A" c  
  
-----  
1 $ dotnet fsi quickStartSumFct.fsx  
2 1221
```

same for the two programs, and the computation performed is almost the same. A step-by-step manner by replacement of the computation performed in line 3 is

```
let c = sum 357 864 ~> let c = 357 + 864 ~> let c = 1221
```

The main difference is that with the function `sum` we have an independent unit, which can be reused elsewhere in the code.

2.4 Asking the user for input

The `printfn` function allows us to write to the screen, which is useful, but sometimes we wish to start a dialogue with the user. One way to get user input is to ask the user to type something on the keyboard. Technically, input from the keyboard is called an *stdin stream*. This terminology is intended to remind us of characters streaming from the keyboard like the flow of water in a stream. Computer streams are different than water streams in that characters (or other items) only flow, when we ask for them. F# provides many libraries of prebuilt functions, and here we will use the `System.Console.ReadLine` function. The “.”-lexeme is read as `ReadLine` is a function which lies in `Console` which in turn lies in `System`. In the function documentation, we can read that `System.Console.ReadLine` takes a unit value as an argument and returns the *string* the user typed. A string is a built-in type, as is integers, and strings contains sequences of characters. The program will not advance until the user presses the newline. An example of a program that multiplies two integers supplied by a user is given in Listing 2.8. In this program, we find a user

Listing 2.8 quickStartSumInput.fsx:

Asking the user for input. The user entered 6, pressed the return button, 2, and pressed return again.

```
1 let sum x y = x + y
2 printfn "Adding a and b"
3 printf "Enter a: "
4 let a = int (System.Console.ReadLine ())
5 printf "Enter b: "
6 let b = int (System.Console.ReadLine ())
7 let c = sum a b
8 do printfn "%A" c
```

```
1 dotnet fsi quickStartSumInput.fsx
2 Adding a and b
3 Enter a: 6
4 Enter b: 2
5 8
```

dialogue, and we have designed it such that we assume that the user is unfamiliar with the inner workings of our program, and therefore helps the user understand the

purpose of the input and the expected result. This is good programming practice. Here, we will not discuss the program line-to-line, but it is advised to the novice programmer to match what is printed on the screen and from where in the code, the output comes from. However, let us focus on line 4 and 4, which introduce two new programming constructs. In each of these lines, 3 things happen: First the `System.Console.ReadLine` function is called with the “()” value as argument. This reads all the characters, the user types, up until the user presses the return key. The return value is a string of characters such as “6”. This value is different from the integer 6, and hence, to later be able to perform integer-addition, we *cast* the string value to `int`, meaning that we call the function `int` to convert the string-value to the corresponding integer value. Finally, the result is bound to the names `a` and `b` respectively.

2.5 Conditionally execute code

Often problem requires code evaluated based on conditions, which only can be decided at *runtime*, i.e., at the time, when the program is run. Consider a slight modification of our problem as

Problem 2.2

Ask for two integer values from the user, a and b , and print the result of the integer division a/b .

To solve this problem, we must decide what to do, if the user inputs $b = 0$, since division by zero is ill-defined. This is an example of a user input error, and later, we will investigate many different methods for handling such errors, but here, we will simply write an error message to the user, if the desired division is ill-defined. Thus, we need to decide at *runtime*, whether to divide a and b or to write an error message. For this we will use the `match-with` expression. In this program, the `match-with` expression covers line 7 to 12. When the computer executes these lines, it checks the value b against a list of patterns separated by “|”. The code belonging to each pattern follows the arrow, “ \rightarrow ”, and is called a *branch*, and which lines belongs to each branch is determined by *indentation*. Hence, the code belonging to the “ 0.0 ” branch is line 9 and to the “ $_$ ” branch is line 11 to 12. The branches are checked one at a time from top to bottom. I.e., first b is compared with 0 which is equivalent to check whether $b = 0.0$. If this is true, then its branch is executed. Otherwise, the b is compared with the *wildcard* pattern, “ $_$ ”. The wildcard pattern matches anything, and hence, if b is nonzero, then “ $_$ ”-branch is executed. In most cases, F# will give an error, if the list of patterns do not cover the full domain of the type being matched. Here, b is an integer, and thus, we must write branches that takes *all* integer values into account. The wildcard pattern makes this easy and works as a catch-all-other cases, and is often placed as the last case, following the important cases. Assuming

Listing 2.9 quickStartDivisionInput.fsx:
Conditionally divide two user-given values.

```

1 let div x y = x / y
2 printfn "Dividing a by b"
3 printf "Enter a: "
4 let a = int (System.Console.ReadLine ())
5 printf "Enter b: "
6 let b = int (System.Console.ReadLine ())
7 match b with
8     0 ->
9         do printfn "Input error: Cannot divide by zero"
10    | _ ->
11        let c = div a b
12        do printfn "%A" c

```

```

1 % dotnet fsi quickStartDivisionInput.fsx
2 Dividing a by b
3 Enter a: 6
4 Enter b: 2
5 3
6 % dotnet fsi quickStartDivisionInput.fsx
7 Dividing a by b
8 Enter a: 6
9 Enter b: 0
10 Input error: Cannot divide by zero

```

that the user enters the value 0, then the step-by-step simplification of `match-with` expression is,

```

match b with 0 -> ... | _ -> ...
~> do printfn "Input error: Cannot divide by zero"

```

2.6 Repeatedly execute code

Often code needs to be evaluated many times or looped. For example, instead of stopping the program in Listing 2.9 if the user inputs $b = 0$, then we could repeat the question as many times as needed until the user inputs a non-zero value for b . This is called a loop, and there are several programming constructions for this purpose.

Let us first consider recursion. A recursive function is one, which calls itself, e.g., $f(f(f(\dots(x))))$ is an example of a function f which calls itself many times, possibly infinitely many. In the latter case, we say that the recursion has entered an infinite loop, and we will experience that either the program runs forever or that the execution stops due to a memory error. If we had infinite memory. To avoid this,

recursive functions must always have a stopping criterion. Thus, we can design a function for asking the user for a non-zero input value as shown in Listing 2.10. The function `readNonZeroValue` takes no input denoted by “()”, and repeatedly

Listing 2.10 `quickStartRecursiveInput.fsx`:
Recursively call `ReadLine` until a non-zero value is entered.

```

1 let rec readNonZeroValue () =
2     let a = int (System.Console.ReadLine ())
3     match a with
4     | 0 ->
5         printfn "Error: zero value entered. Try again"
6         readNonZeroValue ()
7     | _ ->
8         a
9 printfn "Please enter a non-zero value"
10 let b = readNonZeroValue ()
11 printfn "You typed: %A" b

```

```

1 $ dotnet fsi quickStartRecursiveInput.fsx
2 Please enter a non-zero value
3 0
4 Error: zero value entered. Try again
5 3
6 You typed: 3

```

calls itself until the $a \neq 0$ condition is met. It is recursive since its body contains a call to itself. For technical reasons, F# requires recursive functions to be declared by the `rec`-keyword as demonstrated. The function has been designed to stop if $a \neq 0$, and in F#, this is tested with the “<>” operator. Thus, if the stopping condition is satisfied, then the `then`-branch is executed, which does not call itself, and thus the recursion goes no deeper. If the condition is not met, then the `else`-branch is executed, and the function is eventually called anew. The example execution of the program demonstrates this for the case that the user first inputs the value 0 and then the value 3.

As an alternative to recursive functions, loops may also be implemented using the `while`-expression. In Listing 2.10 is an example of a solution where the recursive loop has been replaced with `while`-loop. As for other constructs, the lines to be repeated are indicated by indentation, in this case, lines 4 to 5, and in the end, the result of the `readNonZeroValueAlt` function is the last expression evaluated, which is the trivial expression `a` in line 6. In comparison with the recursive version of the program, the `while`-loop has a continuation conditions (line 3), i.e., the content of the loop is repeated as long as `a = 0` evaluates to `true`. Another difference is that in Listing 2.10 we could simplify our program to only using `let` value-bindings, here we need a new concept: *variables* also known as a `mutable` value. Mutable values allow us to update the value associated with a given name. Thus, the value associated with a name of mutable type depends on when it is accessed.

Listing 2.11 quickStartWhileInput.fsx:
Replacing recursion in Listing 2.10 with a `while`-loop.

```

1 let readNonZeroValueAlt () =
2     let mutable a = int (System.Console.ReadLine ())
3     while a = 0 do
4         printfn "Error: zero value entered. Try again"
5         a <- int (System.Console.ReadLine ())
6     a
7 printfn "Please enter a non-zero value"
8 let b = readNonZeroValueAlt ()
9 printfn "You typed: %A" b

```

```

1 $ dotnet fsi quickStartWhileInput.fsx
2 Please enter a non-zero value
3 0
4 Error: zero value entered. Try again
5 3
6 You typed: 3.0

```

This construction makes programs much more complicated and error-prone, and their use should be minimized. The syntax of mutable values is that first it should be defined with the `mutable`-keyword as shown in line 2, and when its value is to be updated then the “<-”-notation must be used as demonstrated in line 5. Note that the execution of the two programs Listing 2.10 and Listing 2.11, gives identical output, when presented with identical input. Hence, they solve the same problem by two quite different means. This is a common property of solutions to problems as a program: Often several different solutions exist, which are identical on the surface, but where the quality of the solution depends on how quality is defined and which programming constructions have been used. Here, the main difference is that the recursive solution avoids the use of mutable values, which turns out to be better for proving the correctness of programs and for adapting programs to super-computer architectures. However, recursive solutions may be very memory intensive, if the recursive call is anywhere but the last line of the function.

2.7 Programming as a form of communication

When programming it is important to consider the time dimension of a program. Some usually very small programs are only used for a short while, e.g., to test a programming construction or an idea to a solution. Others small as well as large may be used again and again over a long period, and possibly given to other programmers to use, maintain, and extend. In this case, programming is an act of communication, where what is being communicated is the solution to a problem as well as

the thoughts behind the chosen solution. Common experiences among programmers are that it is difficult to fully understand the thoughts behind a program written by a fellow programmer from its source code alone, and for code written perhaps just weeks earlier by the same programmer, said programmer can find it difficult to remember the reasons for specific programming choices. To support this communication, programmers use *code-comments*. As a general concept, this is also called in-code documentation. Documentation may also be an accompanying manual or report. Documentation serves several purposes:

1. Communicate what the code should be doing, e.g., describe functions in terms of their input-output relation.
2. Highlight big insights essential for the code.
3. Highlight possible conflicts and/or areas where the code could be changed later.

F# has two different syntaxes for comments. A block comment is everything bracketed by `(* *)`, and a line comment, which is everything between `//` and the end of the line. For example, adding comments to Listing 2.10 could look like Listing 2.12. Comments are ignored by the computer and serve solely as programmer-

Listing 2.12 `quickStartRecursiveInputComments.fsx`:
Adding comments to Listing 2.10.

```
1  (*
2     Demonstration of recursion for keyboard input.
3     Author: Jon Sporring
4     Date: 2022/7/28
5  *)
6
7  // Description: Repeatedly ask the user for a non-zero number
8  // until a non-zero value is entered.
9  // Arguments: None
10 // Result: the non-zero value entered
11 let rec readNonZeroValue () =
12     // Note that the value of a is different for every
13     // recursive call.
14     let a = int (System.Console.ReadLine ())
15     match a with
16     | 0 ->
17         printfn "Error: zero value entered. Try again"
18         readNonZeroValue ()
19     | _ ->
20         a
21 printfn "Please enter a non-zero value"
22 let b = readNonZeroValue ()
23 printfn "You typed: %A" b
```

to-programmer communication, there are no or few rules for specifying, what is good and bad documentation of a program. The essential point is that coding is a

journey in problem-solving, and proper documentation is an aid in understanding the solution and the journey that lead to it.

2.8 Key concepts and terms in this chapter

- F# has two modes of operation: **Interactive** and **compile** mode. The first chapters of this book will focus on the interactive mode.
- F# is accessed through the **console/terminal/command-line**, which is another program, in which text commands can be given such as starting the dotnet program in interactive mode.
- Programs are written in a human-readable form called the **source-code**.
- Source code consists of several syntactical elements such as **operators** such as "*" and "<-", **keywords** such as "let" and "while", **values** such as 1.2 and the string "hello world", and **user-defined names** such as "a" and "str". All words, which F# recognizes are called **lexemes**.
- A program consists of a sequence of **expressions**, which comes in two types: **let** and **do**.
- Values have **types** such as **int** and **string**. When performing calculations, the type defines which calculations can be done.
- **Functions** are a type of value and defined using a let-binding. They are used to encapsulate code to make the code easier to read and understand and to make code reusable.
- The **conditional match-with** expression is used to control what code is to be executed at **runtime**. Each piece of conditional code is called a **branch**
- **Recursion** and **while**-loops are programming structure to execute the same code several times.
- **Mutable values** are in contrast to **immutable values** may change value over time, and makes programmer harder to understand.
- **Comments** are **in-code documentation** and are ignored by the computer but serve as an important tool for communication between programmers.

Chapter 3

Using F# as a Calculator

Abstract In the previous chapter, we introduced some key F# programming tools and concepts without going into depth on opportunities and limitations. In the following chapters, we will dive deeper into methods for solving problems by writing programs, and what facilities are available in F# to express these solutions. As a first step, we must acquaint ourselves with the basic building blocks of basic types, constants, and operators:

- an introduction to the basic types and how to write constants of those types
- arithmetic of basic operations

with these tools, you will be able to evaluate expressions as if F# was a simple calculator. Examples of problems, you will be able to solve after reading this chapter, is:

- What is the result of $3 \cos(4 * \pi / 180) + 4 \sin(4 * \pi / 180)$.
 - Calculate how many characters are there in the text string "Hello World!".
 - What is the ASCII value of the character 'J'.
 - How to convert between whole and binary numbers.
-

3.1 Literals and Basic Types

All programs rely on processing of data, and an essential property of data is its *type*. A *literal* is a fixed value like the number 3, and if we type the number 3 in an interactive session at the input prompt, then F# responds as shown in Listing 3.1. What this means is that F# has inferred the type to be *int* and bound it to the

Listing 3.1: Typing the number 3.

```
1 > 3;;  
2 val it: int = 3
```

identifier *it*. For more on binding and identifiers see Chapter 4. Types matter, since the operations that can be performed on integers, are quite different from those that can be performed on, e.g., strings. Therefore, the number 3 has many different representations as shown in Listing 3.2. Each literal represents the number 3, but

Listing 3.2: Many representations of the number 3 but using different types.

```
1  
2 > 3;;  
3 val it: int = 3  
4  
5 > 3.0;;  
6 val it: float = 3.0  
7  
8 > '3';;  
9 val it: char = '3'  
10  
11 > "3";;  
12 val it: string = "3"
```

their types are different, and hence they are quite different values. The types *int* for integer numbers, *float* for floating point numbers, *bool* for Boolean values, *char* for characters, and *string* for strings of characters are the most common types of literals. A table of all *basic types* predefined in F# is given in Table 3.1. In addition to these built-in types, F# is designed such that it is easy to define new types.

Humans like to use the *decimal number* system for representing numbers. Decimal numbers are *base 10*, which means that a value is represented as two sequences of decimal digits separated by a *decimal point*, where each *digit* *d* has a position and a value $d \in \{0, 1, 2, \dots, 9\}$. The part before the decimal point is called the *whole part* and the part after is called the *fractional part* of the number. An *integer* is a number with only a whole part and neither a decimal point nor a fractional part. As an example 35.7 is a decimal number, whose value is $3 \cdot 10^1 + 5 \cdot 10^0 + 7 \cdot 10^{-1}$, and 128 is an integer, whose value is $1 \cdot 10^2 + 2 \cdot 10^1 + 8 \cdot 10^0$. In F#, a decimal number is called a *floating point number*. Floating point numbers may alternatively be given

Metatype	Type name	Description
Boolean	<u>bool</u>	Boolean values true or false
Integer	<u>int</u>	Integer values from -2,147,483,648 to 2,147,483,647
	byte	Integer values from 0 to 255
	sbyte	Integer values from -128 to 127
	int8	Synonymous with sbyte
	uint8	Synonymous with byte
	int16	Integer values from -32768 to 32767
	uint16	Integer values from 0 to 65535
	int32	Synonymous with int
	uint32	Integer values from 0 to 4,294,967,295
	int64	Integer values from -9,223,372,036,854,775,808 to 9,223,372,036,854,775,807
	uint64	Integer values from 0 to 18,446,744,073,709,551,615
Real	<u>float</u>	64-bit IEEE 754 floating point value from $-\infty$ to ∞
	double	Synonymous with float
	single	A 32-bit floating point type
	float32	Synonymous with single
	decimal	A floating point data type that has at least 28 significant digits
Character	<u>char</u>	Unicode character
	<u>string</u>	Unicode sequence of characters
None	<u>unit</u>	The value ()
Object	<u>obj</u>	An object
Exception	<u>exn</u>	An exception

Table 3.1 List of some of the basic types. The most commonly used types are underlined. For a description of integer see Appendix B.1, for floating point numbers see Appendix B.2, for ASCII and Unicode characters see Appendix C, for objects see Chapter 23, and for exceptions see Chapter 13.

using *scientific notation*, such as 3.5×10^{-4} and 4×10^2 , where the e-notation is translated to a value as $3.5 \times 10^{-4} = 3.5 \cdot 10^{-4} = 0.00035$, and $4 \times 10^2 = 4 \cdot 10^2 = 400$.

The basic unit of information in almost all computers is the binary digit or *bit* for short. Internally, programs and data are all represented as bits, hence F# has a strong support for binary numbers. A *binary number* consists of a sequence of binary digits separated by a decimal point, where each digit can have values $b \in \{0, 1\}$, and the base is 2. E.g., the binary number $101.01_2 = 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 + 0 \cdot 2^{-1} + 1 \cdot 2^{-2} = 5.25$. Subscripts are often used to indicate the base of a number, e.g., 101.01_2 and 101.01_{10} are different numbers. Since base 10 is so common, the subscript for base 10 numbers is often omitted.

Binary numbers are closely related to *octal* and *hexadecimal numbers*. Octals uses 8 as basis and hexadecimals use 16 as basis. Each octal digit can be represented by exactly three bits, and each hexadecimal digit can be represented by exactly four bits. The hexadecimal digits use 0–9 to represent the values 0–9 and a–f in lower or alternatively upper case to represent the values 10–15. Thus, Octals and hexadecimals conveniently serve as shorthand for the much longer binary representation. As examples, the octal number 37_8 is $3 \cdot 8^1 + 7 \cdot 8^0 = 31$, and the hexadecimal number $f3_{16}$ is $15 \cdot 16^1 + 3 \cdot 16^0 = 243$.

To denote integers in bases different than 10, F# uses the prefix '0b' for binary, '0o' for octal, and '0x' for hexadecimal numbers. For example, the value 367_{10} may be written as an integer 367, as a binary number `0b101101111`, as a octal number `0o557`, and as a hexadecimal number `0x16f`. In F#, the character sequences `0b12` and `ff` are not recognized as numbers.

A *character* is a *Unicode code point*, and character literals are enclosed in single quotation marks. Appendix C.3 contains more details on code points. The character type in F# is denoted *char*. Examples of characters are 'a', 'D', '3', and examples of non-characters are '23' and 'abc'. Some characters, such as the tabulation character, do not have a visual representation. These can still be represented as a character using *escape sequences*. A character escape sequence starts with “\” followed by letter for simple escapes such as `\t` for tabulation and `\n` for newline. Escape sequences can also be a numerical representation of a code point, and three versions exist: The trigraph `\DDD`, where D is a decimal digit, is used to specify the first 256 code points, the hexadecimal escape codes `\uXXXX`, where X is a hexadecimal digit, is used to specify the first 65536 code points, and `\UXXXXXXXX` is used to specify any of the approximately $4.3 \cdot 10^9$ possible code points. All escape sequences are shown in Table 3.2. Examples of *char* representations of the letter 'a' are: 'a', '\097',

Character	Escape sequence	Description
BS	<code>\b</code>	Backspace
LF	<code>\n</code>	Line feed
CR	<code>\r</code>	Carriage return
HT	<code>\t</code>	Horizontal tabulation
\	<code>\\</code>	Backslash
"	<code>\"</code>	Quotation mark
'	<code>\'</code>	Apostrophe
BEL	<code>\a</code>	Bell
FF	<code>\f</code>	Form feed
VT	<code>\v</code>	Vertical tabulation
	<code>\uXXXX</code> , <code>\UXXXXXXXX</code> , <code>\DDD</code>	Unicode character ('X' is any hexadecimal digit, and 'D' is any decimal digit)

Table 3.2 Escape characters. The escapecode `\DDD` is sometimes called a tricode.

'\u0061', '\U00000061'.

A *string* is a sequence of characters enclosed in double quotation marks. Examples are "a", "this is a string", and "-&#@". Note that the string "a" and the character 'a' are not the same. Some strings are so common that they are given special names: One or more spaces " " is called *whitespace*, and both "`\n`" and "`\r\n`" are called *newline*. The escape-character “\” may be used to break a line in two. This and other examples are shown in Listing 3.3. Note that the response from `fsharp` is shown in double quotation marks, but this is not part of the string.

F# supports *literal types*, where the type of a literal is indicated as a prefix or suffix as shown in Table 3.3.

Listing 3.3: Examples of string literals.

```

1 > "abcde";;
2 val it: string = "abcde"
3
4 > "abc
5   de";;
6 val it: string = "abc
7   de"
8
9 > "abc\
10  de";;
11 val it: string = "abcde"
12
13 > "abc\nde";;
14 val it: string = "abc
15 de"

```

Type	syntax	Examples	Value
int, int32	<int xint> <int xint>l	3, 0x3 3l, 0x3l	3
uint32	<int xint>u <int xint>ul	3u 3ul	3
byte, uint8	<int xint>uy '<char>'B	97uy 'a'B	97
byte[]	"<string>"B @"<string>"B	"a\n"B @"a\n"B	[[97uy; 10uy]] [[97uy; 92uy; 110uy]]
sbyte, int8	<int xint>y	3y	3
int16	<int xint>s	3s	3
uint16	<int xint>us	3us	3
int64	<int xint>L	3L	3
uint64	<int xint>UL <int xint>uL	3UL 3uL	3
float, double	<float> <xint>LF	3.0 0x013LF	3.0 9.387247271e-323
single, float32	<float>F <float>f <xint>lf	3.0F 3.0f 0x013lf	3.0 3.0 4.4701421e-43f
decimal	<float int>M <float int>m	3.0M, 3M 3.0m, 3m	3.0
string	"<string>" @"<string>" ""<string>""	"\"quote\".\n" @"\"quote\".\n" ""\"quote\".\n""	"quote".<newline> "quote\".\n. "quote\".\n

Table 3.3 List of literal types. The syntax notation <> means that the programmer replaces the brackets and content with a value of the appropriate form. The <xint> is one of the integers on hexadecimal, octal, or binary forms such as 0x17, 0o21, and 0b10001. The [|] brackets means that the value is an array, see Section 20.3 for details.

The literal type is closely connected to how the values are represented internally. For example, a value of type `int32` use 32 bits and can be both positive and negative, while a `uint32` value also use 32 bits, but is unsigned. A `byte` is an 8-bit number, and `sbyte` is a signed 8-bit number. Values of type `float` use 64 bits, while `float32` only uses 32 bits. The number of bits used to represent numbers directly relates to the

range and precession these types can represent. This is summarized in Table 3.1 and discussed in more detail in Appendix B. String literals may be *verbatim* by the @-notation or triple double quotation marks, meaning that the escape sequences are not converted to their code point. The two types of string verbatim treat quotation marks differently, as illustrated in the table. Further examples are shown in Listing 3.4.

Listing 3.4: Named and implied literals.

```
1 > 3;;
2 val it: int = 3
3
4 > 4u;;
5 val it: uint32 = 4u
6
7 > 5.6;;
8 val it: float = 5.6
9
10 > 7.9f;;
11 val it: float32 = 7.9000000095f
12
13 > 'A';;
14 val it: char = 'A'
15
16 > 'B'B;;
17 val it: byte = 66uy
18
19 > "ABC";;
20 val it: string = "ABC"
21
22 > @"abc\nde";;
23 val it: string = "abc\nde"
```

Many basic types are compatible, and the type of a literal may be changed by *typecasting*. An example of casting to a float is shown in Listing 3.5. When

Listing 3.5: Casting an integer to a floating point number.

```
1 > float 3;;
2 val it: float = 3.0
```

`float` is given an argument, then it acts as a function rather than a type, and for the integer 3 it returns the floating point number 3.0. For more on functions see Chapter 4. Boolean values are often treated as the integer values 0 and 1, but no short-hand function names exist for their conversions. Instead, use functions from the `System.Convert` family of functions, as demonstrated in Listing 3.6. Here `System.Convert.ToBoolean` is the identifier of a function `ToBoolean`, which is a *member* of the *class* `Convert` that is included in the *namespace* `System`. Namespaces, classes, and members will be discussed in Chapter 18.

Typecasting is often a destructive operation, e.g., typecasting a `float` to `int` removes the fractional part without rounding as shown in Listing 3.7. Here we typecasted to

Listing 3.6: Casting booleans.

```

1 > System.Convert.ToBoolean 1;;
2 val it: bool = true
3
4 > System.Convert.ToBoolean 0;;
5 val it: bool = false
6
7 > System.Convert.ToInt32 true;;
8 val it: int = 1
9
10 > System.Convert.ToInt32 false;;
11 val it: int = 0

```

Listing 3.7: Fractional part is removed by downcasting.

```

1 > int 357.6;;
2 val it: int = 357

```

a lesser type, in the sense that the set of integers is a subset of floating point numbers, and this is called *downcasting*. The opposite is called *upcasting* and is often non-destructive, as Listing 3.5 showed. Since floating point numbers are a superset of integers, the value is retained. As a side note, *rounding* a number $y.x$, where y is the *whole part* and x is the *fractional part*, is the operation of mapping numbers in the interval $y.x \in [y.0, y.5)$ to y , and those in $y.x \in [y.5, y + 1)$ to $y + 1$. This can be performed by downcasting, as shown in Listing 3.8. I.e., $357.6 + 0.5 = 358.1$

Listing 3.8: Rounding by modified downcasting.

```

1 > int (357.6 + 0.5);;
2 val it: int = 358

```

and removing the fractional part by downcasting results in 358, which is the correct answer.

3.2 Operators on Basic Types

Expressions are the basic building block of all F# programs, and this section will discuss operator expressions on basic types. A typical calculation, such used in Listing 3.8, is

$$\underbrace{357.6}_{\text{operand}} \quad \underbrace{+}_{\text{operator}} \quad \underbrace{0.5}_{\text{operand}} \quad (3.1)$$

is an example of an arithmetic *expression*, and the above expression consists of two *operands* and an *operator*. Since this operator takes two operands, it is called a

binary operator. The expression is written using *infix notation*, since the operands appear on each side of the operator.

In order to discuss general programming structures, we will use a simplified language to describe valid syntactical structures. In this simplified language, the syntax of basic binary operators is shown in the following.

Listing 3.9: Syntax for a binary expression.

```
1 <expr><op><expr>
```

Here `<expr>` is any expression supplied by the programmer, and `<op>` is a binary infix operator. F# supports a range of arithmetic binary infix operators on its built-in types, such as addition, subtraction, multiplication, division, and exponentiation, using the “+”, “-”, “*”, “/”, “**” lexemes, respectively. Not all operators are defined for all types, e.g., addition is defined for integer and float types as well as for characters and strings, but multiplication is only defined for integer and floating-point types. A complete list of built-in operators on basic types is shown in Table 3.4 and 3.5, and a range of mathematical functions is shown in Table 3.6. Note that

Operator	bool	ints	floats	char	string	Example	Result	Description
+		✓	✓	✓	✓	5 + 2	7	Addition
-		✓	✓			5.0 - 2.0	3.0	Subtraction
*		✓	✓			5 * 2	10	Multiplication
/		✓	✓			5.0 / 2.0	2.5	Division
%		✓	✓			5 % 2	1	Remainder
**			✓			5.0 ** 2.0	25.0	Exponentiation
+		✓	✓			+3	3	identity
-		✓	✓			-3.0	-3.0	negation
&&	✓					true && false	false	boolean and
	✓					true false	true	boolean or
not	✓					not true	false	boolean negation
&&&		✓				0b101 &&& 0b110	0b100	bitwise boolean and
		✓				0b101 0b110	0b111	bitwise boolean or
^^^		✓				0b101 ^^^ 0b110	0b011	bitwise boolean exclusive or
<<<		✓				0b110uy <<< 2	0b11000uy	bitwise left shift
>>>		✓				0b110uy >>> 2	0b1uy	bitwise right shift
~~~		✓				~~~0b110uy	0b11111001uy	bitwise boolean negation

**Table 3.4** Arithmetic operators on basic types. Ints and floats means all built-in integer and float types. Note that for the bitwise operations, digits 0 and 1 are taken to be `true` and `false`.

expressions can themselves be arguments to expressions, and thus, 4+5+6 is also a legal statement. Technically, F# interprets the expression as (4+5)+6 meaning that first 4+5 is evaluated according to the `<expr><op><expr>` syntax. Then the result replaces the parenthesis to yield 9+6, which, once again, is evaluated according to the `<expr><op><expr>` syntax to give 15. This is called *recursion*, which is the name for a type of rule or function that uses itself in its definition. See Chapter 8 for more on recursive functions.

Operator	bool	ints	floats	char	string	Example	Result	Description
<	✓	✓	✓	✓	✓	<code>true &lt; false</code>	<code>false</code>	Less than
>	✓	✓	✓	✓	✓	<code>5 &gt; 2</code>	<code>true</code>	Greater than
=	✓	✓	✓	✓	✓	<code>5.0 = 2.0</code>	<code>false</code>	Equal
<=	✓	✓	✓	✓	✓	<code>'a' &lt;= 'b'</code>	<code>true</code>	Less than or equal
>=	✓	✓	✓	✓	✓	<code>"ab" &gt;= "cd"</code>	<code>false</code>	Greater than or equal
<>	✓	✓	✓	✓	✓	<code>5 &lt;&gt; 2</code>	<code>true</code>	Not equal

**Table 3.5** Comparison operators on basic types. Types cannot be mixed, e.g., `3 < 'a'` is a syntax error.

Operator	bool	ints	floats	char	string	Example	Result	Description
abs		✓	✓			<code>abs -3</code>	3	Absolute value
acos			✓			<code>acos 0.8</code>	0.644	Inverse cosine
asin			✓			<code>asin 0.8</code>	0.927	Inverse sinus
atan			✓			<code>atan 0.8</code>	0.675	Inverse tangent
atan2			✓			<code>atan2 0.8 2.3</code>	0.335	Inverse tangentvariant
ceil			✓			<code>ceil 0.8</code>	1.0	Ceiling
cos			✓			<code>cos 0.8</code>	0.697	Cosine
exp			✓			<code>exp 0.8</code>	2.23	Natural exponent
floor			✓			<code>floor 0.8</code>	0.0	Floor
log			✓			<code>log 0.8</code>	-0.223	Natural logarithm
log10			✓			<code>log10 0.8</code>	-0.0969	Base-10 logarithm
max	✓	✓	✓	✓		<code>max 3.0 4.0</code>	4.0	Maximum
min	✓	✓	✓	✓		<code>min 3.0 4.0</code>	3.0	Minimum
pown	✓					<code>pown 3 2</code>	9	Integer exponent
round			✓			<code>round 0.8</code>	1.0	Rounding
sign	✓	✓				<code>sign -3</code>	-1	Sign
sin			✓			<code>sin 0.8</code>	0.717	Sinus
sqrt			✓			<code>sqrt 0.8</code>	0.894	Square root
tan			✓			<code>tan 0.8</code>	1.03	Tangent

**Table 3.6** Predefined functions for arithmetic operations.

Unary operators take only one argument and have the syntax:

#### Listing 3.10: A unary expressions.

```
1 <op><expr>
```

An example of a unary operator is `-3`, where `-` here is used to negate a positive integer. Since the operator appears before the operand, it is a *prefix operator*.

The concept of *precedence* is an important concept in arithmetic expressions. If parentheses are omitted in Listing 3.8, then F# will interpret the expression as `(int 357.6) + 0.5`, which is erroneous since the addition of an integer with a float is undefined. This is an example of precedence, i.e., function evaluation takes precedence over addition which means that function evaluation is performed first and

addition second. Consider the arithmetic expression shown in Listing 3.11. Here, the

**Listing 3.11: A simple arithmetic expression.**

```
1 > 3 + 4 * 5;;
2 val it: int = 23
```

addition and multiplication functions are shown in infix notation with the *operator* lexemes “+” and “*”. To arrive at the resulting value 23, F# has to decide in which order to perform the calculation. There are 2 possible orders,  $3 + (4 * 5)$  and  $(3 + 4) * 5$  that gives different results. For integer arithmetic, the correct order is, of course, multiplication before addition, and we say that multiplication takes *precedence* over addition. Every atomic operation that F# can perform is ordered in terms of its precedence, and for some common built-in operators shown in Table 3.7, the precedence is shown by the order they are given in the table.

Operator	Associativity	Description
+<expr> -<expr> ~~~<expr>	Left	Unary identity, negation, and bitwise negation operators
f <expr>	Left	Function application
<expr> ** <expr>	Right	Exponentiation
<expr> * <expr> <expr> / <expr> <expr> % <expr>	Left	Multiplication, division and remainder
<expr> + <expr> <expr> - <expr>	Left	Addition and subtraction binary operators
<expr> ^^^ <expr>	Right	Bitwise exclusive or
<expr> < <expr> <expr> <= <expr> <expr> > <expr> <expr> >= <expr> <expr> = <expr> <expr> <> <expr> <expr> <<< <expr> <expr> >>> <expr> <expr> &&& <expr> <expr>     <expr>	Left	Comparison operators, bitwise shift, and bitwise 'and' and 'or'.
<expr> && <expr>	Left	Boolean and
<expr>    <expr>	Left	Boolean or

**Table 3.7** Some common operators, their precedence, and their associativity. Rows are ordered from highest to lowest precedences, such that <expr> * <expr> has higher precedence than <expr> + <expr>. Operators in the same row have the same precedence..

Associativity describes the order in which calculations are performed for binary operators of the same precedence. Some operator’s associativity are given in Table 3.7. In the table we see that “*” is left associative, which means that  $3.0 * 4.0 * 5.0$  is evaluated as  $(3.0 * 4.0) * 5.0$ . Conversely, “**” is right associative, so  $4.0 ** 3.0 ** 2.0$  is evaluated as  $4.0 ** (3.0 ** 2.0)$ . For some operators, like multiplication, association matters little, e.g.,  $4 * 3 * 2 = 4 * (3 * 2) = (4 * 3) * 2$ , and for other operators, like exponentiation, association makes a huge difference, e.g.,



$4^{(3^2)} \neq (4^3)^2$ . Examples of this is shown in Listing 3.12. **Whenever in doubt of** ★

**Listing 3.12: Precedence rules define implicit parentheses.**

```

1 > 4.0 * 3.0 * 2.0;;
2 val it: float = 24.0
3
4 > (4.0 * 3.0) * 2.0;;
5 val it: float = 24.0
6
7 > 4.0 * (3.0 * 2.0);;
8 val it: float = 24.0
9
10 > 4.0 ** 3.0 ** 2.0;;
11 val it: float = 262144.0
12
13 > (4.0 ** 3.0) ** 2.0;;
14 val it: float = 4096.0
15
16 > 4.0 ** (3.0 ** 2.0);;
17 val it: float = 262144.0

```

association or any other basic semantic rules, it is a good idea to use parentheses. It is also a good idea to test your understanding of the syntax and semantic rules by making a simple script.

### 3.3 Boolean Arithmetic

Boolean arithmetic is the basis of almost all computers and particularly important for controlling program flow, which will be discussed in Chapter 21. Boolean values are one of 2 possible values, true or false, which is also sometimes written as 1 and 0. Basic operations on Boolean values are 'and', 'or', and 'not', which in F# are written respectively as the binary operators &&, ||, and the function not. Since the domain of Boolean values is so small, all possible combination of input on these values can be written on the tabular form, known as a *truth table*, and the truth tables for the basic Boolean operators and functions are shown in Table 3.8. A good mnemonic

a	b	a && b	a    b	not a
false	false	false	false	true
false	true	false	true	true
true	false	false	true	false
true	true	true	true	false

**Table 3.8** Truth table for boolean 'and', 'or', and 'not' operators. Value 0 is false and 1 is true.

for remembering the result of the 'and' and 'or' operators is to use 1 for true, 0 for false, multiplication for the Boolean 'and' operator, and addition for the Boolean 'or' operator, e.g., true and false in this mnemonic translates to  $1 \cdot 0 = 0$ , and the result

translates back to the Boolean value `false`. In F#, the truth table for the basic Boolean operators can be produced by a program, as shown in Listing 3.13. Here, we used

**Listing 3.13: Boolean operators and truth tables.**

```

1
2 > printfn "a b a*b a+b not a"
3 printfn "%A %A %A %A %A"
4   false false (false && false) (false || false) (not false)
5 printfn "%A %A %A %A %A"
6   false true (false && true) (false || true) (not false)
7 printfn "%A %A %A %A %A"
8   true false (true && false) (true || false) (not true)
9 printfn "%A %A %A %A %A"
10  true true (true && true) (true || true) (not true);;
11 a b a*b a+b not a
12 false false false false true
13 false true false true true
14 true false false true false
15 true true true true false
16 val it: unit = ()

```

the `printfn` function to present the results of many expressions on something that resembles a tabular form. The spacing produced using the `printfn` function is not elegant, and in ?? we will discuss better options for producing more beautiful output. Notice that the arguments for `printfn` was given on the next line with indentation. The indentation is an important part of telling F# which part of what you write belong together. This is an example of the so-called lightweight syntax. Generally, F# ignores newlines and whitespaces except when using the lightweight syntax. The difference between verbose and lightweight syntax is discussed in Chapter 4.

### 3.4 Integer Arithmetic

The set of integers is infinitely large, but since all computers have limited resources, it is not possible to represent it in its entirety. The various integer types listed in Table 3.1 are finite subsets reduced by limiting their ranges. An in-depth description of integer implementation can be found in Appendix B. The type `int` is the most common type.

Table 3.4–3.6 give examples of operators and functions pre-defined for integer types. Notice that fewer functions are available for integers than for floating point numbers. For most addition, subtraction, multiplication, and negation, the result is straightforward. However, performing arithmetic operations on integers requires extra care, since the result may cause *overflow* and *underflow*. For example, an `sbyte` is specified using the “y”-literal and can hold values `[-128 .. 127]`. This causes problems

in the example in Listing 3.14. Here  $100 + 30 = 130$ , which is larger than the biggest

**Listing 3.14: Adding integers may cause overflow.**

```
1 > 100y;;
2 val it: sbyte = 100y
3
4 > 30y;;
5 val it: sbyte = 30y
6
7 > 100y + 30y;;
8 val it: sbyte = -126y
```

sbyte, and the result is an overflow. Similarly, we get an underflow, when the arithmetic result falls below the smallest value storable in an sbyte, as demonstrated in Listing 3.15. I.e., we were expecting a negative number but got a positive number

**Listing 3.15: Subtracting integers may cause underflow.**

```
1 > -100y - 30y;;
2 val it: sbyte = 126y
```

instead.

The overflow error in Listing 3.14 can be understood in terms of the binary representation of integers: In binary,  $130 = 10000010_2$ , and this binary pattern is interpreted differently as byte and sbyte, see Listing 3.16. That is, for signed bytes, the left-

**Listing 3.16: The leftmost bit is interpreted differently for signed and unsigned integers, which gives rise to potential overflow errors.**

```
1 > 0b10000010uy;;
2 val it: byte = 130uy
3
4 > 0b10000010y;;
5 val it: sbyte = -126y
```

most bit is used to represent the sign, and since the addition of  $100 = 01100100_2$  and  $30 = 00011110_2$  is  $130 = 10000010_2$ , which causes the left-most bit to be used, this is wrongly interpreted as a negative number when stored in an sbyte. Similar arguments can be made explaining underflows.

The `operator` discards the fractional part after division, and the *integer remainder* operator calculates the remainder after integer division, as demonstrated in Listing 3.17. Together, the integer division and remainder can form a lossless representation of the original number, see Listing 3.18. Here we see that integer division of 7 by 3 followed by multiplication by 3 is less than 7, and that the difference is  $7 \% 3$ .

Notice that neither overflow nor underflow error gave rise to an error message, which is why such bugs are difficult to find. Dividing any non-zero number by 0 is infinite, which is also outside the domain of any of the integer types, but in this case, F#

**Listing 3.17: Integer division and remainder operators.**

```

1 > 7 / 3;;
2 val it: int = 2
3
4 > 7 % 3;;
5 val it: int = 1

```

**Listing 3.18: Integer division and remainder is a lossless representation of an integer, compare with Listing 3.17.**

```

1 > (7 / 3) * 3;;
2 val it: int = 6
3
4 > (7 / 3) * 3 + (7 % 3);;
5 val it: int = 7

```

casts an *exception*, as shown in Listing 3.19. The output looks daunting at first sight,

**Listing 3.19: Integer division by zero causes an exception runtime error.**

```

1 > 3/0;;
2 System.DivideByZeroException: Attempted to divide by zero.
3   at <StartupCode$FSI_0002>.$FSI_0002.main@()

```

but the first and last lines of the error message are the most important parts, which tell us what exception was cast and why the program stopped. The middle contains technical details concerning which part of the program caused the error and can be ignored for the time being. Exceptions are a type of *runtime error*, and are discussed in Chapter 13

Integer exponentiation is not defined as an operator but is available as the built-in function `pown`. This function is demonstrated in Listing 3.20 for calculating  $2^5$ .

**Listing 3.20: Integer exponent function.**

```

1 > pown 2 5;;
2 val it: int = 32

```

For binary arithmetic on integers, the following operators are available: `<leftExpr> <<< <rightExpr>`, which shifts the bit pattern of `<leftExpr>` `<rightExpr>` positions to the left while inserting 0's to right; `<leftExpr> >>> <rightExpr>`, which shifts the bit pattern of `<leftExpr>` `<rightExpr>` positions to the right while inserting 0's to left; `~~~ <expr>` returns a new integer, where all 0 bits are changed to 1 bits and vice-versa; `<expr> &&& <expr>` returns the result of taking the Boolean 'and' operator position-wise; `<expr> ||| <expr>` returns the result of taking the Boolean 'or' operator position-wise; and `<expr> ^^^ <expr>` returns the result of the Boolean 'xor' operator defined by the truth table in Table 3.9.

a	b	a ^^^ b
false	false	false
false	true	true
true	false	true
true	true	false

**Table 3.9** Boolean exclusive or truth table.

### 3.5 Floating Point Arithmetic

Like integers, the set of reals is also infinitely large, hence, floating point types are finite subsets reduced by sampling the space of reals. An in-depth description of floating point implementations can be found in Appendix B. The type `float` is the most common type.

Table 3.4–3.6 give examples of operators and functions pre-defined for floating point types. Note that the remainder operator for floats calculates the remainder after division and discards the fractional part, see Listing 3.21. The remainder for

#### Listing 3.21: Floating point division and remainder operators.

```
1 > 7.0 / 2.5;;
2 val it: float = 2.8
3
4 > 7.0 % 2.5;;
5 val it: float = 2.0
```

floating point numbers can be fractional, but division, discarding fractional part, and the remainder is still a lossless representation of the original number, as demonstrated in Listing 3.22.

#### Listing 3.22: Floating point division, downcasting, and remainder is a lossless representation of a number.

```
1 > float (int (7.0 / 2.5));;
2 val it: float = 2.0
3
4 > (float (int (7.0 / 2.5))) * 2.5;;
5 val it: float = 5.0
6
7 > (float (int (7.0 / 2.5))) * 2.5 + 7.0 % 2.5;;
8 val it: float = 7.0
```

Arithmetic using `float` will not cause over- and underflow problems, since the IEEE 754 standard includes the special numbers  $\pm\infty$  and NaN. As shown in Listing 3.23, no exception is thrown. However, the `float` type has limited precision, since there is only a finite number of numbers that can be stored in a float. E.g., addition and subtraction can give surprising results, as demonstrated in Listing 3.24. That is, addition and subtraction associates to the left, hence the expression is interpreted as  $(357.8 + 0.1) - 357.9$  and we see that we do not get the expected 0. The

**Listing 3.23: Floating point numbers include infinity and Not-a-Number.**

```

1 > 1.0/0.0;;
2 val it: float = infinity
3
4 > 0.0/0.0;;
5 val it: float = nan

```

**Listing 3.24: Floating point arithmetic has finite precision.**

```

1 > 357.8 + 0.1 - 357.9;;
2 val it: float = 5.684341886e-14

```

reason is that the calculation is done stepwise, and in the process, the numbers are represented using the imprecise floating point standard. Thus,  $357.8 + 0.1$  is represented as a number close to but not identical to what  $357.9$  is represented as, and thus, when subtracting these two representations, we get a very small nonzero number. Such errors tend to accumulate, and comparing the result of expressions of floating point values should, therefore, be treated with care. Thus, **equivalence of two floating point expressions should only be considered up to sufficient precision, e.g., comparing  $357.8 + 0.1$  and  $357.9$  up to  $1e-10$  precision should be tested as, `abs ((357.8 + 0.1) - 357.9) < 1e-10`.**

### 3.6 Char and String Arithmetic

Addition is the only operator defined for characters. Nevertheless, character arithmetic is often done by casting to an integer. A typical example is the conversion of character case, e.g., to convert the lowercase character 'z' to uppercase. Here, we use the *ASCIIbetical order*, add the difference between any Basic Latin Block letters in upper- and lowercase as integers, and cast back to `char`, see Listing 3.25. I.e., the

**Listing 3.25: Converting case by casting and integer arithmetic.**

```

1 > char (int 'z' - int 'a' + int 'A');;
2 val it: char = 'Z'

```

code point difference between upper and lower case for any alphabetical character 'a' to 'z' is constant, hence we can change case by adding or subtracting the difference between any corresponding character. Unfortunately, this does not generalize to characters from other languages.

A large collection of operators and functions exist for `string`. The simplest is concatenation using the “+” operator, as demonstrated in Listing 3.26. Characters and strings cannot be concatenated, which is why the above example used the string of a space “ ” instead of the space character ' '. The characters of a string may

**Listing 3.26: Example of string concatenation.**

```
1 > "hello" + " " + "world";  
2 val it: string = "hello world"
```

be indexed as using the `[]` notation. This is demonstrated in Listing 3.27. Notice

**Listing 3.27: String indexing using square brackets.**

```
1  
2 > "abcdefg"[0];;  
3 val it: char = 'a'  
4  
5 > "abcdefg"[3];;  
6 val it: char = 'd'  
7  
8 > "abcdefg"[3..];;  
9 val it: string = "defg"  
10  
11 > "abcdefg"[..3];;  
12 val it: string = "abcd"  
13  
14 > "abcdefg"[1..3];;  
15 val it: string = "bcd"  
16  
17 > "abcdefg"[*];;  
18 val it: string = "abcdefg"
```

that the first character has index 0, and to get the last character in a string, we use the string's `length` property. This is done as shown in Listing 3.28. Since index

**Listing 3.28: String length attribute and string indexing.**

```
1 > "abcdefg".Length;;  
2 val it: int = 7  
3  
4 > "abcdefg"[7-1];;  
5 val it: char = 'g'
```

counting starts at 0, and since the string length is 7, the index of the last character is 6. There is a long list of built-in functions in `System.String` for working with strings, some of which will be discussed in Section 10.1.

The *dot notation* is an example of Structured programming, where technically speaking, the string `"abcdefg"` is an immutable *object* of *class* `string`, `[]` is an object *method*, and `Length` is a property. For more on objects, classes, and methods, see Chapter 23.

Strings are compared letter by letter. For two strings to be equal, they must have the same length and all the letters must be identical. E.g., `"abs" = "absalon"` is false, while `"abs" = "abs"` is true. The `"<>"` operator is the boolean negation of the `"="` operator, e.g., `"abs" <> "absalon"` is true, while `"abs" <> "abs"` is false.

For the “<”, “<=”, “>”, and “>=” operators, the strings are ordered alphabetically, such that `"abs" < "absalon" && "absalon" < "milk"` is true, that is, the “<” operator on two strings is true if the left operand should come before the right when sorting alphabetically. The algorithm for deciding the boolean value of `leftOp < rightOp` is as follows: we start by examining the first character, and if `leftOp[0]` and `rightOp[0]` are different, then `leftOp < rightOp` is equal to `leftOp[0] < rightOp[0]`. E.g., `"milk" < "abs"` is the same as `'m' < 'a'`, which is false, since the letter 'm' does not come before the letter 'a' in the alphabet, or more precisely, the codepoint of 'm' is not less than the codepoint of 'a'. If `leftOp[0]` and `rightOp[0]` are equal, then we move on to the next letter and repeat the investigation, e.g., `"abe" < "abs"` is true, since `"ab" = "ab"` is true and `'e' < 's'` is true. If we reach the end of either of the two strings, then the shorter word is smaller than the longer word, e.g., `"abs" < "absalon"` is true, while `"abs" < "abs"` is false. The “<=”, “>”, and “>=” operators are defined in a similar manner.

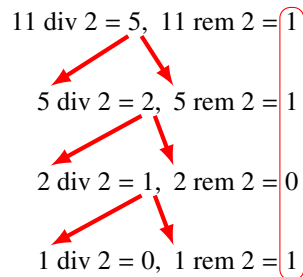


### 3.7 Programming Intermezzo: Hand Conversion Between Decimal and Binary Numbers

Conversion of integers between decimal and binary form is a key concept one must grasp in order to understand some of the basic properties of calculations on the computer. Converting from binary to decimal is straightforward if using the power-of-two algorithm, i.e., given a sequence of  $n + 1$  binary digits  $b_i$  written as  $b_n b_{n-1} \dots b_0$ , and where  $b_n$  and  $b_0$  are the most and least significant bits respectively, then the decimal value is calculated as,

$$v = \sum_{i=0}^n b_i 2^i \quad (3.2)$$

For example,  $10011_2 = 1 + 2 + 16 = 19$ . Converting from decimal to binary is a little more complex, but a simple divide-by-two algorithm exists. The key to understanding the divide-by-two algorithm is to realize that dividing a number by two is equivalent to shifting its binary representation one position to the right. E.g.,  $10 = 1010_2$  and  $10/2 = 5 = 101_2$ . Odd numbers have  $b_0 = 1$ , e.g.,  $11_{10} = 1011_2$  and  $11_{10}/2 = 5.5 = 101.1_2$ . Hence, if we divide any number by two and get a non-integer number, then its least significant bit was 1. Another way to express this is to say that the least significant bit is the remainder after integer division by two. Sequential application of this idea leads directly to the divide-by-two algorithm. E.g., if we were to convert the number  $11_{10}$  in decimal form to binary form, we would perform the following steps:



Here we used `div` and `rem` to signify the integer division and remainder operators. The algorithm stops when the result of integer division is zero. Reading off the remainder from below and up, we find the sequence  $1011_2$ , which is the binary form of the decimal number  $11_{10}$ . Using the interactive mode, we can perform the same calculation, as shown in Listing 3.29.

**Listing 3.29: Converting the number  $11_{10}$  to binary form.**

```

> printfn "(%d, %d)" (11 / 2) (11 % 2);;
(5, 1)
val it : unit = ()
> printfn "(%d, %d)" (5 / 2) (5 % 2);;
(2, 1)
val it : unit = ()
> printfn "(%d, %d)" (2 / 2) (2 % 2);;
(1, 0)
val it : unit = ()
> printfn "(%d, %d)" (1 / 2) (1 % 2);;
(0, 1)
val it : unit = ()

```

Thus, by reading the second integer-response from `printfn` from below and up, we again obtain the binary form of  $11_{10}$  to be  $1011_2$ . For integers with a fractional part, the divide-by-two algorithm may be used on the whole part, while multiply-by-two may be used in a similar manner on the fractional part.

### 3.8 Key concepts and terms in this chapter

In this chapter you have learned about:

- the **basic types**: **int** of various kinds which are all a subset of integers, **float** of various kinds which are all subsets of reals, **bool** which captures the notion of true and false, and **char** and **string** which holds characters and sequences of characters;
- how to write constants of the basic types, which are called **literals**;
- **operators** such as “+” and “-” and whose arguments are called **operands**;
- **unary** and **binary** operators;
- **escape sequences** for characters and strings;
- how to get the **length** of a string using the **dot** notation, and how to extract substrings using the **slice** notation.

## Chapter 4

# Values, Functions, and Statements

**Abstract** In the previous chapter, you got an introduction to the fundamental concepts of booleans, numbers, characters, and strings, how to perform calculations with them, and some of the limitations they have on the computer. This allows us to perform simple calculations as if the computer was an advanced pocket calculator. In this chapter, we will look at how we can:

- make assign values to names to make programs that are easier to read and write
- organise lines of code in functions, to make the same line reusable, and to make programs shorter, easier to understand.
- use operators as functions
- conditionally execute code
- how we can simulate the computer's execution of code by tracing-by-hand, to improve our understanding of, how it interprets the code, we write, and find errors.

Examples of problems, you can solve, after having read this chapter is:

- Write a function that given the parameters  $a$  and  $b$  in  $f(x) = ax + b$ , find the value of  $x$  when  $f(x) = 0$ .
- 

---

In this chapter, we will see how we can bind expressions to identifiers either as new constants, functions, or operators, how this saves time when building large programs,

and how this makes programs easier to read and debug. As an example, consider the following problem,

**Problem 4.1**

or given set constants  $a$ ,  $b$ , and  $c$ , solve for  $x$  in

$$ax^2 + bx + c = 0 \quad (4.1)$$

To solve for  $x$  we use the quadratic formula from elementary algebra,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \quad (4.2)$$

which gives the general solution for any values of the coefficients. Here, we will assume a positive discriminant,  $b^2 - 4ac > 0$ . In order to write a program where the code may be reused later, we define a function

```
discriminant : float -> float -> float -> float
```

that is, a function that takes 3 arguments,  $a$ ,  $b$ , and  $c$ , and calculates the discriminant. Likewise, we will define

```
positiveSolution : float -> float -> float -> float
```

and

```
negativeSolution : float -> float -> float -> float
```

that also take the polynomial's coefficients as arguments and calculate the solution corresponding to choosing the positive and negative sign for  $\pm$  in the equation. Details on function definition is given in Section 4.2. Our solution thus looks like Listing 4.1. Here, we have further defined names of values  $a$ ,  $b$ , and  $c$  which are used as inputs to our functions, and the results of function application are bound to the names  $d$ ,  $xn$ , and  $xp$ . The names of functions and values given here are examples of identifiers, and with these, we may reuse the quadratic formulas and calculated values later, while avoiding possible typing mistakes and reducing the amount of code which needs to be debugged.

The use of identifiers is central in programming. For F#, not to be confused with built-in functionality, identifiers must follow a specific set of rules:

**Identifier**

- Identifiers are used as names for values, functions, types etc.

**Listing 4.1** identifiersExample.fsx:

Finding roots for quadratic equations using function name binding.

```

1 let discriminant a b c = b ** 2.0 - 4.0 * a * c
2 let positiveSolution a b c = (-b + sqrt (discriminant a b c))
  / (2.0 * a)
3 let negativeSolution a b c = (-b - sqrt (discriminant a b c))
  / (2.0 * a)
4
5 let a = 1.0
6 let b = 0.0
7 let c = -1.0
8 let d = discriminant a b c
9 let xp = positiveSolution a b c
10 let xn = negativeSolution a b c
11 do printfn "0 = %A * x ** 2.0 + %A * x + %A" a b c
12 do printfn "    has discriminant %A and solutions %A and %A" d
   xn xp

```

---

```

1 $ dotnet fsi identifiersExample.fsx
2 0 = 1.0 * x ** 2.0 + 0.0 * x + -1.0
3    has discriminant 4.0 and solutions -1.0 and 1.0

```

- They must start with a Unicode letter or underscore ' _ ', but can be followed by zero or more of letters, digits, and a range of special characters except for SP, LF, and CR (space, line feed, and carriage return). See Appendix C.3 for more on codepoints that represents letters.
- They can also be a sequence of identifiers separated by a period.
- They cannot be keywords, see Table 4.1.

Type	Keyword
Regular	<code>abstract</code> , <code>and</code> , <code>as</code> , <code>assert</code> , <code>base</code> , <code>begin</code> , <code>class</code> , <code>default</code> , <code>delegate</code> , <code>do</code> , <code>done</code> , <code>downcast</code> , <code>downto</code> , <code>elif</code> , <code>else</code> , <code>end</code> , <code>exception</code> , <code>extern</code> , <code>false</code> , <code>finally</code> , <code>for</code> , <code>fun</code> , <code>function</code> , <code>global</code> , <code>if</code> , <code>in</code> , <code>inherit</code> , <code>inline</code> , <code>interface</code> , <code>internal</code> , <code>lazy</code> , <code>let</code> , <code>match</code> , <code>member</code> , <code>module</code> , <code>mutable</code> , <code>namespace</code> , <code>new</code> , <code>null</code> , <code>of</code> , <code>open</code> , <code>or</code> , <code>override</code> , <code>private</code> , <code>public</code> , <code>rec</code> , <code>return</code> , <code>sig</code> , <code>static</code> , <code>struct</code> , <code>then</code> , <code>to</code> , <code>true</code> , <code>try</code> , <code>type</code> , <code>upcast</code> , <code>use</code> , <code>val</code> , <code>void</code> , <code>when</code> , <code>while</code> , <code>with</code> , and <code>yield</code> .
Reserved	<code>atomic</code> , <code>break</code> , <code>checked</code> , <code>component</code> , <code>const</code> , <code>constraint</code> , <code>constructor</code> , <code>continue</code> , <code>eager</code> , <code>fixed</code> , <code>fori</code> , <code>functor</code> , <code>include</code> , <code>measure</code> , <code>method</code> , <code>mixin</code> , <code>object</code> , <code>parallel</code> , <code>params</code> , <code>process</code> , <code>protected</code> , <code>pure</code> , <code>recursive</code> , <code>sealed</code> , <code>tailcall</code> , <code>trait</code> , <code>virtual</code> , and <code>volatile</code> .
Symbolic	<code>let!</code> , <code>use!</code> , <code>do!</code> , <code>yield!</code> , <code>return!</code> , <code> </code> , <code>-&gt;</code> , <code>&lt;-</code> , <code>..</code> , <code>:</code> , <code>(</code> , <code>)</code> , <code>[</code> , <code>]</code> , <code>[&lt;</code> , <code>&gt;]</code> , <code>[ </code> , <code> ]</code> , <code>{</code> , <code>}</code> , <code>'</code> , <code>#</code> , <code>:?&gt;</code> , <code>:?</code> , <code>:&gt;</code> , <code>...</code> , <code>::</code> , <code>:=</code> , <code>;;</code> , <code>;</code> , <code>=</code> , <code>_</code> , <code>?</code> , <code>??</code> , <code>(*)</code> , <code>&lt;@</code> , <code>@</code> , <code>&lt;@&gt;</code> , and <code>@&gt;</code> .
Reserved symbolic	<code>~</code> and <code>`</code>

**Table 4.1** Table of (possibly future) *keywords* and symbolic keywords in F#.

Examples of identifiers are: `a`, `theCharacter9`, `Next_Word`, `_tok`, and `f.sharp.rocks`.

- ★ Since programmers often work in multilingual environment dominated by the English language it is advisable to **restrict identifiers to use letters from the English alphabet, numbers, period, and '_'**. However, the number of possible identifiers is enormous. The full definition refers to the Unicode general categories described in Appendix C.3, and there are currently 19,345 possible Unicode code points in the letter category and 2,245 possible Unicode code points in the special character category.

Identifiers may be used to carry information about their intended content and use, and careful selection of identifiers can aid programmers to communicate thoughts about the code. Thus, identifiers are often a word or several concatenated words conveying some relevant meaning. For example, in the function definition `let discriminant a b c = b ** 2.0 - 4.0 * a * c`, the function identifier has been chosen to be `discriminant`. F# places no special significance to the word 'discriminant', and the program would work exactly the same had the function been called `let f a b c = b ** 2.0 - 4.0 * a * c`. However, to programmers, the word 'discriminant' informs us of the intended role of the function and thus

- ★ is much preferred. This is a general principle: **identifier names should be chosen to reflect their semantic value**. The arguments `a`, `b`, and `c` are short, but adheres to a textbook tradition of elementary algebra. Again, we might as well have used, `let discriminant c a b = a ** 2.0 - 4.0 * c * b`, which is semantically identical to the original expression, but due to tradition, this would confuse most readers of the code. Thus, **identifier names should be chosen consistently with the readers' traditions**. Finally, identifiers are often concatenations of words, as `positiveSolution` in Listing 4.1. Concatenations can be difficult to read. Without the capitalization of the second word, we would have had `positivesolution`. This is readable at most times, but takes longer time to understand in general. Typical solutions are to use a separator, such as `positive_solution`, *lower camel case* also known as *mixed case* as in the example `positiveSolution`, and *upper camel case* also known as *pascal case* as `PositiveSolution`. In this book, we use lower camel case except where F# requires a capital first letter. Again, the choice does not influence what a program does, only how readable it is to a fellow programmer.
- ★ The important part is that **identifier names consisting of concatenated words are often preferred over names with few character, and concatenation should be emphasized, e.g., by camel casing**. Choosing the length of identifier names is a balancing act, since when working with large programs, very long identifier names can be tiresome to write, and a common practice is that the length of identifier names is proportional to the complexity of the program. I.e., complex programs use long names, simple programs use short names. What is complex and what is simple is naturally in the eye of the beholder, but when you program, remember that a future reader of the program most likely has not had time to work with the problem as long
- ★ as the programmer, thus **choose identifier names as if you were to explain the meaning of a program to a knowledgeable outsider**.

Another key concept in F# is expressions. An expression can be a mathematical expression, such as  $3 * 5$ , a function application, such as  $f3$ , and many other things. Central in this chapter is the binding of values and functions to identifiers, which is done with the keyword `let`, e.g., `let a = 1.0`.

Expressions are the main workhorse of F# and have an enormous variety in how they may be written. We will in this book gradually work through some of the more important facets.

### Expressions

- An Expression is a computation such as  $3 * 5$ .
- They can be value bindings between identifiers and expressions that evaluate to a value or a function, see Sections 4.1 and 4.2.
- They can be `do`-bindings that produce side-effects and whose result are ignored, see Section 4.2
- They can be assignments to variables, see Section 4.1.
- They can be a sequence of expressions separated with the “;” lexeme.
- They can be annotated with a type by using the “:” lexeme.

Before we begin a deeper discussion on bindings, note that F# adheres to two different syntaxes: *verbose* and *lightweight*. In the verbose syntax, newlines and whitespaces are generally ignored, while in lightweight syntax, certain keywords and lexemes may be replaced by newlines and whitespaces. The lightweight syntax is the most common and will be used in this book.

## 4.1 Value Bindings

Binding identifiers to literals, or expressions that are evaluated to be values, is called *value-binding*, and examples are `let a = 3.0` and `let b = cos 0.9`. Value bindings have the following syntax:

**Listing 4.2: Value binding expression.**

```
1 let <valueIdent> = <bodyExpr>
```

The `let` keyword binds a value-identifier with an expression. The above notation means that `<valueIdent>` is to be replaced with a name and `<bodyExpr>` with an

expression that evaluates to a value. The binding *is* available in later lines until the end of the scope it is defined in.

The value identifier annotated with a type by using the “:” lexeme followed by the name of a type, e.g., `int`. The “_” lexeme may be used as a value-identifier. This lexeme is called the *wildcard pattern*, and for value-bindings it means that `<bodyExpr>` is evaluated, but the result is discarded. See Chapter 12 for more details on patterns.

For example, letting the identifier `p` be bound to the value `2.0` and using it in an expression is done as shown in Listing 4.3. Note that the expression `3.0 ** p` must

**Listing 4.3** `letValueLightWeight.fsx`:

Lightweight syntax does not require the `in` keyword, but the expression must be aligned with the `let` keyword.

```
1 let p = 2.0
2 do printfn "%A" (3.0 ** p)

-----

1 $ dotnet fsi letValueLightWeight.fsx
2 9.0
```

be put in parentheses here, to force F# to *first* calculate the result of the expression and *then* give it to `printfn` to be printed on the screen. The same expression in interactive mode will also show with the inferred types, as shown in Listing 4.4. By

**Listing 4.4:** Interactive mode also outputs inferred types.

```
1 > let p = 2.0
2 do printfn "%A" (3.0 ** p);;
3 9.0
4 val p: float = 2.0
5 val it: unit = ()
```

the `val` keyword in the line `val p : float = 2.0`, we see that `p` is inferred to be of type `float` and bound to the value `2.0`. The inference is based on the type of the right-hand-side which is `float`. Identifiers may be defined to have a type using the “:” lexeme, but the types on the left-hand-side and right-hand-side of the “=” lexeme must be identical. Mixing types gives an error, as shown in Listing 4.5. Here, the left-hand-side is defined to be an identifier of type `float`, while the right-hand-side is a literal of type `integer`.

A key concept of programming is *scope*. When F# seeks the value bound to a name, it looks left and upward in the program text for its `let`-binding in the present or higher scopes. This is called *lexical scope*. Some special bindings are mutable, that is, they can change over time in which case F# uses the *dynamic scope*. This will be discussed in Section 20.1.



**Listing 4.5 letValueTypeError.fsx:**  
Binding error due to type mismatch.

```
1 let p = 2.0
2 do printfn "%A" (3 ** p)

-----

1 $ dotnet fsi letValueTypeError.fsx
2
3
4 letValueTypeError.fsx(2,18): error FS0001: The type 'int'
   does not support the operator 'Pow'
```

Scopes are given levels, and scopes may be nested, where the nested scope has a level one lower than its parent. F# distinguishes between the top and lower levels, and at the top level in the lightweight syntax, redefining values is not allowed, as shown in Listing 4.6. However, using parentheses, we create a *code block*, i.e., a

**Listing 4.6 letValueScopeLowerError.fsx:**  
Redefining identifiers is not allowed in lightweight syntax at top level.

```
1 let p = 3
2 let p = 4
3 do printfn "%A" p;

-----

1 $ fsharpc --nologo -a letValueScopeLowerError.fsx
2
3 letValueScopeLowerError.fsx(2,5): error FS0037: Duplicate
   definition of value 'p'
```

*nested scope*, as demonstrated in Listing 4.7. In lower scope-levels, redefining is

**Listing 4.7 letValueScopeBlockAlternative3.fsx:**  
A block may be created using parentheses.

```
1 let p = 3
2 (
3   let p = 4
4   do printfn "%A" p
5 )

-----

1 $ dotnet fsi letValueScopeBlockAlternative3.fsx
2 4
```

allowed but **avoid reusing names unless it's in a deeper scope**. Inside the block in Listing 4.7 we used indentation, which is good practice, but not required here. ★

Defining blocks is used for controlling the extent of a lexical scope of bindings. For example, bindings inside a nested scope are not available outside, as shown in

Listing 4.8. Nesting is a natural part of structuring code, e.g., through function

**Listing 4.8 letValueScopeNestedScope.fsx:**  
Bindings inside a scope are not available outside.

```
1 let p = 3
2 (
3     let q = 4
4     do printfn "%A" q
5 )
6 do printfn "%A %A" p q
```

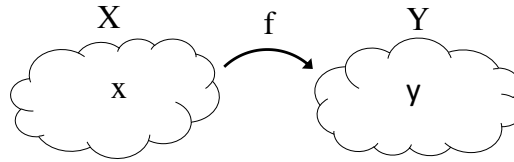
---

```
1 $ fsharp --nologo -a letValueScopeNestedScope.fsx
2
3 letValueScopeNestedScope.fsx(6,22): error FS0039: The value
   or constructor 'q' is not defined.
```

definitions to be discussed in Section 4.2 and flow control structures to be discussed in Chapter 21. Blocking code by nesting is a key concept for making robust code that is easy to use by others, without the user necessarily needing to know the details of the inner workings of a block of code.

## 4.2 Function Bindings

A function is a mapping between an input and output domain, as illustrated in Figure Figure 4.1. A key advantage of using functions when programming is that



**Fig. 4.1** A function  $f : X \rightarrow Y$  is a mapping between two domains, such that  $f(x) = y$ ,  $x \in X$ ,  $y \in Y$ .

they encapsulate code into smaller units, that may be reused and are easier to find errors in. F# is a functional first programming language and offers a number of alternative methods for specifying parameters, which will be discussed in this section. Binding identifiers to functions follows a syntax similar to value-binding,

### Listing 4.9: Function binding expression

```
1 let <funcIdent> (<arg> {<arg>} | () = <bodyExpr>)
```

Here **<funcIdent>** is an identifier and is the name of the function, **<arg>** is zero or more identifiers, that bind to the value used when calling the function, and which is to be used in the *body* of the function, the expression **<bodyExpr>**. The **|** notation denotes a choice, i.e., either that on the left-hand-side or that on the right-hand-side. Thus `let f x = x * x` and `let f () = 3` are valid function bindings, but `let f = 3` would be a value binding, not a function binding. The arguments and the function may be annotated with a type, in which case for arguments we write

### Listing 4.10: Function binding expression

```
1 let <funcIdent> ((<arg> : <type>) {(<arg> : <type>)} : <type> |
  () : <type>) = <bodyExpr>
```

where **<type>** is a name of an existing type. The argument types are given in parentheses, and the return type is given last.

Functions are a key concept in F#, and in this chapter we will discuss the very basics. Recursive functions will be discussed in Chapter 21 and higher-order functions in Chapter 9.

The function's body can be placed either on the same line as the **let**-keyword or on the following lines using indentation. An example of defining a function and using it in interactive mode is shown in Listing 4.11. Here we see that the function is interpreted to have the type `val sum : x:float -> y:float -> float`. The “**->**” lexeme means a mapping between sets, in this case, floats. The function is also

**Listing 4.11: An example of a binding of an identifier and a function.**

```

1
2 > let sum (x : float) (y : float) : float = x + y
3 let c = sum 357.6 863.4
4 do printfn "%A" c;;
5 1221.0
6 val sum: x: float -> y: float -> float
7 val c: float = 1221.0
8 val it: unit = ()

```

a higher-order function, to be discussed in detail below, and here it suffices to think of `sum` as a function that takes 2 floats as argument and returns a float.

Not all types need to be declared, just a sufficient number for F# to be able to infer the types for the full statement. For the example, one is sufficient, and we could just have declare the type of the result, as in Listing 4.12. Or even just one of the

**Listing 4.12 letFunctionAlternative.fsx:  
Not every type needs to be declared.**

```

1 let sum x y : float = x + y

```

arguments, as in Listing 4.13. In both cases, since the `+` operator is only defined for

**Listing 4.13 letFunctionAlternative2.fsx:  
Just one type is often enough for F# to infer the rest.**

```

1 let sum (x : float) y = x + y

```

*operands* of the same type, declaring the type of either arguments or result implies the type of the remainder.

Arguments need not always be inferred to types, but may be of the generic type when *type safety* is ensured, as shown in Listing 4.14. Here, the function `second`

**Listing 4.14: Type safety implies that a function will work for any type.**

```

1 > let second x y = y
2 let a = second 3 5
3 do printfn "%A" a
4 let b = second "horse" 5.0
5 do printfn "%A" b;;
6 5
7 5.0
8 val second: x: 'a -> y: 'b -> 'b
9 val a: int = 5
10 val b: float = 5.0
11 val it: unit = ()

```

does not use the first argument `x`, which therefore can be of any type, and which F#, therefore, calls `'a`. The type of the second element, `y`, can also be of any type and not necessarily the same as `x`, so it is called `'b`. Finally, the result is the same type

as *y*, whatever it is. This is an example of a *generic function*, since it will work on any type.

A function may contain a sequence of expressions but must return a value. E.g., the quadratic formula may be written as shown in Listing 4.15. Here, we use a

**Listing 4.15** `identifiersExampleAdvance.fsx`:  
A function may contain sequences of expressions.

```

1 let solution a b c sgn =
2     let discriminant a b c =
3         b ** 2.0 - 4.0 * a * c
4     let d = discriminant a b c
5     (-b + sgn * sqrt d) / (2.0 * a)
6
7 let a = 1.0
8 let b = 0.0
9 let c = -1.0
10 let xp = solution a b c +1.0
11 let xn = solution a b c -1.0
12 do printfn "0 = %A * x ** 2.0 + %A * x + %A" a b c
13 do printfn "  has solutions %A and %A" xn xp

```

---

```

1 $ dotnet fsi identifiersExampleAdvance.fsx
2 0 = 1.0 * x ** 2.0 + 0.0 * x + -1.0
3   has solutions -1.0 and 1.0

```

set of nested scopes. In the scope of the function `solution` there are further two functions defined, each with their own scope, which F# identifies by the level of indentation. The amount of space used for indentation does not matter, but all lines in the same scope must use the same amount. The scope ends before the first line with the previous indentation or none. Notice how the last expression is not bound to an identifier, but is the result of the function, i.e., in contrast to many other languages, F# does not have an explicit keyword for returning values, but requires a final expression, which will be returned to the caller of the function. Note also that since the function `discriminant` is defined in the nested scope of `solution`, and because the scope ends before `let a = 1.0`, the function `discriminant` cannot be called outside `solution`.

*Lexical scope* and function definitions can be a cause of confusion, as the following example in Listing 4.16 shows. Here, the value-binding for `a` is redefined after it has been used to define a helper function `f`. So which value of `a` is used when we later apply `f` to an argument? To resolve the confusion, remember that value-binding is lexically defined, i.e., the binding `let f z = a * z` uses the value of `a` as it is defined by the ordering of the lines in the script, not dynamically by when `f` was called. Hence, **think of lexical scope as substitution of an identifier with its value or function immediately at the place of definition.** Since `a` and `3.0` are ★

**Listing 4.16 lexicalScopeNFunction.fsx:**Lexical scope means that  $f(z) = 3x$  and not  $4x$  at the time of calling.

```

1 let testScope x =
2     let a = 3.0
3     let f z = a * z
4     let a = 4.0
5     f x
6 do printfn "%A" (testScope 2.0)

```

---

```

1 $ dotnet fsi lexicalScopeNFunction.fsx
2 6.0

```

synonymous in the first lines of the program, the function `f` is really defined as `let f z = 3.0 * z`.

Functions do not need a name, but may be declared as an *anonymous function* using the `fun` keyword and the “`->`” lexeme, as shown in Listing 4.17. Here, a

**Listing 4.17 functionDeclarationAnonymous.fsx:**

Anonymous functions are functions as values.

```

1 let first = fun x y -> x
2 do printfn "%d" (first 5 3)

```

---

```

1 $ dotnet fsi functionDeclarationAnonymous.fsx
2 5

```

name is bound to an anonymous function which returns the first of two arguments. The difference to `let first x y = x` is that anonymous functions may be treated as values, meaning that they may be used as arguments to other functions and the new values may be reassigned to their identifiers when mutable, as will be discussed in Section 20.1. A common use of anonymous functions is as arguments to other functions, as demonstrated in Listing 4.18. Note that here `apply` is given

**Listing 4.18 functionDeclarationAnonymousAdvanced.fsx:**

Anonymous functions are often used as arguments for other functions.

```

1 let apply f x y = f x y
2 let mul = fun a b -> a * b
3 do printfn "%d" (apply mul 3 6)

```

---

```

1 $ dotnet fsi functionDeclarationAnonymousAdvanced.fsx
2 18

```

3 arguments: the function `mul` and 2 integers. It is not given the result of `mul`

★ 3 6, since that would not match the definition of `apply`. **Anonymous functions**

**and functions as arguments are powerful concepts, but tend to make programs harder to read, and their use should be limited.**

The result of one function is often used as an argument of another. This is function composition, and an example is shown in Listing 4.19. In the example we combine

**Listing 4.19 functionComposition.fsx:**  
Composing functions using intermediate bindings.

```
1 let f x = x + 1
2 let g x = x * x
3
4 let a = f 2
5 let b = g a
6 let c = g (f 2)
7 do printfn "a = %A, b = %A, c = %A" a b c
```

---

```
1 $ dotnet fsi functionComposition.fsx
2 a = 3, b = 9, c = 9
```

two functions *f* and *g* by storing the result of *f* 2 in *a* and using that as argument of *g*. This is the same as *g* (*f* 2), and in the later case, the compiler creates a temporary value for *f* 2. Such compositions are so common in F# that a special set of operators has been invented, called the *pipng* operators: “|>” and “<|”. They are used as demonstrated in Listing 4.20. The example shows regular composition,

**Listing 4.20 functionPiping.fsx:**  
Composing functions by piping.

```
1 let f x = x + 1
2 let g x = x * x
3
4 let a = g (f 2)
5 let b = 2 |> f |> g
6 let c = g <| (f <| 2)
7 do printfn "a = %A, b = %A, c = %A" a b c
```

---

```
1 $ dotnet fsi functionPiping.fsx
2 a = 9, b = 9, c = 9
```

left-to-right, and right-to-left piping. The word piping is a pictorial description of data as if it were flowing through pipes, where functions are connection points of pipes distributing data in a network. The three expressions in Listing 4.20 perform the same calculation. The left-to-right piping in line 5 corresponds to the left-to-right reading direction, i.e., the value 2 is used as argument to *f*, and the result is used as argument to *g*. In contrast, right-to-left piping in line 6 has the order of arithmetic composition as line 4. Unfortunately, since the piping operators are left-associative, without the parenthesis in line 6 *g* <| *f* <| 2, F# would read the expression as (*g*

<| f) <| 2. That would have been an error, since `g` takes an integer as argument, not a function. F# can also define composition on a function level. Further discussion on this is deferred to Chapter 9.

A *procedure* is a generalization of the concept of functions, and in contrast to functions, procedures need not return values. This is demonstrated in Listing 4.21. In F#, this is automatically given the unit type as the return value. Procedural

#### Listing 4.21 procedure.fsx:

A procedure is a function that has no return value, and in F# returns “()”.

```
1 let printIt a = printfn "This is '%A'" a
2 do printIt 3
3 do printIt 3.0

-----

1 $ dotnet fsi procedure.fsx
2 This is '3'
3 This is '3.0'
```

thinking is useful for *encapsulation* of scripts, but is prone to *side-effects*. For this reason, it is advised to **prefer functions over procedures**. More on side-effects in Section 20.1.

In F#, functions (and procedures) are *first-class citizens*, which means that functions are values: They may be passed as arguments, returned from a function, and bound to a name. For first-class citizens, the name it is bound to does not carry significance to the language, as, e.g., illustrated with the use of anonymous functions. Technically, a function is stored as a *closure*. A closure is a description of the function, its arguments, its expression, and the environment at the time it was created, i.e., the triple  $(args, exp, env)$ . Consider the listing in Listing 4.22. It defines two functions

#### Listing 4.22 functionFirstClass.fsx:

The function `ApplyFactor` has a non-trivial closure.

```
1 let mul x y = x * y
2 let factor = 2.0
3 let applyFactor fct x =
4     let a = fct factor x
5     string a
6
7 do printfn "%g" (mul 5.0 3.0)
8 do printfn "%s" (applyFactor mul 3.0)

-----

1 $ dotnet fsi functionFirstClass.fsx
2 15
3 6
```

`mul` and `applyFactor`, where the latter is a higher-order function taking another



function as an argument and uses part of the environment to produce its result. The two closures are:

$$\text{mul} : (\text{args}, \text{exp}, \text{env}) = ((x, y), (x * y), ()) \quad (4.3)$$

$$\text{applyFactor} : (\text{args}, \text{exp}, \text{env}) = ((x, \text{fct}), (\text{body}), (\text{factor} \rightarrow 2.0)) \quad (4.4)$$

where lazily write `body` instead of the whole function's body. The function `mul` does not use its environment, and everything needed to evaluate its expression are values for its arguments. The function `applyFactor` also takes two arguments, a function and a value. It uses `factor` from the environment, thus this is stored in its closure. When `mul` is given as an argument in Listing 4.22 line 8, then it is its closure which is given to `applyFactor`, and the closure contains everything that `applyFactor` requires to use `mul`. Likewise, if `applyFactor` is given as argument to yet another function, then its closure includes the relevant part of its environment at the time of definition, `factor`, such that when `applyFactor` is applied to two arguments, then its closure contains everything needed to evaluate its expression.

### 4.3 Do-Bindings

Aside from `let`-bindings that binds names with values or functions, sometimes we just need to execute code. This is called a `do`-binding or, alternatively, a *statement*. The syntax is as follows:

Listing 4.23: Syntax for `do`-bindings.

```
1 [do ]<expr>
```

The expression `<expr>` must return `unit`. The keyword `do` is optional in most cases, but using it emphasizes that the expression is not a function that returns a useful value. Procedures are examples of such expressions, and a very useful family of procedures are the `printf` family described below. In the remainder of this book, we will refrain from using the `do` keyword.

### 4.4 Conditional Expressions

Programs often contain code which should only be executed under certain conditions. The `match – with` expressions allows us to write such expressions, and its syntax is as follows:

Listing 4.24: Syntax for `match`-expressions.

```
1 match <inputExpr> with
2   [| ]<pat> [when <guardExpr>] -> <caseExpr>
3   | <pat> [when <guardExpr>] -> <caseExpr>
4   | <pat> [when <guardExpr>] -> <caseExpr>
5   ...
```

where `<inputExpr>` is the *input pattern* to find matches of, `<pat>` is a pattern to match with, `<guardExpr>` is an optional guard expression, and `<caseExpr>` is the resulting expression. Each set starting with `<pat>` is called a case. The indentation must be equal to or higher than the indentation of `match`. All cases must return a value of the same type, and F# reports an error when the complete domain of the input pattern is not covered by cases in `match`-expressions.

For example, a calendar program may need to highlight weekends, and thus highlighting code should be called, if and only if the day of the week is either Saturday or Sunday, as shown in the following. Remember that `match – with` is the last expression in the function `whatToDoToday`, hence the resulting string of `match – with` is also the resulting string of the function. F# examines each case from top to bottom, and as soon as a matching case is found, then the code following the

**Listing 4.25** weekdayPatternSimple.fsx:  
Using `match` – `with` to print discriminated unions.

```

1 let whatToDoToday (d : int) : string =
2     match d with
3     | 0 -> "go to work"
4     | 1 -> "go to work"
5     | 2 -> "go to work"
6     | 3 -> "go to work"
7     | 4 -> "go to work"
8     | 5 -> "take time off"
9     | 6 -> "take time off"
10    | _ -> "unknown day of the week"
11
12 let dayOfWeek = 3
13 let task = whatToDoToday dayOfWeek
14 printfn "Day %A of the week you should %A" dayOfWeek task

```

---

```

1 $ dotnet fsi weekdayPatternSimple.fsx
2 Day 3 of the week you should "go to work"

```

“->”-symbol is executed. This code is called the case’s *branch*. The “_” pattern is a *wildcard* and matches everything.

In the above code, each day has its own return string associated to it, which is great, if we want to return different messages for different days. However, in this code, we only return two different strings, and if, e.g., choose the one for weekdays, then we need to make 5 identical changes to the code. This is wasteful and risks introducing new errors. So instead, we may compact this code by concatenating the “|”s as shown in Listing 4.26. It still seems unnecessarily clumsy to have to mention

**Listing 4.26** weekdayPatternSum.fsx:  
Concatenating cases. Compare with Listing 4.25.

```

1 let whatToDoToday (d : int) : string =
2     match d with
3     | 0 | 1 | 2 | 3 | 4 -> "go to work"
4     | 5 | 6 -> "take time off"
5     | _ -> "unknown day of the week"
6
7 let dayOfWeek = 3
8 let task = whatToDoToday dayOfWeek
9 printfn "Day %A of the week you should %A" dayOfWeek task

```

---

```

1 $ dotnet fsi weekdayPatternSum.fsx
2 Day 3 of the week you should "go to work"

```

the number of each weekday explicitly, and to avoid this, we may use *guards* as illustrated in Listing 4.27. In the guard expression, we match `d` with the name `n`

**Listing 4.27** weekdayPatternGuard.fsx:  
Using guards. Compare with Listing 4.26.

```

1 let whatToDoToday (d : int) : string =
2     match d with
3     | n when 0 <= n && n < 5 -> "go to work"
4     | n when 0 <= 5 && n <= 6 -> "take time off"
5     | _ -> "unknown day of the week"
6
7 let dayOfWeek = 3
8 let task = whatToDoToday dayOfWeek
9 printfn "Day %A of the week you should %A" dayOfWeek task

```

---

```

1 $ dotnet fsi weekdayPatternGuard.fsx
2 Day 3 of the week you should "go to work"

```

as long as the condition is fulfilled, i.e., as long  $0 \leq n < 5$  or as it is written in F#, `0 <= n && n < 5`. The logical and-operator (“&&”) is needed in F#, since both `0 <= n` and `n < 5` needs to be true, and F# can only evaluate them individually.

Note that `match – with` expressions will give a warning, if there are not cases for the full domain of what is being match. I.e., if we don’t end with the wildcard pattern, when matching for integers, we would be missing cases for all other patterns

**Listing 4.28** weekdayPatternError.fsx:  
Using `match – with` to print discriminated unions.

```

1 let whatToDoToday (d : int) : string =
2     match d with
3     | n when 0 <= n && n < 5 -> "go to work"
4     | n when 5 <= n && n <= 6 -> "take time off"
5
6 let dayOfWeek = 3
7 let task = whatToDoToday dayOfWeek
8 printfn "Day %A of the week you should %A" dayOfWeek task

```

---

```

1 $ dotnet fsi weekdayPatternError.fsx
2
3
4 weekdayPatternError.fsx(2,9): warning FS0025: Incomplete
   pattern matches on this expression.
5
6 Day 3 of the week you should "go to work"

```

An alternative to `match – with` is the `if – then` expressions.

Listing 4.29: Conditional expressions.

```
1 if <cond> then <expr> {elif <cond> then <expr>} [else <expr>]
```

The condition `<con>` is an expression resulting in a Boolean value, and there can be zero or more `elif` conditions, as indicated by `{}`. Each expression `<expr>` is called a *branch*, and all branches must have the same type, such that regardless of which branch is chosen, the type of the result of the conditional expression is the same. Then the expression of the first if-branch, whose condition is true, is evaluate. If all conditions are false then the `else`-branch is evaluated. If no `else` expression is present, then `()` will be returned. See Listing 4.30 for a simple example. The branches are often several lines of code, in which case it is more

Listing 4.30 weekdayIfThenElse.fsx:

Conditional computation with `if – then`. Compare with Listing 4.27.

```
1 let whatToDoToday (d : int) : string =
2     if 0 <= d && d < 5 then "go to work"
3     elif 5 <= d && d <= 6 then "take time off"
4     else "unknown day of the week"
5
6 let dayOfWeek = 3
7 let task = whatToDoToday dayOfWeek
8 printfn "Day %A of the week you should %A" dayOfWeek task
-----
1 $ dotnet fsi weekdayIfThenElse.fsx
2 Day 3 of the week you should "go to work"
```

useful to write them indented, below the keywords, which may also make the code easier to read. The identical `whatToDoToday` function with indented branches is shown in Listing 4.31. In contrast to `match – with`, the `if – then` expression is

Listing 4.31 weekdayIfThenElseIndentation.fsx:

Conditional computation with `if – then`. Compare with Listing 4.27.

```
1 let whatToDoToday (d : int) : string =
2     if 0 <= d && d < 5 then
3         "go to work"
4     elif 5 <= d && d <= 6 then
5         "take time off"
6     else
7         "unknown day of the week"
```

not as thorough in investigating whether cases of the domain in question have been covered. For example, in both

```
let a = if true then 3
```

and

```
let a = if true then 3 elif false then 4
```

the value of `a` are uniquely determined, but F# finds them to be erroneous, since F# looks for the `else` to ensure all cases have been covered, and that the branches have the identical type. Hence,

```
let a = if true then 3 else 4
```

is the only valid expression of the 3. In practice, F# assumes that the omitted branch returns “()”, and thus it is fine to say `let a = if true then ()` and `if true then printfn "hej"`. Nevertheless, it is good practice in F# to always include an `else` branch.

## 4.5 Tracing code by hand

The concept of Tracing by hand, will be developed throughout this book. Here we will concentrate in the basics, and as we introduce more complicated programming structures, we will develop the Tracing by hand accordingly. Tracing may seem tedious in the beginning, but in conjunction with strategically placed debugging `printfn` statements, it is a very valuable tool for debugging.

Consider the program in Listing 19.6. The program calls `testScope 2.0`, and by

**Listing 4.32 lexicalScopeTracing.fsx:**  
Example of lexical scope and closure environment.

```
1 let testScope x =  
2   let a = 3.0  
3   let f z = a * z  
4   let a = 4.0  
5   f x  
6 printfn "%A" (testScope 2.0)  
  
1 $ dotnet fsi lexicalScopeTracing.fsx  
2 6.0
```

running the program, we see that the return-value is `6.0` and not `8.0`, as we had expected. Hence, we will use tracing to understand the result.

Tracing a program by hand means that we simulate its execution and, as part of that, keep track of the bindings, assignments closures, scopes, and input and output of the program. To do this, we need to consider the concept of *environments*.

Environments describe bindings available to the program at the present scope and at a particular time and place in the code. There is always an outer environment, called  $E_0$ , and each time we call a function or create a scope, we create a new environment. Only one environment can be active at a time, and it is updated as we simulate the execution of code with new bindings and temporary evaluations of expressions. Once a scope is closed, then its environment is deleted and a return-value is transported to its enclosing environment. In tracing, we note return-values explicitly. Likewise, output from, e.g., `printfn` is reported with a special notation.

To trace code, we make a table with 4 columns: Step, Line, Environment, and Bindings and evaluations. The Step column enumerates the steps performed. The Line column contains the program-line treated in a step *where* the present environment is updated. The Environment contains the name of the present environment, and Bindings ... shows *what* in the environment is updated.

The code in Listing 19.6 contains a function definition and a call, hence, the first lines of our table looks like,

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	testScope = ((x), testScope-body, ())
2	6	$E_0$	testScope 2.0 = ?

The elements of the table is to be understood as follows. Step 0 initializes the outer environment. In order for us to remember that the environment is empty, we write the unit value “()”. Reading the code from top to bottom, the first nonempty and non-comment line we meet is line 1, hence, in Step 1, we update the environment with the binding of a function to the name `testScope`. Since functions are values in F#, we note their bindings by their closures: a list of argument names, the function-body, and the values lexically available at the place of binding. See Section 4.2 for more information on closures. Following the function-binding, the `printfn` statement is called in line 6 to print the result `testScope 2.0`. However, before we can produce any output, we must first evaluate `testScope 2.0`. Since we do not yet know what this function evaluates to, in Step 2 we simply write the call with a question mark. The call causes the creation of a new environment, and we continue our table as follows,

Step	Line	Env.	Bindings and evaluations
3	1	$E_1$	((x = 2.0), testScope-body, ())

This means that we are going to execute the code in `testScope-body`. The function was called with 2.0 as argument, causing  $x = 2.0$ . Hence, the only binding available at the start of this environment is to the name `x`. In the `testScope-body`, we make 3 further bindings and a function call. First to `a`, then to `f`, then to another `a`, which will overshadow the previous binding, and finally we call `f`. Thus, our table is updated as follows,

Step	Line	Env.	Bindings and evaluations
4	2	$E_1$	$a = 3.0$
5	3	$E_1$	$f = ((z), a * z, (a = 3.0, x = 2.0))$
6	4	$E_1$	$a = 4.0$
7	5	$E_1$	$f\ x = ?$

Note that by lexical scope, the closure of  $f$  includes everything above its binding in  $E_1$ , and therefore we add  $a = 3.0$  and  $x = 2.0$  to the environment element in its closure. This has consequences for the following call to  $f$  in line 5, which creates a new environment based on  $f$ 's closure and the value of its arguments. The value of  $x$  in Step 7 is found by looking in the previous steps for the last binding to the name  $x$  in  $E_1$ , which occurs in Step 3. Note that the binding to a name  $x$  in Step 5 is an internal binding in the closure of  $f$  and is irrelevant here. Hence, we continue the table as,

Step	Line	Env.	Bindings and evaluations
8	3	$E_2$	$((z = 2.0), a * z, (a = 3.0, x = 2.0))$

Executing the body of  $f$ , we initially have 3 bindings available:  $z = 2.0$ ,  $a = 3.0$ , and  $x = 2.0$ . Thus, to evaluate the expression  $a * z$ , we use these bindings and write,

Step	Line	Env.	Bindings and evaluations
9	3	$E_2$	$a * z = 6.0$
10	3	$E_2$	return = 6.0

The 'return'-word is used to remind us that this is the value to replace the question mark with in Step 7. Here we will make a mental note and not physically replace the question mark with the calculated value. If you are ever in doubt which call is connected with which return value, seek upwards in the table from the return statement for the first question mark. Now we delete  $E_2$  and return to the enclosing environment,  $E_1$ . Here the function call was the last expression, hence the return-value from `testScope` will be equal to the return-value from  $f$ , and we write,

Step	Line	Env.	Bindings and evaluations
11	3	$E_1$	return = 6.0

Similarly, we delete  $E_1$  and return to the question mark in Step 2, which is replaced by the value 6.0. We can now finish the `printfn` statement and produce the output,

Step	Line	Env.	Bindings and evaluations
12	6	$E_0$	output = "6.0\n"

The return-value of a `printfn` statement is `()`, and since this line is the last of our program, we return `()` and end the program:



Step	Line	Env.	Bindings and evaluations
13	6	$E_0$	return = ()

The full table is shown for completeness in Table 19.3. Hence, we conclude that

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	testScope = ((x), testScope-body, ())
2	6	$E_0$	testScope 2.0 = ?
3	1	$E_1$	((x = 2.0), testScope-body, ())
4	2	$E_1$	a = 3.0
5	3	$E_1$	f = ((z), a * z, (a = 3.0, x = 2.0))
6	4	$E_1$	a = 4.0
7	5	$E_1$	f x = ?
8	3	$E_2$	((z = 2.0), a * z, (a = 3.0, x = 2.0))
9	3	$E_2$	a * z = 6.0
10	3	$E_2$	return = 6.0
11	3	$E_1$	return = 6.0
12	6	$E_0$	output = "6.0\n"
13	6	$E_0$	return = ()

**Table 4.2** The complete table produced while tracing the program in Listing 19.6 by hand.

the program outputs the value 6.0, since the function `f` uses the first binding of `a = 3.0`, and this is because the binding of `f` to the expression `a * z` creates a closure with a lexical scope. Thus, in spite that there is an overshadowing value of `a`, when `f` is called, this binding is ignored in the body of `f`. To correct this, we update the code as shown in Listing 19.7.

#### Listing 4.33 lexicalScopeTracingCorrected.fsx:

Tracing the code in Listing 19.6 by hand produced the table in Table 19.3, and to get the desired output, we correct the code as shown here.

```

1 let testScope x =
2     let a = 4.0
3     let f z = a * z
4     f x
5 printfn "%A" (testScope 2.0)

-----

1 $ dotnet fsi lexicalScopeTracingCorrected.fsx
2 8.0

```

## 4.6 Key concepts and terms in this chapter

This chapter we have taken a first look at organising code. Key concepts have been:

- **Binding** values and functions using the **let** statements.
- Function **closures**, which are the values bound in **let** statements of functions.
- Certain names are forbidden in particular **keywords**, which are reserved for other uses.
- In contrast to **let** expressions, **do** statements do something, such as `println` prints to the screen. They return the “()” value.
- Conditional expressions using **match-with** and some **patterns** and **guards**. Alternatively, **if-then** expressions can be used to a similar effect.
- **Trace by hand** as a method for simulating execution and in particular keeping track of the **environments** defined by the code structure.

## Chapter 5

# Programming with Types

F# is a strongly typed language, meaning that types are known or inferred at compile time. In the previous chapters, we have used *primitive types* such as `float` and `bool`, function types, and compound types implicitly defined by tuples. These types are used for simple programming tasks, and everything that can be programmed can be accomplished using these types. However, larger programs are often easier to read and write when using more complicated type structures. In this chapter, we will discuss type abbreviations, enumerated types, discriminated unions, records, and structs. Class types are discussed in depth in Chapter 23.

### 5.1 Tuples

*Tuples* are a direct extension of constants. They are immutable and have neither concatenations nor indexing operations. Tuples are unions of immutable types and have the following syntax:

**Listing 5.1:** Tuples are list of expressions separated by commas.

```
1 <expr>{, <expr>}
```

Tuples are identified by the “,” lexeme and often enclosed in parentheses, but that is not required. An example is a triple, also known as a 3-tuple, `(2, true, "hello")`. In interactive mode, the type of tuples is demonstrated in Listing 5.2. The values `2`, `true`, and `"hello"` are *members*, and the number of elements of a tuple is its *length*. From the response of F#, we see that the tuple is inferred to have the type `int * bool * string`. The “*” denotes the Cartesian product between sets. Tuples can be products of any types and follow the lexical scope rules like value and function bindings. Notice also that a tuple may be printed as a single entity

**Listing 5.2: Tuple types are products of sets.**

```

1 > let tp = (2, true, "hello")
2 printfn "%A" tp;;
3 (2, true, "hello")
4 val tp: int * bool * string = (2, true, "hello")
5 val it: unit = ()

```

by the `%A` placeholder. In the example we bound `tp` to the tuple. The opposite is also possible, as demonstrated in Listing 5.3. In this example, a function is defined

**Listing 5.3: Definition of a tuple.**

```

1 > let deconstructNPrint tp =
2   let (a, b, c) = tp
3   printfn "tp = (%A, %A, %A)" a b c
4 deconstructNPrint (2, true, "hello")
5 deconstructNPrint (3.14, "Pi", 'p');;
6 tp = (2, true, "hello")
7 tp = (3.14, "Pi", 'p')
8 val deconstructNPrint: 'a * 'b * 'c -> unit
9 val it: unit = ()

```

that takes 1 argument, a 3-tuple. If we wanted a function with 3 arguments, then the function binding should have been `let deconstructNPrint a b c = ...`. The value binding `let (a, b, c) = tp`, binds a tuple with 3 named members to a value, thus deconstructing it in terms of its members. This is called pattern matching and will be discussed in further details in Chapter 12. Since we used the `\%A` placeholder in the `printfn` function, the function can be called with 3-tuples of different types. F# informs us that the tuple type is variable by writing `'a * 'b * 'c`. The `"'"` notation means that the type can be decided at run-time, see Section 5.7 for more on variable types.

Pairs or 2-tuples are so common that F# includes two built-in functions, `fst` and `snd`, to extract the first and second element of a pair. This is demonstrated in Listing 5.4.

**Listing 5.4 pair.fsx:****Deconstruction of pairs with the built-in functions `fst` and `snd`.**

```

1 let pair = ("first", "second")
2 printfn "fst(pair) = %s, snd(pair) = %s" (fst pair) (snd pair)

```

---

```

1 $ fsharp --nologo pair.fsx && mono pair.exe
2 fst(pair) = first, snd(pair) = second

```

Tuples of equal lengths can be compared, and the comparison is defined similarly to string comparison. Tuples of equal length are compared element by element. E.g., `(1,2) = (1,3)` is false, while `(1,2) = (1,2)` is true. The `"<>"` operator is the

boolean negation of the “=” operator. For the “<”, “<=”, “>”, and “>=” operators, the strings are ordered lexicographically, such that `('a', 'b', 'c') < ('a', 'b', 's')` && `('a', 'b', 's') < ('c', 'o', 's')` is true, that is, the “<” operator on two tuples is true if and only if the left operand should come before the right when sorting alphabetically. See Listing 5.5 for an example. The algorithm

**Listing 5.5 tupleCompare.fsx:**  
Tuples comparison is similar to string comparison.

```

1 let lessThan (a, b, c) (d, e, f) =
2     if a <> d then a < d
3     elif b <> e then b < d
4     elif c <> f then c < f
5     else false
6
7 let printTest x y =
8     printfn "%A < %A is %b" x y (lessThan x y)
9
10 let a = ('a', 'b', 'c');
11 let b = ('d', 'e', 'f');
12 let c = ('a', 'b', 'b');
13 let d = ('a', 'b', 'd');
14 printTest a b
15 printTest a c
16 printTest a d

```

---

```

1 $ fsharp --nologo tupleCompare.fsx && mono tupleCompare.exe
2 ('a', 'b', 'c') < ('d', 'e', 'f') is true
3 ('a', 'b', 'c') < ('a', 'b', 'b') is false
4 ('a', 'b', 'c') < ('a', 'b', 'd') is true

```

for deciding the boolean value of `(a1, a2) < (b1, b2)` is as follows: we start by examining the first elements, and if `a1` and `b1` are different, then the result of `(a1, a2) < (b1, b2)` is equal to the result of `a1 < b1`. If `a1` and `b1` are equal, then we move on to the next letter and repeat the investigation. The “<=”, “>”, and “>=” operators are defined similarly.

Binding tuples to mutables does not make the tuple mutable. This is demonstrated in Listing 5.6. However, it is possible to define a mutable variable of type tuple such that new tuple values can be assigned to it, as shown in Listing 5.7. Mutable tuples are value types, meaning that binding to new names makes copies, not aliases, as demonstrated in Listing 5.8. The use of tuples shortens code and highlights semantic content at a higher level, e.g., instead of focusing on the elements, tuples focus on their union. While this may look elegant and short there is the risk of *obfuscation*, i.e., writing compact code that is difficult to read, where an unprepared reader of the code may not easily understand the computation nor appreciate its elegance without an accompanying explanation. Hence, **always keep an eye out for compact and concise ways to write code, but never at the expense of readability.** ★

**Listing 5.6 tupleOfMutables.fsx:**

A mutable changes value, but the tuple defined by it does not refer to the new value.

```
1 let mutable a = 1
2 let mutable b = 2
3 let c = (a, b)
4 printfn "%A, %A, %A" a b c
5 a <- 3
6 printfn "%A, %A, %A" a b c
```

---

```
1 $ fsharp --nologo tupleOfMutables.fsx && mono
   tupleOfMutables.exe
2 1, 2, (1, 2)
3 3, 2, (1, 2)
```

**Listing 5.7 mutableTuple.fsx:**

A mutable tuple can be assigned a new value.

```
1 let mutable pair = 1,2
2 printfn "%A" pair
3 pair <- (3,4)
4 printfn "%A" pair
```

---

```
1 $ fsharp --nologo mutableTuple.fsx && mono mutableTuple.exe
2 (1, 2)
3 (3, 4)
```

**Listing 5.8 mutableTupleValue.fsx:**

A mutable tuple is a value type.

```
1 let mutable pair = 1,2
2 let mutable aCopy = pair
3 pair <- (3,4)
4 printfn "%A %A" pair aCopy
```

---

```
1 $ fsharp --nologo mutableTupleValue.fsx && mono
   mutableTupleValue.exe
2 (3, 4) (1, 2)
```

## 5.2 Type Abbreviations

F# allows for renaming of types, which is called *type abbreviation* or *type aliasing*. The syntax is:

Listing 5.9: Syntax for type abbreviation.

```
1 type <ident> = <aType>
```

where the identifier is a new name, and the type-name is an existing type or a compound of existing types. Listing 5.10 shows examples of the definition of several type abbreviations. Here we define the abbreviations `size`, `position`, `person`, and

Listing 5.10 typeAbbreviation.fsx:

Defining four type abbreviations, three of which are compound types.

```
1 type size = int
2 type position = float * float
3 type person = string * int
4 type intToFloat = int -> float
5
6 let sz : size = 3
7 let pos : position = (2.5, -3.2)
8 let pers : person = ("Jon", 50)
9 let conv : intToFloat = fun a -> float a
10 printfn "%A, %A, %A, %A" sz pos pers (conv 2)
-----
1 $ fsharp --nologo typeAbbreviation.fsx && mono
   typeAbbreviation.exe
2 3, (2.5, -3.2), ("Jon", 50), 2.0
```

`intToFloat`, and later make bindings enforcing the usage of these abbreviations.

Type abbreviations are used as short abbreviations of longer types, and they add semantic content to the program text, thus making programs shorter and easier to read. Type abbreviations allow the programmer to focus on the intended structure at a higher level by, e.g., programming in terms of a type `position` rather than `float * float`. Thus, they often result in programs with fewer errors. Type abbreviations also make maintenance easier. For instance, if we at a later stage decide that positions can only have integer values, then we only need to change the definition of the type abbreviation, not every place a value of type `position` is used.

## 5.3 Enumerations

*Enumerations* or *enums* for short are types with named values. Names in enums are assigned to a subset of integer or char values. Their syntax is as follows:

Listing 5.11: Syntax for enumerations.

```

1 type <ident> =
2   [ | ] <ident> = <integerOrChar>
3   | <ident> = <integerOrChar>
4   | <ident> = <integerOrChar>
5   ...

```

An example of using enumerations is given in Listing 5.12. In this example, we

Listing 5.12 enum.fsx:

An enum type acts as a typed alias to a set of integers or chars.

```

1 type medal =
2   Gold = 0
3   | Silver = 1
4   | Bronze = 2
5
6 let aMedal = medal.Gold
7 printfn "%A has value %d" aMedal (int aMedal)

```

---

```

1 $ fsharp --nologo enum.fsx && mono enum.exe
2 Gold has value 0

```

define an enumerated type for medals, which allows us to work with the names rather than the values. Since the values most often are arbitrary, we can program using semantically meaningful names instead. Being able to refer to an underlying integer type allows us to interface with other – typically low-level – programs that require integers, and to perform arithmetic. E.g., for the medal example, we can typecast the enumerated types to integers and calculate an average medal harvest.

## 5.4 Discriminated Unions

A discriminated union is a union of a set of named cases. These cases can further be of specified types. The syntax for defining a discriminated union is as follows:

Listing 5.13: Syntax for type abbreviation.

```

1 [<attributes>]
2 type <ident> =
3   [ | ]<ident> [of [<ident> :] <aType> [* [<ident> :] <aType>
4     ...]]
5   | <ident> [of [<ident> :] <aType> [* [<ident> :] <aType>
6     ...]]
7   ...

```



Discriminated unions are reference types, i.e., their content is stored on *The Heap*, see Section 20.2 for a discussion on reference types. Since they are immutable, there is no risk of side-effects. As reference types, they only pass a reference when used as arguments to and returned from a function. This is in contrast to value types, which transport a complete copy of the data structure. Discriminated unions are thus effective for large data structures. Discriminated unions can also be represented as structures using the [`<Struct>`] attribute, in which case they are value types. See Section 5.6 for a discussion on structs.

An example just using the named cases but no further specification of types is given in Listing 5.14. Here, we define a discriminated union as three named cases

**Listing 5.14** `discriminatedUnions.fsx`:  
A discriminated union of medals. Compare with Listing 5.12.

```
1 type medal =  
2   Gold  
3   | Silver  
4   | Bronze  
5  
6 let aMedal = medal.Gold  
7 printfn "%A" aMedal  
-----  
1 $ fsharp --nologo discriminatedUnions.fsx && mono  
   discriminatedUnions.exe  
2 Gold
```

signifying three different types of medals. Comparing with the enumerated type in Listing 5.12, we see that the only difference is that the cases of the discriminated unions have no value. A commonly used discriminated union is the *option type*, see Section 13.2 for more detail.

Discriminated unions may also be used to store data. Where the names in enumerated types are aliases of single values, the names used in discriminated unions can hold any value specified at the time of creation. An example is given in Listing 5.15. In this case, we define a discriminated union of two and three-dimensional vectors. Values of these types are created using their names followed by a tuple of their arguments. The names are also called field names. The field names may be used when creating discriminated union values, as shown in Line 6. When used, then the arguments may be given in arbitrary order, nevertheless, values for all fields must be given.

Discriminated unions can be defined recursively. This feature is demonstrated in Listing 5.16. In this example we define a tree as depicted in Figure 5.1.

**Listing 5.15** discriminatedUnionsOf.fsx:  
A discriminated union using explicit subtypes.

```

1 type vector =
2   Vec2D of float * float
3   | Vec3D of x : float * y : float * z : float
4
5 let v2 = Vec2D (1.0, -1.2)
6 let v3 = Vec3D (x = 1.0, z = -1.2, y = 0.9)
7 printfn "%A and %A" v2 v3

```

---

```

1 $ fsharp --nologo discriminatedUnionsOf.fsx && mono
   discriminatedUnionsOf.exe
2 Vec2D (1.0, -1.2) and Vec3D (1.0, 0.9, -1.2)

```

**Listing 5.16** discriminatedUnionTree.fsx:  
A discriminated union modelling binary trees.

```

1 type Tree =
2   Leaf of int
3   | Node of Tree * Tree
4
5 let one = Leaf 1
6 let two = Leaf 2
7 let three = Leaf 3
8 let tree = Node (Node (one, two), three)
9 printfn "%A" tree

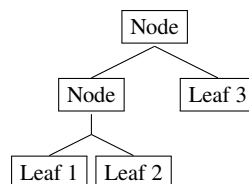
```

---

```

1 $ fsharp --nologo discriminatedUnionTree.fsx && mono
   discriminatedUnionTree.exe
2 Node (Node (Leaf 1, Leaf 2), Leaf 3)

```



**Fig. 5.1** The tree with 3 leaves.

Pattern matching must be used in order to define functions on values of a discriminated union. E.g., in Listing 5.17 we define a function that traverses a tree and prints the content of the nodes.

Discriminated unions are very powerful and can often be used instead of class hierarchies. Class hierarchies are discussed in Section 24.1.

**Listing 5.17** discriminatedUnionPatternMatching.fsx:  
A discriminated union modelling binary trees.

```

1 type Tree = Leaf of int | Node of Tree * Tree
2 let rec traverse (t : Tree) : string =
3     match t with
4         Leaf(v) -> string v
5         | Node(left, right) -> (traverse left) + ", " +
6             (traverse right)
7
8 let tree = Node (Node (Leaf 1, Leaf 2), Leaf 3)
9 printfn "%A: %S" tree (traverse tree)

```

---

```

1 $ fsharp -nologo discriminatedUnionPatternMatching.fsx &&
   mono discriminatedUnionPatternMatching.exe
2 Node (Node (Leaf 1, Leaf 2), Leaf 3): 1, 2, 3

```

## 5.5 Records

A record is a compound of named values, and a record type is defined as follows:

**Listing 5.18:** Syntax for defining record types.

```

1 [ <attributes> ]
2 type <ident> = {
3     [ mutable ] <label1> : <type1>
4     [ mutable ] <label2> : <type2>
5     ...
6 }

```

Records are collections of named variables and values of possibly different types. They are reference types, and thus their content is stored on *The Heap*, see Section 20.2 for a discussion on reference types. Records can also be *struct records* using the [`<Struct>`] attribute, in which case they are value types. See Section 5.6 for a discussion on structs. An example of using records is given in Listing 5.19. The values of individual members of a record are obtained using the “.” notation. This example illustrates how record type is used to store varied data about a person.

If two record types are defined with the same label set, then the latter dominates the former. This is demonstrated in Listing 5.20. In the example, two identical record types are defined, and we use the built-in `GetType()` method to inspect the type of bindings. We see that `lecturer` is of `RecordsDominance+teacher` type, since `teacher` dominates the identical `person` type definition. However, we may enforce the `person` type by either specifying it for the name, as in `let author : person = ...`, or by fully or partially specifying it in the record expression following the “=” sign. In both cases, they are of `RecordsDominance+person` type. The built-in

**Listing 5.19 records.fsx:**

A record is defined for holding information about a person.

```

1 type person = {
2     name : string
3     age : int
4     height : float
5 }
6
7 let author = {name = "Jon"; age = 50; height = 1.75}
8 printfn "%A\nname = %s" author author.name

```

```

1 $ fsharp --nologo records.fsx && mono records.exe
2 { name = "Jon"
3   age = 50
4   height = 1.75 }
5 name = Jon

```

**Listing 5.20 recordsDominance.fsx:**

Redefined types dominate old record types, but earlier definitions are still accessible using explicit or implicit specification for bindings.

```

1 type person = { name : string; age : int; height : float }
2 type teacher = { name : string; age : int; height : float }
3
4 let lecturer = {name = "Jon"; age = 50; height = 1.75}
5 printfn "%A : %A" lecturer (lecturer.GetType())
6 let author : person = {name = "Jon"; age = 50; height = 1.75}
7 printfn "%A : %A" author (author.GetType())
8 let father = {person.name = "Jon"; age = 50; height = 1.75}
9 printfn "%A : %A" author (author.GetType())

```

```

1 $ fsharp --nologo recordsDominance.fsx && mono
   recordsDominance.exe
2 { name = "Jon"
3   age = 50
4   height = 1.75 } : RecordsDominance+teacher
5 { name = "Jon"
6   age = 50
7   height = 1.75 } : RecordsDominance+person
8 { name = "Jon"
9   age = 50
10  height = 1.75 } : RecordsDominance+person

```

`GetType()` method is inherited from the base class for all types, see Chapter 23 for a discussion on classes and inheritance.

Note that when creating a record you must supply a value to all fields, and you cannot refer to other fields of the same record, i.e., `{name = "Jon"; age = height * 3; height = 1.75}` is illegal.

Since records are per default reference types, binding creates aliases, not copies. This matters for mutable members, in which case when copying, we must explicitly create a new record with the old data. Copying can be done either by using referencing to the individual members of the source or using the short-hand *with* notation. This is demonstrated in Listing 5.21. Here, `age` is defined as a mutable value and can be

#### Listing 5.21 recordCopy.fsx:

**Bindings are references. To copy and not make an alias, explicit copying must be performed.**

```

1 type person = {
2   name : string;
3   mutable age : int;
4 }
5
6 let author = {name = "Jon"; age = 50}
7 let authorAlias = author
8 let authorCopy = {name = author.name; age = author.age}
9 let authorCopyAlt = {author with name = "Noj"}
10 author.age <- 51
11 printfn "author : %A" author
12 printfn "authorAlias : %A" authorAlias
13 printfn "authorCopy : %A" authorCopy
14 printfn "authorCopyAlt : %A" authorCopyAlt

```

---

```

1 $ fsharp --nologo recordCopy.fsx && mono recordCopy.exe
2 author : { name = "Jon"
3   age = 51 }
4 authorAlias : { name = "Jon"
5   age = 51 }
6 authorCopy : { name = "Jon"
7   age = 50 }
8 authorCopyAlt : { name = "Noj"
9   age = 50 }

```

changed using the usual “<-” assignment operator. The example demonstrates two different ways to create records. Note that when the mutable value `author.age` is changed in line 10, then `authorAlias` also changes, since it is an alias of `author`, but neither `authorCopy` nor `authorCopyAlt` changes, since they are copies. As illustrated, copying using *with* allows for easy copying and partial updates of another record value.

## 5.6 Structures

*Structures*, or *structs* for short, have much in common with records. They specify a compound type with named fields, but they are value types, and they allow for some customization of what is to happen when a value of its type is created. Since they are value types, they are best used for small amounts of data. The syntax for defining struct types are:

Listing 5.22: Syntax for type abbreviation.

```

1 [ <attributes> ]
2 [<Struct>]
3 type <ident> =
4     val [ mutable ] <label1> : <type1>
5     val [ mutable ] <label2> : <type2>
6     ...
7     [new (<arg1>, <arg2>, ...) = {<label1> = <arg1>; <label1> =
8     <arg2>; ...}]
9     [new (<arg1>, <arg2>, ...) = {<label1> = <arg1>; <label1> =
10    <arg2>; ...}]
11    ...

```

The syntax makes use of the `val` and `new` keywords. Like `let`, the keyword `val` binds a name to a value, but unlike `let`, the value is always the type's default value. The `new` keyword denotes the function used to fill values into the fields at time of creation. This function is called the *constructor*. No `let` or `do`-bindings are allowed in structure definitions. Fields are accessed using the “.” notation. An example is given in Listing 5.23.

Listing 5.23 struct.fsx:  
Defining a struct type and creating a value of it.

```

1 [<Struct>]
2 type position =
3     val x : float
4     val y : float
5     new (a : float, b : float) = {x = a; y = b}
6
7 let p = position (3.0, 4.2)
8 printfn "%A: x = %A, y = %A" p p.x p.y

```

---

```

1 $ fsharp --nologo struct.fsx && mono struct.exe
2 Struct+position: x = 3.0, y = 4.2

```

Structs are small versions of classes and allows, e.g., for overloading of the `new` constructor and for overriding of the inherited `ToString()` function. This is demonstrated in Listing 5.24. We defer further discussion of these concepts to Chapter 23.

**Listing 5.24 structOverloadNOVERRIDE.fsx:**

Overloading the `new` constructor and overriding the default `ToString()` function.

```

1  [<Struct>]
2  type position =
3      val x : float
4      val y : float
5      new (a : float, b : float) = {x = a; y = b}
6      new (a : int, b : int) = {x = float a; y = float b}
7      override this.ToString() =
8          "(" + (string this.x) + ", " + (string this.y) + ")"
9
10 let pFloat = position (3.0, 4.2)
11 let pInt = position (3, 4)
12 printfn "%A and %A" pFloat pInt

```

---

```

1  $ fsharp --nologo structOverloadNOVERRIDE.fsx && mono
   structOverloadNOVERRIDE.exe
2  (3, 4.2) and (3, 4)

```

The use of structs are generally discouraged, and instead, it is recommended to use enums, records, and discriminated unions, possibly with the `[<Struct>]` attribute for the last two in order to make them value types.

## 5.7 Variable Types

An advanced topic in F# is *variable types*. There are three different versions of variable types in F#: *runtime resolved*, which have the syntax `'<ident>`, *anonymous*, which are written as `"_"`, and *statically resolved*, which have the syntax `^<ident>`. Variable types are particularly useful for functions that work for many types. An example of a generic function and its use is given in Listing 5.25. In this example, the

**Listing 5.25 variableType.fsx:**

A function apply with runtime resolved types.

```

1  let apply (f : 'a -> 'a -> 'a) (x : 'a) (y : 'a) : 'a = f x y
2  let intPlus (x : int) (y : int) : int = x + y
3  let floatPlus (x : float) (y : float) : float = x + y
4
5  printfn "%A %A" (apply intPlus 1 2) (apply floatPlus 1.0 2.0)

```

---

```

1  $ fsharp --nologo variableType.fsx && mono variableType.exe
2  3 3.0

```

function `apply` has runtime resolved variable type, and it accepts three parameters: `f`, `x`, and `y`. The function will work as long as the parameters for `f` is a function of two parameters of identical type, and `x` and `y` are values of the same type. Thus, in the `printfn` statement we are able to use `apply` for both an integer and a float variant.

The example in Listing 5.25 illustrates a very complicated way to add two numbers. The “+” operator works for both types out of the box, so why not something simpler like relying on the F# type inference system by not explicitly specifying types, as attempted in Listing 5.26? Unfortunately, the example fails to compile, since the type

**Listing 5.26** `variableTypeError.fsx`:

Even though the “+” operator is defined for both integers and floats, the type inference is static and infers `plus : int -> int`.

```

1 let plus x y = x + y
2
3 printfn "%A %A" (plus 1 2) (plus 1.0 2.0)
-----
1 $ fsharp --nologo variableTypeError.fsx && mono
   variableTypeError.exe
2
3 variableTypeError.fsx(3,34): error FS0001: This expression
   was expected to have type
4     'int'
5 but here has type
6     'float'
7
8 variableTypeError.fsx(3,38): error FS0001: This expression
   was expected to have type
9     'int'
10 but here has type
11     'float'

```

inference is performed at compile time, and by `plus 1 2`, it is inferred that `plus : int -> int`. Hence, calling `plus 1.0 2.0` is a type error. Function bindings allow for the use of the `inline` keyword, and adding this successfully reuses the definition of `plus` for both types, as shown in Listing 5.27. In the example, adding the `inline` does two things: Firstly, it copies the code to be performed to each place the function is used, and secondly, it forces statically resolved variable type checking independently in each place. The type annotations inferred as a result of the `inline`-keyword may be written explicitly, as shown in Listing 5.28. The example in Listing 5.28 demonstrates the statically resolved variable type syntax, `<ident>`, as well as the use of *type constraints*, using the keyword `when`. Type constraints have a rich syntax, but will not be discussed further in this book. In the example, the type constraint `when ^a : (static member ( + ) : ^a * ^a -> ^a)` is given using the object-oriented properties of the type variable `^a`, meaning that the only acceptable type values are those which have a member function (+) taking



**Listing 5.27** `variableTypeInline.fsx`:

The keyword `inline` forces static and independent inference each place the function is used. Compare to the error case in Listing 5.26.

```

1 let inline plus x y = x + y
2
3 printfn "%A %A" (plus 1 2) (plus 1.0 2.0)
-----
1 $ fsharp --nologo variableTypeInline.fsx && mono
   variableTypeInline.exe
2 3 3.0

```

**Listing 5.28** `compiletimeVariableType.fsx`:

Explicitly spelling out of the statically resolved type variables from Listing 5.26.

```

1 let inline plus (x : ^a) (y : ^a) : ^a when ^a : (static
   member ( + ) : ^a * ^a -> ^a) = x + y
2
3 printfn "%A %A" (plus 1 2) (plus 1.0 2.0)
-----
1 $ fsharp --nologo compiletimeVariableType.fsx && mono
   compiletimeVariableType.exe
2 3 3.0

```

a tuple and giving a value all of identical type, and where the type can be inferred at compile time. See Chapter 23 for details on member functions.

The `inline` construction is useful when generating generic functions and still profiting from static type checking. However, explicit copying of functions is often something better left to the compiler to optimize over. An alternative seems to be using runtime resolved variable types with the '`<ident>`' syntax. Unfortunately, this is not possible in case of most operators, since they have been defined in the `FSharp.Core` namespace to be statically resolved variable types. E.g., the “+” operator has type `( + ) : ^T1 -> ^T2 -> ^T3 (requires ^T1 with static member (+) and ^T2 with static member (+))`.



## Chapter 6

# Making programs and documenting them

**Abstract** Introductory text about the objectives of this chapter

- ...

---

### 6.1 7 step guide to making programs

...

### 6.2 Programming as a communication activity

Documentation is a very important part of writing programs, since it is most unlikely that you will be writing really obvious code. Moreover, what seems obvious at the point of writing may be mystifying months later to the author and to others. Documentation serves several purposes:

1. Communicate what the code should be doing.
2. Highlight big insights essential for the code.
3. Highlight possible conflicts and/or areas where the code could be changed later.

The essential point is that coding is a journey in problem-solving, and proper documentation is an aid in understanding the solution and the journey that lead to it. Documentation is most often a mixture of in-code documentation and accompanying documents. Here, we will focus on in-code documentation which arguably causes problems in multi-language environments and run the risk of bloating code.

F# has two different syntaxes for comments. Comments can be block comments:

**Listing 6.1: Block comments.**

```
1 (*<any text>*)
```

The comment text (<any text>) can be any text and is still parsed by F# as keywords and basic types, implying that `(* a comment (* in a comment *) *)` and `(* "*)" *)` are valid comments, while `(* " *)` is invalid.

Alternatively, comments may also be line comments,

**Listing 6.2: Line comments.**

```
1 //<any text>
```

where the comment text ends after the first newline.

The F# compiler has an option for generating *Extensible Markup Language (XML)* files from scripts using the C# documentation comments tags¹. The XML documentation starts with a triple-slash `///`, i.e., a `lineComment` and a slash, which serve as comments for the code construct that follows immediately after. XML consists of tags which always appear in pairs, e.g., the tag “tag” would look like `<tag> ... </tag>`. F# accept any tags, but recommends those listed in Table 6.1. If no tags are used, then it is automatically assumed to be a `<summary>`. An example of a documented script is shown in Listing 6.3. is:

Mono’s `fsharpc` command may be used to extract the comments into an XML file, as demonstrated in Listing 6.4.

**Listing 6.4, Converting in-code comments to XML.**

```
$ fsharpc --doc:commentExample.xml commentExample.fsx
F# Compiler for F# 4.0 (Open Source Edition)
Freely distributed under the Apache 2.0 Open Source License
```

This results in an XML file with the content shown in Listing 6.5.

¹ For specification of C# documentations comments see ECMA-334: <http://www.ecma-international.org/publications/files/ECMA-ST/ECma-334.pdf>

Tag	Description
<c>	Set text in a code-font.
<code>	Set one or more lines in code-font.
<example>	Set as an example.
<exception>	Describe the exceptions a function can throw.
<list>	Create a list or table.
<para>	Set text as a paragraph.
<param>	Describe a parameter for a function or constructor.
<paramref>	Identify that a word is a parameter name.
<permission>	Document the accessibility of a member.
<remarks>	Further describe a function.
<returns>	Describe the return value of a function.
<see>	Set as link to other functions.
<seealso>	Generate a See Also entry.
<summary>	Main description of a function or value.
<typeparam>	Describe a type parameter for a generic type or method.
<typeparamref>	Identify that a word is a type parameter name.
<value>	Describe a value.

**Table 6.1** Recommended XML tags for documentation comments, from ECMA-334 3rd Edition, Annex E, Section 2.

#### Listing 6.5, An XML file generated by fsharpc.

```

1  <?xml version="1.0" encoding="utf-8"?>
2  <doc>
3  <assembly><name>commentExample</name></assembly>
4  <members>
5  <member name="M:CommentExample.solution(System.Double,System
6  .Double,System.Double,System.Double)">
7  <summary>Find x when 0 = ax^2+bx+c.</summary>
8  <remarks>Negative discriminants are not checked.</remarks>
9  <example>
10   The following code:
11   <code>
12       let a = 1.0
13       let b = 0.0
14       let c = -1.0
15       let xp = (solution a b c +1.0)
16       printfn "0 = %.1fx^2 + %.1fx + %.1f => x_+ = %.1f" a b
17       c xp
18   </code>
19   prints <c>0 = 1.0x^2 + 0.0x + -1.0 => x_+ = 0.7</c> to
20   the console.
21 </example>
22 <param name="a">Quadratic coefficient.</param>
23 <param name="b">Linear coefficient.</param>
24 <param name="c">Constant coefficient.</param>
25 <param name="sgn">+1 or -1 determines the solution.</param>
26 <returns>The solution to x.</returns>
27 </member>
28 <member name="M:CommentExample.discriminant(System.Double,
29 System.Double,System.Double)">
30 <summary>
31   The discriminant of a quadratic equation with parameters a,
32   b, and c
33 </summary>
34 </member>
35 </members>
36 </doc>

```

**Listing 6.3** commentExample.fsx:  
Code with XML comments.

```

1  /// The discriminant of a quadratic equation with
2  /// parameters a, b, and c
3  let discriminant a b c = b ** 2.0 - 4.0 * a * c
4
5  /// <summary>Find x when 0 = ax^2+bx+c.</summary>
6  /// <remarks>Negative discriminants are not checked.</remarks>
7  /// <example>
8  ///     The following code:
9  ///     <code>
10 ///         let a = 1.0
11 ///         let b = 0.0
12 ///         let c = -1.0
13 ///         let xp = (solution a b c +1.0)
14 ///         printfn "0=%.1fx^2+%.1fx+%.1f => x_+=%.1f" a b c xp
15 ///     </code>
16 ///     prints <c>0=1.0x^2+0.0x+-1.0 => x_+=0.7</c>.
17 /// </example>
18 /// <param name="a">Quadratic coefficient.</param>
19 /// <param name="b">Linear coefficient.</param>
20 /// <param name="c">Constant coefficient.</param>
21 /// <param name="sgn">+1 or -1 determines the
    ///     solution.</param>
22 /// <returns>The solution to x.</returns>
23 let solution a b c sgn =
24     let d = discriminant a b c
25     (-b + sgn * sqrt d) / (2.0 * a)
26
27 let a = 1.0
28 let b = 0.0
29 let c = -1.0
30 let xp = (solution a b c +1.0)
31 printfn "0 = %.1fx^2 + %.1fx + %.1f => x_+ = %.1f" a b c xp

```

The extracted XML is written in C# type by convention, since F# is part of the Mono and .Net framework that may be used by any of the languages using Assemblies. Besides the XML inserted in the script, the XML has added the `<?xml ...>` header, `<doc>`, `<assembly>`, `<members>`, and `<member>` tags. The header and the `<doc>` tag are standards for XML. The extracted XML is geared towards documenting big libraries of codes and thus highlights the structured programming organisation, see Chapters 18 and 23, and `<assembly>`, `<members>`, and `<member>` are indications for where the functions belong in the hierarchy. As an example, the prefix `M:CommentExample.` indicates that the method is in the namespace `commentExample`, which in this case is the name of the file. Furthermore, the function type

```
val solution : a:float->b:float->c:float->sgn:float->float
```

is in the XML documentation

```
M:CommentExample.solution(System.Double,System.Double,System.Double,System.Double),
```

which is the C# equivalent.

An accompanying program in the Mono suite is `mdoc`, whose primary use is to perform a syntax analysis of an assembly and generate a scaffold XML structure for an accompanying document. With the `-i` flag, it is further possible to include the in-code comments as initial descriptions in the XML. The XML may be updated gracefully by `mdoc` as the code develops, without destroying manually entered documentation in the accompanying documentation. Finally, the XML may be exported to HTML.

The primary use of the `mdoc` command is to analyze compiled code and generate an empty XML structure with placeholders to describe functions, values, and variables. This structure can be updated and edited as the program develops, and the edited XML files can be exported to *Hyper Text Markup Language (HTML)* files and viewed in any browser. Using the console, all of this is accomplished by the procedure shown in Listing 6.6, and the result is shown in Figure 6.1.

#### Listing 6.6, Converting an XML file to HTML.

```
$ mdoc update -o commentExample -i commentExample.xml
commentExample.exe
New Type: CommentExample
Member Added: public static double determinant (double a,
double b, double c);
Member Added: public static double solution (double a,
double b, double c, double sgn);
Member Added: public static double a { get; }
Member Added: public static double b { get; }
Member Added: public static double c { get; }
Member Added: public static double xp { get; }
Namespace Directory Created:
New Namespace File:
Members Added: 6, Members Deleted: 0
$ mdoc export-html -out commentExampleHTML commentExample
.CommentExample
```

A full description of how to use `mdoc` is found here².

² <http://www.mono-project.com/docs/tools+libraries/tools/monodoc/generating-documentation/>

**solution Method**

Find  $x$  when  $0 = ax^2 + bx + c$ .

**Syntax**

```
[Microsoft.FSharp.Core.CompilationArgumentCounts(Mono.Cecil.CustomAttributeArgument[])]
public static double solution (double a, double b, double c, double sgn)
```

**Parameters**

*a* Quadratic coefficient.  
*b* Linear coefficient.  
*c* Constant coefficient.  
*sgn* +1 or -1 determines the solution.

**Returns**

The solution to  $x$ .

**Remarks**

Negative discriminants are not checked.

**Example**

The following code:

```
Example
let a = 1.0
let b = 0.0
let c = -1.0
let xp = (solution a b c +1.0)
printfn "0 = %.1fx^2 + %.1fx + %.1f => x_+ = %.1f" a b c xp
```

prints  $0 = 1.0x^2 + 0.0x + -1.0 \Rightarrow x_+ = 0.7$  to the console.

**Requirements**

**Namespace:**  
**Assembly:** commentExample (in commentExample.dll)  
**Assembly Versions:** 0.0.0.0

Fig. 6.1 Part of the HTML documentation as produced by mdoc and viewed in a browser.

## 6.3 Key concepts and terms in this chapter

Summary text about the key concepts from this chapter

- ...

**Abstract** Introductory text about the objectives of this chapter



- ...
-



## Chapter 7

### Lists

*Lists* are unions of immutable values of the same type. A list can be expressed as a *sequence expression*,

**Listing 7.1:** The syntax for a list using the sequence expression.

```
1 [[<expr>{; <expr>}]]
```

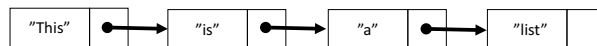
For example, `[1; 2; 3]` is a list of integers, `["This"; "is"; "a"; "list"]` is a list of strings, `[(fun x -> x); (fun x -> x*x)]` is a list of functions, and `[]` is the empty list. Lists may also be given as ranges,

**Listing 7.2:** The syntax for a list using the range expressions.

```
1 [<expr> .. <expr> [.. <expr>]]
```

where `<expr>` in *range expressions* must be of integers, floats, or characters. Examples are `[1 .. 5]`, `[-3.0 .. 2.0]`, and `['a' .. 'z']`. Range expressions may include a step size, thus, `[1 .. 2 .. 10]` evaluates to `[1; 3; 5; 7; 9]`.

A list type is identified with the `list` keyword, such that a list of integers has the type `int list`. Like strings, lists may be indexed using the `[]` notation, the lengths of lists is retrieved using the `Length` property, and we may test whether a list is empty by using the `IsEmpty` property. These features are demonstrated in Listing 7.3. F# implements lists as linked lists, as illustrated in Figure 7.1. As a consequence, index-



**Fig. 7.1** A list is a linked list: Here is illustrated the linked list of `["This"; "is"; "a"; "list"]`.

ing element  $i$  has *computational complexity*  $O(i)$ . The computational complexity of an operation is a description of how long a computation will take without considering the hardware it is performed on. The notation is sometimes called *Big-O* notation or

## Listing 7.3 listIndexing.fsx:

Lists are indexed as strings and has a Length property.

```

1 let printList (lst : int list) : unit =
2     for i = 0 to lst.Length - 1 do
3         printf "%A " lst[i]
4     printfn ""
5
6 let lst = [3; 4; 5]
7 printfn "lst = %A, lst[1] = %A" lst lst[1]
8 printfn "lst.Length = %A, lst.isEmpty = %A" lst.Length
9     lst.IsEmpty
10 printList lst

```

---

```

1 $ dotnet fsi listIndexing.fsx
2 lst = [3; 4; 5], lst[1] = 4
3 lst.Length = 3, lst.isEmpty = false
4 3 4 5

```

*Landau notation.* In the present case, the complexity is  $O(i)$ , which means that the complexity is linear in  $i$  and indexing element  $i + 1$  takes 1 unit longer than indexing element  $i$  when  $i$  is very large. The size of the unit is on purpose unspecified and depends on implementation and hardware details. Nevertheless, Big-O notation is a useful tool for reasoning about the efficiency of an operation. F# has access to the list's elements only by traversing the list from its beginning. I.e., to obtain the value of element  $i$ , F# starts with element 0, follows the link to element 1 and so on, until element  $i$  is reached. To reach element  $i + 1$  instead, we would need to follow 1 more link, and assuming that following a single link takes some constant amount of time we find that the computational complexity is  $O(i)$ . Compared to arrays, to be

★ discussed below, this is slow, which is why **indexing lists should be avoided**.

Notice especially that lists are zero-indexed, and thus, the last element in a list `lst` is `lst.Length - 1`. This is a very common source of error! Therefore, indexing in lists using *for*-loops is supported using a special notation with the `in` keyword,

## Listing 7.4: For-in loop with in expression.

```

1 for <ident> in <list> do <bodyExpr> [done]

```

In **for-in** loops, the loop runs through each element of the `<list>`, and assigns it to the identifier `<ident>`. This is demonstrated in Listing 7.5. Using **for-in** expressions remove the risk of off-by-one indexing errors, and thus, **for-in is to be preferred over for-to**.

★

Lists support slicing identically to strings, as demonstrated in Listing 7.6.

Lists may be concatenated using either the “@” *concatenation* operator or the “:.” *cons* operators. The difference is that “@” concatenates two lists of identical types,

**Listing 7.5 listFor.fsx:**

The **for-in** loops are preferred over **for-to** loops.

```

1 let printList (lst : int list) : unit =
2     for elm in lst do
3         printf "%A " elm
4     printfn ""
5
6 printList [3; 4; 5]

```

---

```

1 $ fsharpc --nologo listFor.fsx && mono listFor.exe
2 3 4 5

```

**Listing 7.6: Examples of list slicing. Compare with Listing 3.27.**

```

1 > let lst = ['a' .. 'g'];;
2 val lst: char list = ['a'; 'b'; 'c'; 'd'; 'e'; 'f'; 'g']
3
4 > lst[0];;
5 val it: char = 'a'
6
7 > lst[3];;
8 val it: char = 'd'
9
10 > lst[3..];;
11 val it: char list = ['d'; 'e'; 'f'; 'g']
12
13 > lst[..3];;
14 val it: char list = ['a'; 'b'; 'c'; 'd']
15
16 > lst[1..3];;
17 val it: char list = ['b'; 'c'; 'd']
18
19 > lst[*];;
20 val it: char list = ['a'; 'b'; 'c'; 'd'; 'e'; 'f'; 'g']

```

while “`::`” concatenates an element and a list of identical types. This is demonstrated in Listing 7.7. Since lists are represented as linked lists, the `cons` operator

**Listing 7.7: Examples of list concatenation.**

```

1 > ([1] @ [2; 3]);;
2 val it: int list = [1; 2; 3]
3
4 > ([1; 2] @ [3; 4]);;
5 val it: int list = [1; 2; 3; 4]
6
7 > (1 :: [2; 3]);;
8 val it: int list = [1; 2; 3]

```

is very efficient and has computational complexity  $O(1)$ , while concatenation has computational complexity  $O(n)$ , where  $n$  is the length of the first list.

It is possible to make multidimensional lists as lists of lists, as shown in Listing 7.8. The example shows a *ragged multidimensional list*, since each row has a different

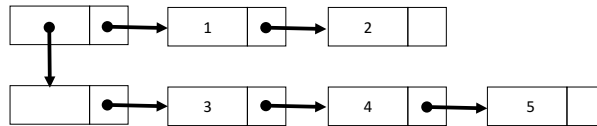
**Listing 7.8** listMultidimensional.fsx:

A ragged multidimensional list, built as lists of lists, and its indexing.

```
1 let a = [[1;2];[3;4;5]]
2 let row = a.Item 0 in printfn "%A" row
3 let elm = row.Item 1 in printfn "%A" elm
4 let elm = (a.Item 0).Item 1 in printfn "%A" elm

1 $ fsharp --nologo listMultidimensional.fsx && mono
   listMultidimensional.exe
2 [1; 2]
3 2
4 2
```

number of elements. This is also illustrated in Figure 7.2.



**Fig. 7.2** A list is a ragged linked list: Here is illustrated the linked list of `[[1;2];[3;4;5]]`.

The indexing of a particular element is slow due to the linked list implementation of lists, which is why arrays are often preferred for two- and higher-dimensional data structures, see Section 20.3.

## 7.1 List Properties

Lists support a number of properties, some of which are listed below.

**Head:** Returns the first element of a list.

### Listing 7.9: Head

```
1 > [1; 2; 3].Head;;  
2 val it: int = 1
```

**IsEmpty:** Returns true if the list is empty.

### Listing 7.10: IsEmpty

```
1 > [1; 2; 3].IsEmpty;;  
2 val it: bool = false
```

**Length:** Returns the number of elements in the list.

### Listing 7.11: Length

```
1  
2 > [1; 2; 3].Length;;  
3 val it: int = 3
```

**Tail:** Returns the list, except for its first element.

### Listing 7.12: Tail

```
1 > [1; 2; 3].Tail;;  
2 val it: int list = [2; 3]
```

## 7.2 The List Module

The built-in `List` module contains a wealth of functions for lists, some of which are briefly summarized below:

`List.collect: f:('T -> 'U list) -> lst:'T list -> 'U list.`

Applies `f` to each element in `lst` and return a concatenated list of the results.

### Listing 7.13: List.collect

`List.contains: elm:'T -> lst:'T list -> bool.`

Returns true or false depending on whether or not `elm` is contained in `lst`.

### Listing 7.14: List.contains

```
1 > List.contains 3 [1; 2; 3];;  
2 val it: bool = true
```

`List.filter: f:('T -> bool) -> lst:'T list -> 'T list.`

Returns a new list with all the elements of `lst` for which `f` evaluates to true.

### Listing 7.15: List.filter

```
1 > List.filter (fun x -> x % 2 = 1) [0 .. 9];;  
2 val it: int list = [1; 3; 5; 7; 9]
```

`List.find: f:('T -> bool) -> lst:'T list -> 'T.`

Returns the first element of `lst` for which `f` is true.

### Listing 7.16: List.find

`List.findIndex: f:('T -> bool) -> lst:'T list -> int.`

Returns the index of the first element of `lst` for which `f` is true.

### Listing 7.17: List.findIndex

```
1 > List.findIndex (fun x -> x = 'k') ['a' .. 'z'];;  
2 val it: int = 10
```

`List.fold: f:('S -> 'T -> 'S) -> elm:'S -> lst:'T list -> 'S.`

Updates an accumulator iteratively by applying `f` to each element in `lst`. The initial value of the accumulator is `elm`. For example, when `lst` consists of `n+1` elements `List.fold` calculates:

$$f \text{ } (\dots (f \text{ } (f \text{ } elm \text{ } lst[0]) \text{ } lst[1]) \dots) \text{ } lst[n].$$



**Listing 7.18: List.fold**

```

1 > let addSquares acc elm = acc + elm*elm
2 List.fold addSquares 0 [0 .. 9];;
3 val addSquares: acc: int -> elm: int -> int
4 val it: int = 285

```

**List.foldBack:** `f:('T -> 'S -> 'S) -> lst:'T list -> elm:'S -> 'S`.  
 Updates an accumulator iteratively backwards by applying `f` to each element in `lst`. The initial value of the accumulator is `elm`. For example, when `lst` consists of `n+1` elements `List.foldBack` calculates:

```
f lst[0] (f lst[1] (...(f lst[n] elm) ...)).
```

**Listing 7.19: List.foldBack**

```

1 > let addSquares elm acc = acc + elm*elm
2 List.foldBack addSquares [0 .. 9] 0;;
3 val addSquares: elm: int -> acc: int -> int
4 val it: int = 285

```

**List.forall:** `f:('T -> bool) -> lst:'T list -> bool`.  
 Returns true if all elements in `lst` are true when `f` is applied to them.

**Listing 7.20: List.forall**

```

1 > List.forall (fun x -> x % 2 = 1) [0 .. 9];;
2 val it: bool = false

```

**List.head:** `lst:'T list -> int`.  
 Returns the first element in `lst`. An exception is raised if `lst` is empty. See Section 13.1 for more on exceptions.

**Listing 7.21: List.head**

```

1 > List.head [1; -2; 0];;
2 val it: int = 1

```

**List.init:** `m:int -> f:(int -> 'T) -> 'T list`.  
 Create a list with `m` elements and whose value is the result of applying `f` to the index of the element.

**Listing 7.22: List.init**

```

1 > List.init 10 (fun i -> i * i);;
2 val it: int list = [0; 1; 4; 9; 16; 25; 36; 49; 64; 81]

```

**List.isEmpty:** `lst:'T list -> bool`.  
 Returns true if `lst` is empty.

**Listing 7.23: List.isEmpty**

```
1  
2 > List.isEmpty [1; 2; 3];;  
3 val it: bool = false
```

**List.iter:** `f:('T -> unit) -> lst:'T list -> unit.`

Applies `f` to every element in `lst`.

**Listing 7.24: List.iter**

```
1 > List.iter (fun x -> printfn "%A " x) [0; 1; 2];;  
2 0  
3 1  
4 2  
5 val it: unit = ()
```

**List.map:** `f:('T -> 'U) -> lst:'T list -> 'U list.`

Returns a list as a concatenation of applying `f` to every element of `lst`.

**Listing 7.25: List.map**

```
1 > List.map (fun x -> x*x) [0 .. 9];;  
2 val it: int list = [0; 1; 4; 9; 16; 25; 36; 49; 64; 81]
```

**List.ofArray:** `arr:'T [] -> 'T list.`

Returns a list whose elements are the same as `arr`. See Section 20.3 for more on arrays.

**Listing 7.26: List.ofArray**

```
1 > List.ofArray [|1; 2; 3|];;  
2 val it: int list = [1; 2; 3]
```

**List.rev:** `lst:'T list -> 'T list.`

Returns a new list with the same elements as in `lst` but in reversed order.

**Listing 7.27: List.rev**

```
1 > List.rev [1; 2; 3];;  
2 val it: int list = [3; 2; 1]
```

**List.sort:** `lst:'T list -> 'T list.`

Returns a new list with the same elements as in `lst` but where the elements are sorted.

**Listing 7.28: List.sort**

**List.tail:** `'T list -> 'T list.`

Returns a new list identical to `lst` but without its first element. An Exception is raised if `lst` is empty. See Section 13.1 for more on exceptions.

**Listing 7.29: List.tail**

```

1 > List.tail [1; 2; 3];;
2 val it: int list = [2; 3]
3
4 > let a = [1; 2; 3] in List.tail a;;
5 val it: int list = [2; 3]

```

**List.toArray:** `lst:'T list -> 'T []`.

Returns an array whose elements are the same as `lst`. See Section 20.3 for more on arrays.

**Listing 7.30: List.toArray**

```

1 > List.toArray [1; 2; 3];;
2 val it: int[] = [|1; 2; 3|]

```

**List.unzip:** `lst:('T1 * 'T2) list -> 'T1 list * 'T2 list`.

Returns a pair of lists of all the first elements and all the second elements of `lst`, respectively.

**Listing 7.31: List.unzip**

```

1 > List.unzip [(1, 'a'); (2, 'b'); (3, 'c')];;
2 val it: int list * char list = ([1; 2; 3], ['a'; 'b'; 'c'])

```

**List.zip:** `lst1:'T1 list -> lst2:'T2 list -> ('T1 * 'T2) list`.

Returns a list of pairs, where elements in `lst1` and `lst2` are iteratively paired.

**Listing 7.32: List.zip**

```

1 > List.zip [1; 2; 3] ['a'; 'b'; 'c'];;
2 val it: (int * char) list = [(1, 'a'); (2, 'b'); (3, 'c')]

```

## 7.3 Key concepts and terms in this chapter

Summary text about the key concepts from this chapter

- ...

**Abstract** Introductory text about the objectives of this chapter

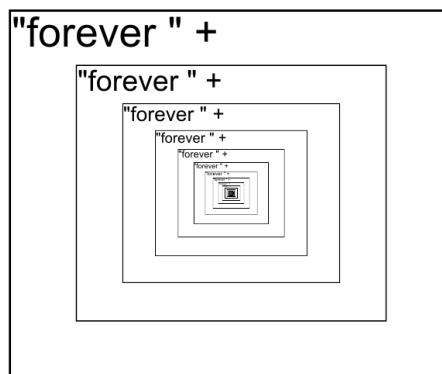
- ...



## Chapter 8

### Recursion

Recursion is a central concept in F# and is used to control flow in loops without the `for` and `while` constructions. Figure 8.1 illustrates the concept of an infinite loop with recursion.



**Fig. 8.1** An infinitely long string of "forever forever forever...", conceptually calculated by `let rec forever () = "forever " + (forever ())`.

#### 8.1 Recursive Functions

A *recursive function* is a function which calls itself, and the syntax for defining recursive functions is an extension of that for regular functions:

**Listing 8.1:** Syntax for defining one or more mutually dependent recursive functions.

```
1 let rec <ident> = <expr> {and <ident> = <expr>} [in] <expr>
```

From a compiler point of view, the `rec` is necessary, since the function is used before the compiler has completed its analysis. If two functions are mutually recursive, then they must be defined jointly using the `and` keyword.

An example of a recursive function that counts from 1 to 10 similarly to Listing 21.5 is given in Listing 8.2. Here the `prt` function calls itself repeatedly, such that the first

**Listing 8.2** `countRecursive.fsx`:  
Counting to 10 using recursion.

```
1 let rec prt a b =
2   if a > b then
3     printf "\n"
4   else
5     printf "%d " a
6     prt (a + 1) b
7
8 prt 1 10
```

---

```
1 $ fsharpc --nologo countRecursive.fsx && mono
   countRecursive.exe
2 1 2 3 4 5 6 7 8 9 10
```

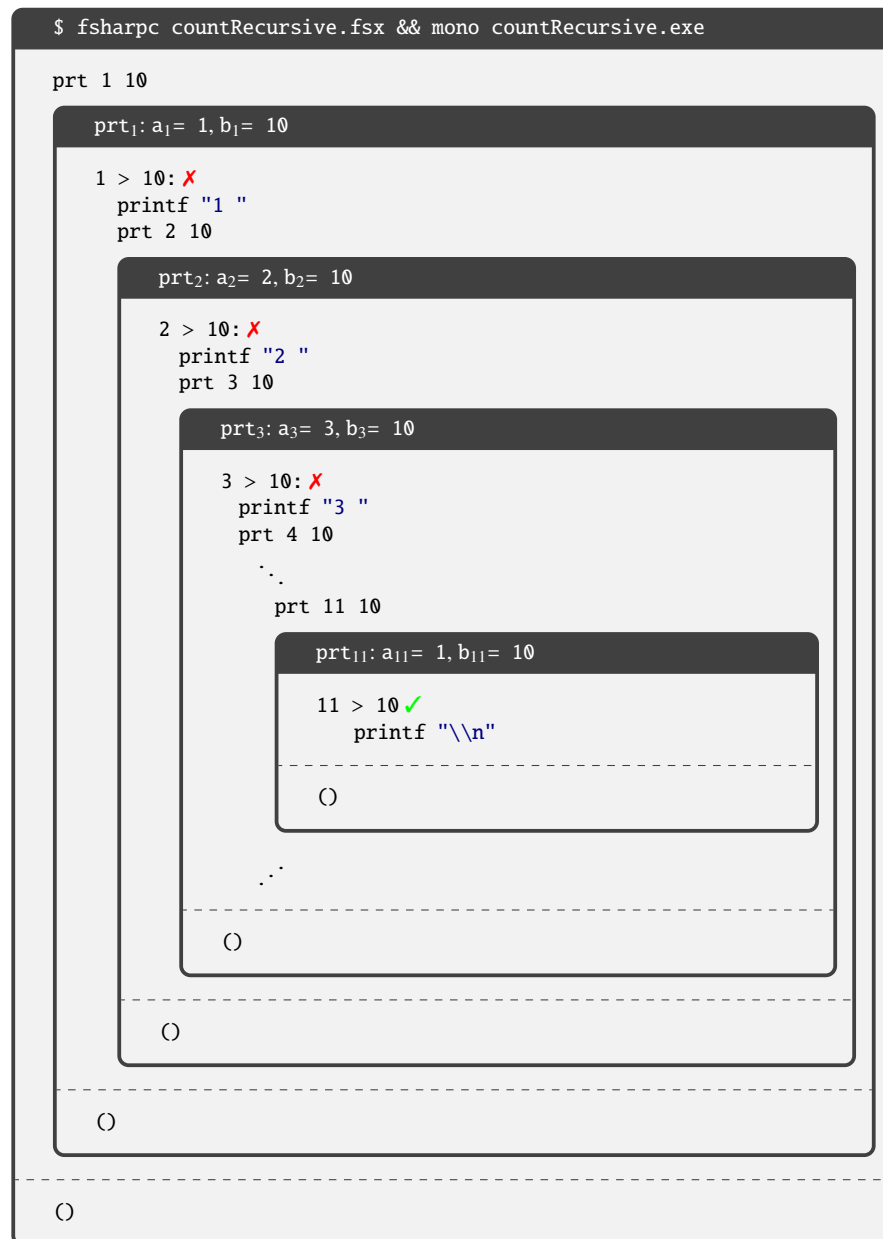
call is `prt 1 10`, which calls `prt 2 10`, and so on until the last call `prt 11 10`. Each time `prt` is called, new bindings named `a` and `b` are made to new values. This is illustrated in Figure 8.2. The old values are no longer accessible, as indicated by subscripts in the figure. E.g., in `prt3`, the scope has access to `a3` but not `a2` and `a1`. Thus, in this program, the process is similar to a `for` loop, where the counter is `a`, and in each loop its value is reduced.

The structure of the function is typical for recursive functions. They very often follow the following pattern.

**Listing 8.3:** Recursive functions consist of a stopping criterium, a stopping expression, and a recursive step.

```
1 let rec f a =
2   if <stopping condition>
3   then <stopping step>
4   else <recursion step>
```

The `match` – `with` are also very common conditional structures. In Listing 8.2, `a > b` is the *stopping condition*, `printfn "\n"` is the *stopping step*, and `printfn "%d " a; prt (a + 1) b` is the *recursion step*.



**Fig. 8.2** Illustration of the recursion used to write the sequence “1 2 3 ... 10” in line 8 in Listing 8.2. Each frame corresponds to a call to `prt`, where new values overshadow old ones. All calls return `unit`.

## 8.2 The Call Stack and Tail Recursion

Fibonacci's sequence of numbers is a recursive sequence of numbers with relations to the Golden ratio and structures in biology. The Fibonacci sequence is the sequence of numbers 1, 1, 2, 3, 5, 8, 13, . . . . The sequence starts with 1, 1 and the next number is recursively given as the sum of the two previous ones. A direct implementation of this is given in Listing 21.8. Here we extended the sequence to 0, 1, 1, 2, 3, 5, . . .

**Listing 8.4** `fibRecursive.fsx`:  
The  $n$ 'th Fibonacci number using recursion.

```

1 let rec fib n =
2   if n < 1 then
3     0
4   elif n = 1 then
5     1
6   else
7     fib (n - 1) + fib (n - 2)
8
9 for i = 0 to 10 do
10  printfn "fib(%d) = %d" i (fib i)

```

---

```

1 $ fsharp --nologo fibRecursive.fsx && mono fibRecursive.exe
2 fib(0) = 0
3 fib(1) = 1
4 fib(2) = 1
5 fib(3) = 2
6 fib(4) = 3
7 fib(5) = 5
8 fib(6) = 8
9 fib(7) = 13
10 fib(8) = 21
11 fib(9) = 34
12 fib(10) = 55

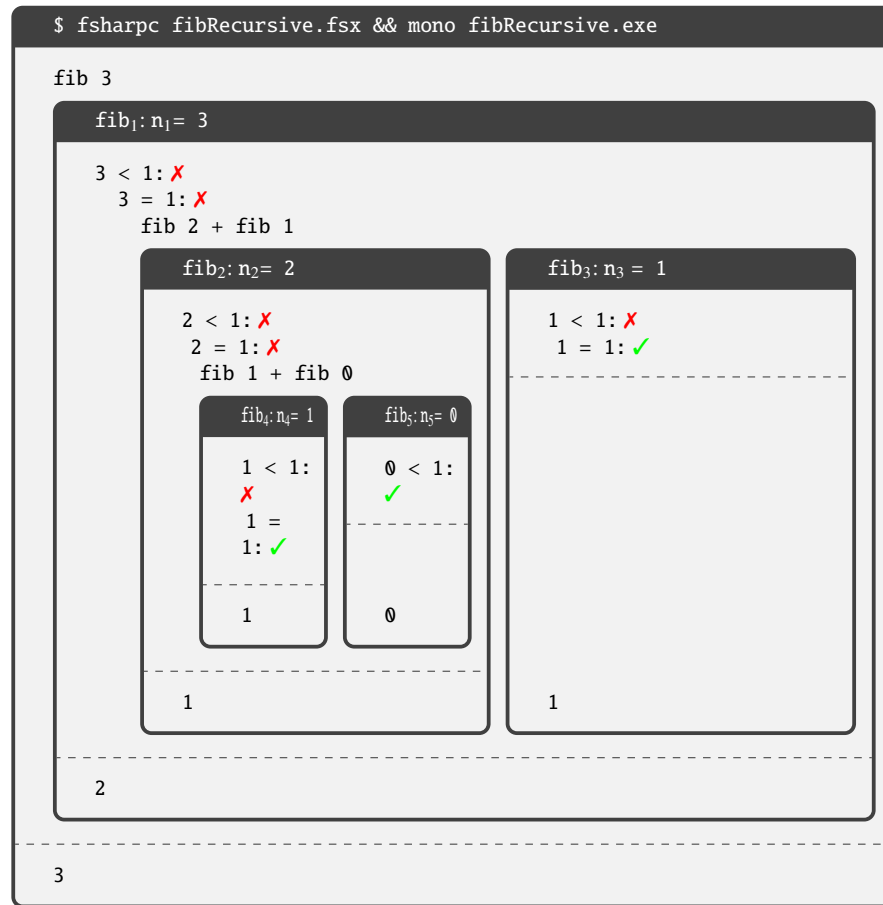
```

with the starting sequence 0, 1, allowing us to define all  $\text{fib}(n) = 0$ ,  $n < 1$ . Thus, our function is defined for all integers, and for the irrelevant negative arguments it fails gracefully by returning 0. This is a general piece of advice: **make functions that fail gracefully**.

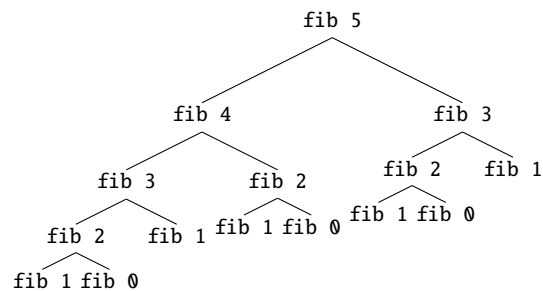
★

A visualization of the calls and the scopes created by `fibRecursive` is shown in Figure 8.3. The figure illustrates that each recursive step results in two calls to the function, thus creating two new scopes. And it gets worse. Figure 8.4 illustrates the tree of calls for `fib 5`. Thus, a call to the function `fib` generates a tree of calls that is five levels deep and has `fib(5)` number of nodes. In general for the program in Listing 8.4, a call to `fib(n)` produces a tree with  $\text{fib}(n) \leq c\alpha^n$  calls to the function for some positive constant  $c$  and  $\alpha \geq \frac{1+\sqrt{5}}{2} \sim 1.6$ . Each call takes time and requires memory, and we have thus created a slow and somewhat memory-intensive function.





**Fig. 8.3** Illustration of the recursion used to write the sequence “1 2 3 ... 10” in line 8 in Listing 8.2. Each frame corresponds to a call to `fib`, where new values overshadow old ones.



**Fig. 8.4** The function calls involved in calling `fib 5`.

This is a hugely ineffective implementation of calculating entries into Fibonacci's sequence, since many of the calls are identical. E.g., in Figure 8.4, `fib 1` is called five times. Before we examine a faster algorithm, we first need to discuss how F# executes function calls.

When a function is called, then memory is dynamically allocated internally for the function on what is known as the *call stack*. Stacks are used for many things in programming, but typically the call stack is considered special, since it is almost always implicitly part of any program execution. Hence, it is often just referred to as *The Stack*. When a function is called, a new *stack frame* is stacked (pushed) on the call stack, including its arguments, local storage such as mutable values, and where execution should return to when the function is finished. When the function finishes, the stack frame is unstacked (popped) and in its stead, the return value of the function is stacked. This return value is then unstacked and used by the caller. After unstacking the return value, the call stack is identical to its state prior to the call. Figure 8.5 shows snapshots of the call stack when calling `fib 5` in Listing 8.4. The call first stacks a frame onto the call stack with everything needed to execute the



**Fig. 8.5** A call to `fib 5` in Listing 8.4 starts a sequence of function calls and stack frames on the call stack.

function body plus a reference to where the return to, when the execution is finished. Then the body of `fib` is executed, which includes calling `fib 4` and `fib 3` in turn. The call to `fib 4` stacks a frame onto the call stack, and its body is executed. Once execution is returned from the call to `fib 4`, the result of the function is on top of the stack. It is unstacked, saved and the call to `fib 3` is treated equally. When the end of `fib 5` is reached, its frame is unstacked, and its result is stacked. In this way, the call stack is returned to its original state except for the result of the function, and execution is returned to the point right after the original call to `fib 5`. Thus, for Listing 8.4  $O(\alpha^n)$ ,  $\alpha = \frac{1+\sqrt{5}}{2}$  stacking operations are performed for a call to `fib n`. The  $O(f(n))$  is the *Landau symbol* used to denote the order of a function, such that if  $g(n) = O(f(n))$  then there exists two real numbers  $M > 0$  and a  $n_0$  such that for all  $n \geq n_0$ ,  $|g(n)| \leq M|f(n)|$ . As indicated by the tree in Figure 8.4, the call tree is at most  $n$  high, which corresponds to a maximum of  $n$  additional stack frames as compared to the starting point.

The implementation of Fibonacci's sequence in Listing 8.4 can be improved to run faster and use less memory. One such algorithm is given in Listing 8.5. Calculating the 45th Fibonacci number a MacBook Pro, with a 2.9 GHz Intel Core i5 using Listing 8.4 takes about 11.2s while using Listing 8.5 is about 224 times faster and only takes 0.050s. The reason is that `fib` in Listing 8.5 calculates every number in

**Listing 8.5 fibRecursiveAlt.fsx:**

A fast, recursive implementation of Fibonacci's numbers. Compare with Listing 8.4.

```

1 let fib n =
2     let rec fibPair n pair =
3         if n < 2 then pair
4         else fibPair (n - 1) (snd pair, fst pair + snd pair)
5     if n < 1 then 0
6     elif n = 1 then 1
7     else fibPair n (0, 1) |> snd
8
9 printfn "fib(10) = %d" (fib 10)
-----
1 $ fsharpc --nologo fibRecursiveAlt.fsx && mono
   fibRecursiveAlt.exe
2 fib(10) = 55

```

the sequence once and only once by processing the list recursively while maintaining the previous two values needed to calculate the next in the sequence. I.e., the function `fibPair` transforms the pair  $(a, b)$  to  $(b, a+b)$  such that, e.g., the 4th and 5th pair  $(3, 5)$  is transformed into the 5th and the 6th pair  $(5, 8)$  in the sequence. What complicates the algorithm is that besides the transformation, we must keep track of when to stop, which here is done using a counter variable, that is recursively reduced by 1 until our stopping criterium.

Listing 8.5 also uses much less memory than Listing 8.4, since its recursive call is the last expression in the function, and since the return value of two recursive calls to `fibPair` is the same as the return value of the last. In fact, the return value of any number of recursive calls to `fibPair` is the return value of the last. This structure is called *tail-recursion*. Compilers can easily optimize the call stack usage for tail recursion, since when in this example `fibPair` calls itself, then its frame is no longer needed, and may be replaced by the new `fibPair` with the slight modification, that the return point should be to `fib` and not the end of the previous `fibPair`. Once the recursion reaches the stopping criteria, then instead of popping a long list of calls of `fibPair` frames, then there is only one, and the return value is equal to the return value of the last call and the return point is to `fib`. Thus, many stack frames in tail recursion are replaced by one. Hence, **prefer tail-recursion whenever possible.** ★

## 8.3 Mutually Recursive Functions

Functions that recursively call each other are called *mutually recursive* functions. F# offers the `let - rec - and` notation for co-defining mutually re-

cursive functions. As an example, consider the function `even : int -> bool`, which returns true if its argument is even and false otherwise, and the opposite function `odd : int -> bool`. A mutually recursive implementation of these functions can be developed from the following relations: `even 0 = true`, `odd 0 = false`, and for  $n > 0$ , `even n = odd (n-1)`, which implies that for  $n > 0$ , `odd n = even (n-1)`: Notice that in the lightweight notation the `and` must

#### Listing 8.6 mutuallyRecursive.fsx:

Using mutual recursion to implement even and odd functions.

```

1 let rec even x =
2   if x = 0 then true
3   else odd (x - 1)
4 and odd x =
5   if x = 0 then false
6   else even (x - 1);;
7
8 let w = 5;
9 printfn "%s %s %s" w "i" w "even" w "odd"
10 for i = 1 to w do
11   printfn "%d %b %b" w i w (even i) w (odd i)

```

---

```

1 $ fsharp --nologo mutuallyRecursive.fsx && mono
   mutuallyRecursive.exe
2   i even odd
3   1 false true
4   2 true false
5   3 false true
6   4 true false
7   5 false true

```

be on the same indentation level as the original `let`.

Without the `and` keyword, F# will issue a compile error at the definition of `even`. However, it is possible to implement mutual recursion by using functions as an argument, e.g., This being said, Listing 8.6 is clearly to be preferred over Listing 8.7.

In the example above, we used the `even` and `odd` function problems to demonstrate mutual recursion. There is, of course, a much simpler solution, which does not use recursion at all: This is to be preferred anytime as the solution to the problem.

**Listing 8.7 mutuallyRecursiveAlt.fsx:**

Mutual recursion without the `and` keyword requires a helper function.

```

1 let rec evenHelper (notEven: int -> bool) x =
2     if x = 0 then true
3     else notEven (x - 1)
4
5 let rec odd x =
6     if x = 0 then false
7     else evenHelper odd (x - 1);;
8
9 let even x = evenHelper odd x
10
11 let w = 5;
12 printfn "%s %s %s" w "i" w "Even" w "Odd"
13 for i = 1 to w do
14     printfn "%d %b %b" w i w (even i) w (odd i)

```

---

```

1 $ fsharp --nologo mutuallyRecursiveAlt.fsx && mono
   mutuallyRecursiveAlt.exe
2     i Even  Odd
3     1 false true
4     2 true  false
5     3 false true
6     4 true  false
7     5 false true

```

**Listing 8.8 parity.fsx:**

A better way to test for parity without recursion.

```

1 let even x = (x % 2 = 0)
2 let odd x = not (even x)

```

## 8.4 Tracing Recursive Programs

Tracing by hand is a very illustrative method for understanding recursive programs. Consider the recursive program in Listing 8.9. The program includes a function for

**Listing 8.9 gcd.fsx:**  
The greatest common divisor of 2 integers.

```

1 let rec gcd a b =
2   if a < b then
3     gcd b a
4   elif b > 0 then
5     gcd b (a % b)
6   else
7     a
8
9 let a = 10
10 let b = 15
11 printfn "gcd %d %d = %d" a b (gcd a b)

```

---

```

1 $ fsharp --nologo gcd.fsx && mono gcd.exe
2 gcd 10 15 = 5

```

calculating the greatest common divisor of 2 integers, and calls this function with the numbers 10 and 15. Following the notation introduced in Section 19.3, we write:

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	$\text{gcd} = ((a, b), \text{gcd-body}, ())$
2	9	$E_0$	$a = 10$
3	10	$E_0$	$b = 15$

In line 11, `gcd` is called before any output is generated, which initiates a new environment  $E_1$  and executes the code in `gcd-body`:

Step	Line	Env.	Bindings and evaluations
4	11	$E_0$	$\text{gcd } a \ b = ?$
5	1	$E_1$	$((a = 10, b = 15), \text{gcd-body}, ())$

In  $E_1$  we have that  $a < b$ , which fulfills the first condition in line 2. Hence, we call `gcd` with switched arguments and once again initiate a new environment,

Step	Line	Env.	Bindings and evaluations
6	3	$E_1$	$\text{gcd } b \ a = ?$
7	1	$E_2$	$((a = 15, b = 10), \text{gcd-body}, ())$

In  $E_2$ ,  $a < b$  in line 2 is false, but  $b > 0$  in line 4 is true, hence, we first evaluate  $a \% b$ , call  $\text{gcd } b \ (a \% b)$ , and then create a new environment,

Step	Line	Env.	Bindings and evaluations
8	5	$E_2$	$a \% b = 5$
9	5	$E_2$	$\text{gcd } b \ (a \% b) = ?$
10	1	$E_3$	$((a = 10, b = 5), \text{gcd-body}, ())$

Again we fall through to line 5, evaluate the remainder operator and initiate a new environment,

Step	Line	Env.	Bindings and evaluations
11	5	$E_3$	$a \% b = 0$
12	5	$E_3$	$\text{gcd } b \ (a \% b) = ?$
13	1	$E_4$	$((a = 5, b = 0), \text{gcd-body}, ())$

This time both  $a < b$  and  $b > 0$  are false, so we fall through to line 7 and return the value of  $a$  from  $E_4$ , which is 5:

Step	Line	Env.	Bindings and evaluations
14	7	$E_4$	$\text{return} = 5$

We scratch  $E_4$ , return to  $E_3$ , either physically or mentally replace the ?-mark with 5 and continue the evaluation of line 5. Since this is also a branch of the last statement in  $\text{gcd}$ , we return the previously evaluated value,

Step	Line	Env.	Bindings and evaluations
15	5	$E_3$	$\text{return} = 5$

Like before, we scratch  $E_3$ , return to  $E_2$ , either physically or mentally replace the ?-mark with 5 and continue the evaluation of line 5. Since this is also a branch of the last statement in  $\text{gcd}$ , we return the just evaluated value,

Step	Line	Env.	Bindings and evaluations
16	5	$E_2$	$\text{return} = 5$

Again, we scratch  $E_2$ , return to  $E_1$ , either physically or mentally replace the ?-mark with 5 and continue the evaluation of line 5. Since this is also a branch of the last statement in  $\text{gcd}$ , we return the just evaluated value,

Step	Line	Env.	Bindings and evaluations
17	3	$E_1$	$\text{return} = 5$

Finally, we scratch  $E_1$ , return to  $E_0$ , either physically or mentally replace the ?-mark with 5 and continue the evaluation of line 5:

3 Step	Line	Env.	Bindings and evaluations
18	11	$E_0$	output = "gcd a b = 5"
19	11	$E_0$	return = ()

Note that the output of `printfn` is a side-effect while its return-value is unit. In any case, since this is the last line in our program, we are done tracing.

## 8.5 Key concepts and terms in this chapter

Summary text about the key concepts from this chapter

- ...



## Chapter 9

# Higher-Order Functions

**Abstract** Introductory text about the objectives of this chapter

• ...

---

A *higher-order function* is a function that takes a function as an argument and/or returns a function. higher-order functions are also sometimes called functionals or functors. F# is a functions-first programming language with strong support for working with functions as values: Functions evaluate as *closures*, see Section 4.2, which can be passed to and from functions as any other value. An example of a higher-order function is `List.map` which takes a function and a list and produces a list, demonstrated in Listing 9.1. Here `List.map` applies the function `inc` to every element of

**Listing 9.1** `higherOrderMap.fsx`:

`List.map` is a higher-order function, since it takes a function as argument.

```
1 let inc x = x + 1
2 let newList = List.map inc [2; 3; 5]
3 printfn "%A" newList
```

```
1 $ fsharp --nologo higherOrderMap.fsx && mono
   higherOrderMap.exe
2 [3; 4; 6]
```

the list. higher-order functions are often used together with *anonymous functions*, where the anonymous function is given as argument. For example, Listing 9.1 may be rewritten using an anonymous function as shown in Listing 9.2. The code may be compacted even further, as shown in Listing 9.3. What was originally three lines in Listing 9.1 including bindings to the names `inc` and `newList` has in Listing 9.3

**Listing 9.2 higherOrderAnonymous.fsx:**

An anonymous function is a higher-order function used here as an unnamed argument. Compare with Listing 9.1.

```
1 let newList = List.map (fun x -> x + 1) [2; 3; 5]
2 printfn "%A" newList

-----

1 $ fsharp --nologo higherOrderAnonymous.fsx && mono
   higherOrderAnonymous.exe
2 [3; 4; 6]
```

**Listing 9.3 higherOrderAnonymousBrief.fsx:**

A compact version of Listing 9.1.

```
1 printfn "%A" (List.map (fun x -> x + 1) [2; 3; 5])

-----

1 $ fsharp --nologo higherOrderAnonymousBrief.fsx && mono
   higherOrderAnonymousBrief.exe
2 [3; 4; 6]
```

been reduced to a single line with no bindings. All three programs result in the same output and as such are equal. Likewise, running times will be equal. However, they differ in readability for a programmer and ease of bug hunting and future maintenance: Bindings allows us to reuse the code at a later stage, but if there is no reuse, then the additional bindings may result in a cluttered program. Further, for compact programs like Listing 9.3, it is not possible to perform a unit test of the function arguments. Finally, bindings emphasize semantic aspects of the evaluation being performed merely by the names we select, and typically long, meaningful names are to be preferred, within reasonable limits. For example instead of `inc` one could have used `increment_by_one` or similar which certainly is semantically meaningful, but many programmers will find that the short is to be preferred in order to reduce the amount of typing to be performed.

Anonymous functions are also useful as return values of functions, as shown in Listing 9.4 Here the `inc` function produces a customized incrementation function

**Listing 9.4 higherOrderReturn.fsx:**

The procedure `inc` returns an increment function. Compare with Listing 9.1.

```
1 let inc n =
2   fun x -> x + n
3 printfn "%A" (List.map (inc 1) [2; 3; 5])

-----

1 $ fsharp --nologo higherOrderReturn.fsx && mono
   higherOrderReturn.exe
2 [3; 4; 6]
```

as argument to `List.map`: It adds a prespecified number to an integer argument. Note that the closure of this customized function is only produced once, when the arguments for `List.map` is prepared, and not every time `List.map` maps the function to the elements of the list. Compare with Listing 9.1.

*Piping* is another example of a set of higher-order function: `(<|)`, `(|>)`, `(<||)`, `(||>)`, `(<|||)`, `(|||>)`. E.g., the functional equivalent of the right-to-left piping operator takes a value and a function and applies the function to the value, as demonstrated in Listing 9.5. Here the piping operator is used to apply the `inc`

#### Listing 9.5 higherOrderPiping.fsx:

The functional equivalent of the right-to-left piping operator is a higher-order function.

```
1 let inc x = x + 1
2 let aValue = 2
3 let anotherValue = (|>) aValue inc
4 printfn "%d -> %d" aValue anotherValue

-----

1 $ fsharp --nologo higherOrderPiping.fsx && mono
   higherOrderPiping.exe
2 2 -> 3
```

function to `aValue`. A more elegant way to write this would be `aValue |> inc`, or even just `inc aValue`.

## 9.1 Function Composition

Piping is a useful shorthand for composing functions, where the focus is on the transformation of arguments and results. Using higher-order functions, we can forgo the arguments and compose functions as functions directly. This is done with the “`>>`” and “`<<`” operators. An example is given in Listing 9.6. In the example we see that `(f >> g) x` gives the same result as `g (f x)`, while `(f << g) x` gives the same result as `f (g x)`. A memo technique for remembering the order of the application, when using the function composition operators, is that `(f >> g) x` is the same as `x |> f |> g`, i.e., the result of applying `f` to `x` is the argument to `g`. However, there is a clear distinction between the piping and composition operators. The type of the piping operator is

```
(|>) : ('a, 'a -> 'b) -> 'b
```

**Listing 9.6** `higherOrderComposition.fsx`:  
Functions defined as compositions of other functions.

```

1 let f x = x + 1
2 let g x = x * x
3 let h = f >> g
4 let k = f << g
5 printfn "%d" (g (f 2))
6 printfn "%d" (h 2)
7 printfn "%d" (f (g 2))
8 printfn "%d" (k 2)

```

---

```

1 $ fsharp -nologo higherOrderComposition.fsx && mono
   higherOrderComposition.exe
2 9
3 9
4 5
5 5

```

i.e., the piping operator takes a value of type 'a and a function of type 'a -> 'b, applies the function to the value, and produces the value 'b. In contrast, the composition operator has type

$$(>>) : ('a \rightarrow 'b, 'b \rightarrow 'c) \rightarrow ('a \rightarrow 'c)$$

i.e., it takes two functions of type 'a -> 'b and 'b -> 'c respectively, and produces a new function of type 'a -> 'c.

## 9.2 Currying

Consider a function `f` of two generic arguments. Its type in F# will be `f : 'a -> 'b -> 'c`, meaning that `f` takes an argument of type 'a and returns a function of type 'b -> 'c. That is, if just one argument is given, then the result is a function, not a value. This is called *partial specification* or *currying* in tribute of Haskell Curry¹. An example is given in Listing 9.7. Here, `mul 2.0` is a partial application of the function `mul x y`, where the first argument is fixed, and hence `timesTwo` is a function of 1 argument being the second argument of `mul`. The same can be achieved using tuple arguments, as shown in Listing 9.8. Conversion between multiple and tuple arguments is easily done with higher-order functions, as demonstrated in Listing 9.9. Conversion between multiple and tuple arguments are useful when working with

¹ Haskell Curry (1900–1982) was an American mathematician and logician who also has a programming language named after him: Haskell.

**Listing 9.7 higherOrderCurrying.fsx:****Currying: defining a function as a partial specification of another.**

```

1 let mul x y = x*y
2 let timesTwo = mul 2.0
3 printfn "%g" (mul 5.0 3.0)
4 printfn "%g" (timesTwo 3.0)

```

---

```

1 $ fsharpc --nologo higherOrderCurrying.fsx && mono
   higherOrderCurrying.exe
2 15
3 6

```

**Listing 9.8 higherOrderTuples.fsx:****Partial specification of functions using tuples is less elegant. Compare with Listing 9.7.**

```

1 let mul (x, y) = x*y
2 let timesTwo y = mul (2.0, y)
3 printfn "%g" (mul (5.0, 3.0))
4 printfn "%g" (timesTwo 3.0)

```

---

```

1 $ fsharpc --nologo higherOrderTuples.fsx && mono
   higherOrderTuples.exe
2 15
3 6

```

**Listing 9.9: Two functions to convert between two and 2-tuple arguments.**

```

1 > let curry f x y = f (x,y)
2 let uncurry f (x,y) = f x y;;
3 val curry: f: ('a * 'b -> 'c) -> x: 'a -> y: 'b -> 'c
4 val uncurry: f: ('a -> 'b -> 'c) -> x: 'a * y: 'b -> 'c

```

higher-order functions such as `Lst.map`. E.g., if `let mul (x, y) = x * y` as in Listing 9.8, then `curry mul` has the type `x:'a -> y:'b -> 'c` as can be seen in Listing 9.9, and thus is equal to the anonymous function `fun x y -> x * y`. Hence, `curry mul 2.0` is equal to `fun y -> 2.0 * y`, since the precedence of function calls is `(curry mul) 2.0`.

Currying makes elegant programs and is often used in functional programming. Nevertheless, currying may lead to obfuscation, and in general, **currying should be used with care and be well documented for proper readability of code.** ★

### **9.3 Key concepts and terms in this chapter**

Summary text about the key concepts from this chapter

- ...

## Chapter 10

# Collections of Data

**Abstract** Introductory text about the objectives of this chapter

- ...

---

F# is tuned to work with collections of data, and there are several built-in types of collections with various properties making them useful for different tasks. Examples include strings, lists, and arrays. Strings were discussed in Chapter 3 and will be revisited here in more details.

The data structures discussed below all have operators, properties, methods, and modules to help you write elegant programs using them.

Properties and methods are common object-oriented terms used in conjunction with the discussed functionality. They are synonymous with values and functions and will be discussed in Chapter 23. Properties and methods for a value or variable are called using the *dot notation*, i.e., with the “.”-lexeme. For example, `"abcdefg".Length` is a property and is equal to the length of the string, and `"abcdefg".ToUpper()` is a method and creates a new string where all characters have been converted to upper case.

The data structures also have accompanying modules with a wealth of functions and where some are mentioned here. Further, the data structures are all implemented as classes offering even further functionality. The modules are optimized for functional programming, see Chapters 8 to 11, while classes are designed to support object-oriented programming, see Chapters 23 to 25.

In the following, a brief overview of many properties, methods, and functions is given by describing their name and type-definition, and by giving a short description and an

example of their use. Several definitions are general and works with many different types. To describe this we will use the notation of generic types, see Section 4.2. The name of a generic type starts with the “'” lexeme, such as 'T. The implication of the appearance of a generic type in, e.g., a function’s type-definition, is that the function may be used with any real type such as `int` or `char`. If the same generic type name is used in several places in the type-definition, then the function must use a real type consistently. For example, The `List.fromArray` function has type `arr: 'T [] -> 'T list`, meaning that it takes an array of some type and returns a list of the same type.

See the F# Language Reference at <https://docs.microsoft.com/en-us/dotnet/fsharp/> for a full description of all available functionality including variants of those included here.

## 10.1 Strings

Strings have been discussed in Chapter 3, the content of which will be briefly revisited here followed by a description of some of the many supporting built-in functions in F# on strings.

A *string* is a sequence of characters. Each character is represented using UTF-16, see Appendix C for further details on the unicode standard. The type `string` is an alias for `System.string`. String literals are delimited by double quotation marks “”” and inside the delimiters, character escape sequences are allowed (see Table 3.2), which are replaced by the corresponding character code. Examples are `"This is a string"`, `"\tTabulated string"`, `"A \"quoted\" string"`, and `""`. Strings may span several lines, and new lines inside strings are part of the string unless the line is ended with a backslash. Strings may be *verbatim* by preceding the string with “@”, in which case escape sequences are not replaced, but two double quotation marks are an escape sequence which is replaced by a one double quotation mark. Examples of “@”-verbatim strings are:

- `@"This is a string"`,
- `@"\tNon-tabulated string"`,
- `@"A ""quoted"" string"`, and
- `@""`.

Alternatively, a verbatim string may be delimited by three double quotation marks. Examples of “"""”-verbatim strings are:



- `""""This is a string"""`,
- `""""\tNon-tabulated string"""`,
- `""""A "quoted" string"""`, and
- `"""""""`.

Strings may be indexed using the `[]` notation, as demonstrated in Listing 3.27.

### 10.1.1 String Properties and Methods

Strings have a few properties which are values attached to each string and accessed using the `“.”` notation. The only to be mentioned here is:

`IndexOf(): str:string -> int.`

Returns the index of the first occurrence of `s` or `-1`, if `str` does not appear in the string.

#### Listing 10.1: IndexOf()

`Length: int.`

Returns the length of the string.

#### Listing 10.2: Length

```
1 > "abcd".Length;;  
2 val it: int = 4
```

`ToLower(): unit -> string.`

Returns a copy of the string where each letter has been converted to lower case.

#### Listing 10.3: ToLower()

```
1 > "aBcD".ToLower();;  
2 val it: string = "abcd"
```

`ToUpper(): unit -> string.`

Returns a copy of the string where each letter has been converted to upper case.

#### Listing 10.4: ToUpper()

```
1 > "aBcD".ToUpper();;  
2 val it: string = "ABCD"
```

**Trim():** `unit -> string`.

Returns a copy of the string where leading and trailing whitespaces have been removed.

**Listing 10.5: Trim()**

```
1 > "  Hello World  ".Trim();;
2 val it: string = "Hello World"
```

**Split():** `unit -> string []`.

Splits a string of words separated by spaces into an array of words. See Section 20.3 for more information about arrays.

**Listing 10.6: Split()**

```
1 > "Hello World".Split();;
2 val it: string[] = [|"Hello"; "World"|]
```

### 10.1.2 The String Module

The `String` module offers many functions for working with strings. Some of the most powerful ones are listed below, and they are all higher-order functions.

**String.collect:** `f:(char -> string) -> str:string -> string`.

Creates a new string whose characters are the results of applying `f` to each of the characters of `str` and concatenating the resulting strings.

**Listing 10.7: String.collect**

```
1 > String.collect (fun c -> (string c) + ", ") "abc";;
2 val it: string = "a, b, c, "
```

**String.exists:** `f:(char -> bool) -> str:string -> bool`.

Returns true if any character in `str` evaluates to true when using `f`.

**Listing 10.8: String.exists**

```
1 > String.exists (fun c -> c = 'd') "abc";;
2 val it: bool = false
```

**String.forall:** `f:(char -> bool) -> str:string -> bool`.

Returns true if all characters in `str` evaluates to true when using `f`.

**Listing 10.9: String.forall**

```
1 > String.forall (fun c -> c < 'd') "abc";;  
2 val it: bool = true
```

**String.init:** `n:int -> f:(int -> string) -> string.`

Creates a new string with length `n` and whose characters are the result of applying `f` to each index of that string.

**Listing 10.10: String.init**

```
1 > String.init 5 (fun i -> (string i) + ", " );;  
2 val it: string = "0, 1, 2, 3, 4, "
```

**String.iter:** `f:(char -> unit) -> str:string -> unit.`

Applies `f` to each character in `str`.

**Listing 10.11: String.iter**

**String.map:** `f:(char -> char) -> str:string -> string.`

Creates a new string whose characters are the results of applying `f` to each of the characters of `str`.

**Listing 10.12: String.map**

```
1  
2 > let toUpper c = c + char (int 'A' - int 'a')  
3 String.map toUpper "abcd";;  
4 val toUpper: c: char -> char  
5 val it: string = "ABCD"
```

## 10.2 Maps

## 10.3 Sets

## 10.4 Key concepts and terms in this chapter

Summary text about the key concepts from this chapter

- ...



## Chapter 11

# The Functional Programming Paradigm

Functional programming is a style of programming which performs computations by evaluating functions. Functional programming avoids mutable values and side-effects. It is declarative in nature, e.g., by the use of value- and function-bindings – `let`-bindings – and avoids statements – `do`-bindings. Thus, the result of a function in functional programming depends only on its arguments, and therefore functions have no side-effect and are deterministic, such that repeated call to a function with the same arguments always gives the same result. In functional programming, data and functions are clearly separated, and hence data structures are dum as compared to objects in object-oriented programming paradigm, see Chapter 25. Functional programs clearly separate behavior from data and subscribes to the view that *it is better to have 100 functions operate on one data structure than 10 functions on 10 data structures*. Simplifying the data structure has the advantage that it is much easier to communicate data than functions and procedures between programs and environments. The .Net, mono, and java's virtual machine are all examples of an attempt to rectify this, however, the argument still holds.

The functional programming paradigm can trace its roots to lambda calculus introduced by Alonzo Church in 1936 [1]. Church designed lambda calculus to discuss computability. Some of the forces of the functional programming paradigm are that it is often easier to prove the correctness of code, and since no states are involved, then functional programs are often also much easier to parallelize than other paradigms.

Functional programming has a number of features:

### Pure functions

Functional programming is performed with pure functions. A pure function always returns the same value, when given the same arguments, and it has no side-effects. A function in F# is an example of a pure function. Pure functions can be replaced by their result without changing the meaning of the program. This is known as *referential transparency*.

### higher-order functions

Functional programming makes use of higher-order functions, where functions may be given as arguments and returned as results of a function application. higher-order functions and *first-class citizenship* are related concepts, where higher-order functions are the mathematical description of functions that operator on functions, while a first-class citizen is the computer science term for functions as values. F# implements higher-order functions.

### Recursion

Functional programs use recursion instead of `for`- and `while`-loops. Recursion can make programs ineffective, but compilers are often designed to optimize tail-recursion calls. Common recursive programming structures are often available as optimized higher-order functions such as *iter*, *map*, *reduce*, *fold*, and *foldback*. F# has good support for all of these features.

### Immutable states

Functional programs operate on values, not on variables. This implies lexicographical scope in contrast to mutable values, which implies dynamic scope.

### Strongly typed

Functional programs are often strongly typed, meaning that types are set no later than at compile-time. F# does have the ability to perform runtime type assertion, but for most parts it relies on explicit type annotations and type inference at compile-time. This means that type errors are caught at compile time instead of at runtime.

### Lazy evaluation

Due to referential transparency, values can be computed any time up until the point when it is needed. Hence, they need not be computed at compilation time, which allows for infinite data structures. F# has support for lazy evaluations using the `lazy`-keyword, sequences using the `seq`-type, and computation expressions, all of which are advanced topics and not treated in this book.

Immutable states imply that data structures in functional programming are different than in imperative programming. E.g., in F# lists are immutable, so if an element of a list is to be changed, a new list must be created by copying all old values except that which is to be changed. Such an operation is therefore linear in computational complexity. In contrast, arrays are mutable values, and changing a value is done by reference to the value's position and changing the value at that location. This has constant computational complexity. While fast, mutable values give dynamic scope and makes reasoning about the correctness of a program harder, since mutable states do not have referential transparency.

Functional programming may be considered a subset of *imperative programming*, in the sense that functional programming does not include the concept of a state, or one may think of functional programming as only having one unchanging state.

Functional programming also has a bigger focus on declaring rules for *what* should be solved, and not explicitly listing statements describing *how* these rules should be combined and executed in order to solve a given problem. Functional programming is often found to be less error-prone at runtime, making more stable, safer programs that are less open for, e.g., hacking.

## 11.1 Functional Design

A key to all good programming designs is encapsulating code into modules. For functional programs, the essence is to consider data and functions as transformations of data. I.e., the basic pattern is a piping sequence,

```
x |> f |> g |> h,
```

where *x* is the input data and *f*, *g*, and *h* are functions that transform the data. Of course, most long programs include lots of control structure, implying that we would need junctions in the pipe system, however, piping is a useful memo technique.

In functional programming there are some pitfalls that you should avoid:

- Creating large data structures, such as a single record containing all data. Since data is immutable, changing a single field in a monstrous record would mean a lot of copying in many parts of your program. In such cases, it is better to use a range of data structures that express isolated semantic units of your problem.
- Non-tail recursion. Relying on the built-in functions `map`, `fold`, etc., is a good start for efficiency.
- Single character identifiers. Since functional programming tends to produce small, well-defined functions, there is a tendency to use single character identifiers, e.g., `let f x = ...`. In the very small, this can be defended, but the names used as identifiers can be used to increase the readability of code to yourself or to others. Typically, identifiers are long and informative in the outermost scope, while decreasing in size as you move in.
- Few comments. Since functional programming is very concise, there is a tendency for us as programmers to forget to add sufficient comments to the code, since at the time of writing, the meaning may be very clear and well thought through. However, experience shows that this clarity deteriorates fast with time.
- Identifiers that are meaningless clones of each other. Since identifiers cannot be reused except by overshadowing in deeper scopes, there is often a tendency to

have a family of identifiers like `a`, `a2`, `newA` etc. It is better to use names that more clearly state the semantic meaning of the values, or, if only used as temporary storage, to discard them completely in lieu of piping and function composition. However, the lattermost often requires comments describing the transformation being performed.

Thus, a design pattern for functional programs must focus on,

- What input data is to be processed
- How the data is to be transformed

For large programs, the design principle is often similar to other paradigms, which are often visualized graphically as components that take input, interact, and produce results often together with a user. The effect of functional programming is mostly seen in the small, i.e., where a subtask is to be structured functionally.



## Chapter 12

# Pattern Matching

**Abstract** Introductory text about the objectives of this chapter

- ...

---

Pattern matching is used to transform values and variables into a syntactical structure. The simplest example is value-bindings. The `let`-keyword was introduced in Section 4.1, its extension with pattern matching is given as,

**Listing 12.1:** Syntax for `let`-expressions with pattern matching.

```
1 [[<Literal>]]
2 let [mutable] <pat> [: <returnType>] = <bodyExpr> [in <expr>]
```

A typical use of this is to extract elements of tuples, as demonstrated in Listing 12.2. Here we extract the elements of a pair twice. First by binding to `x` and `y`, and second

**Listing 12.2** `letPattern.fsx`:

Patterns in `let` expressions may be used to extract elements of tuples.

```
1 let a = (3,4)
2 let (x,y) = a
3 let (alsoX,_) = a
4 printfn "%A: %d %d %d" a x y alsoX

1 $ fsharp --nologo letPattern.fsx && mono letPattern.exe
2 (3, 4): 3 4 3
```

by binding to `alsoX` while using the wildcard pattern to ignore the second element. Thus, again the wildcard pattern in value-bindings is used to underline a disregarded value.

Another common use of patterns is as an alternative to `if-then-else` expressions, particularly when parsing input for a function. Consider the example in Listing 12.3. In the example, a discriminated union and a function are defined. The function

**Listing 12.3 switch.fsx:**

Using `if-then-else` to print discriminated unions.

```
1 type Medal = Gold | Silver | Bronze
2 let statement (m : Medal) : string =
3     if m = Gold then "You won"
4     elif m = Silver then "You almost won"
5     else "Maybe you will win next time"
6
7 let m = Silver
8 printfn "%A : %s" m (statement m)
```

---

```
1 $ fsharp -nologo switch.fsx && mono switch.exe
2 Silver : You almost won
```

converts each case to a supporting statement, using an `if`-expression. The same can be done with the `match-with` expression and patterns, as demonstrated in Listing 12.4. Here we used a pattern for the discriminated union cases and a

**Listing 12.4 switchPattern.fsx:**

Using `match-with` to print discriminated unions.

```
1 type Medal = Gold | Silver | Bronze
2 let statement (m : Medal) : string =
3     match m with
4     | Gold -> "You won"
5     | Silver -> "You almost won"
6     | _ -> "Maybe you can win next time"
7
8 let m = Silver
9 printfn "%A : %s" m (statement m)
```

---

```
1 $ fsharp -nologo switchPattern.fsx && mono switchPattern.exe
2 Silver : You almost won
```

wildcard pattern as default. The lightweight syntax for `match`-expressions is,

**Listing 12.5: Syntax for `match`-expressions.**

```
1 match <inputExpr> with
2   [| ]<pat> [when <guardExpr>] -> <caseExpr>
3   | <pat> [when <guardExpr>] -> <caseExpr>
4   | <pat> [when <guardExpr>] -> <caseExpr>
5   ...
```

where `<inputExpr>` is the *input pattern* to find matches of, `<pat>` is a pattern to match with, `<guardExpr>` is an optional guard expression, and `<caseExpr>` is the resulting expression. Each set starting with `<pat>` is called a case. In lightweight syntax, the indentation must be equal to or higher than the indentation of `match`. All cases must return a value of the same type, and F# reports an error when the complete domain of the input pattern is not covered by cases in `match`-expressions.

Patterns are also used in a version of `for`-loop expressions, and its lightweight syntax is given as,

Listing 12.6: Syntax for `for`-expressions with pattern matching.

```
1 for <pat> in <sourceExpr> do
2   <bodyExpr>
```

Typically, `<sourceExpr>` is a list or an array. An example is given in Listing 12.7. The wildcard pattern is used to disregard the first element in a pair while iterating

Listing 12.7 forPattern.fsx:  
Patterns may be used in `for`-loops.

```
1 for (_,y) in [(1,3); (2,1)] do
2   printfn "%d" y

-----

1 $ fsharp --nologo forPattern.fsx && mono forPattern.exe
2 3
3 1
```

over the complete list. It is good practice to **use wildcard patterns to emphasize unused values.** ★

The final expression involving patterns to be discussed is the *anonymous functions*. Patterns for anonymous functions have the syntax,

Listing 12.8: Syntax for anonymous functions with pattern matching.

```
1 fun <pat> [<pat> ...] -> <bodyExpr>
```

This is an extension of the syntax discussed in Section 4.2. A typical use for patterns in `fun`-expressions is shown in Listing 12.9. Here we use an anonymous function expression and bind it to `f`. The expression has one argument of any type, which it ignores through the wildcard pattern. Some limitations apply to the patterns allowed in `fun`-expressions. The wildcard pattern in `fun`-expressions are often used for *mockup functions*, where the code requires the said function, but its content has yet to be decided. Thus, mockup functions can be used as loose place-holders while experimenting with program design.

**Listing 12.9** funPattern.fsx:  
Patterns may be used in *fun*-expressions.

```
1 let f = fun _ -> "hello"
2 printfn "%s" (f 3)

-----

1 $ fsharp --nologo funPattern.fsx && mono funPattern.exe
2 hello
```

Patterns are also used in exceptions to be discussed in Section 13.1, and in conjunction with the *function*-keyword, a keyword we discourage in this book. We will now demonstrate a list of important patterns in F#.

## 12.1 Wildcard Pattern

A *wildcard pattern* is denoted “*_*” and matches anything, see e.g., Listing 12.10. In this example, anything matches the wildcard pattern, so all cases are covered and

**Listing 12.10** wildcardPattern.fsx:  
Constant patterns match to constants.

```
1 let whatever (x : int) : string =
2     match x with
3         _ -> "If you say so"
4
5 printfn "%s" (whatever 42)

-----

1 $ fsharp --nologo wildcardPattern.fsx && mono
   wildcardPattern.exe
2 If you say so
```

the function always returns the same sentence. This is rarely a useful structure on its own, since this could be replaced by a value binding or by a function ignoring its input. However, wildcard patterns are extremely useful, since they act as the final *else* in *if*-expressions.

## 12.2 Constant and Literal Patterns

A *constant pattern* matches any input pattern with constants, see e.g., Listing 12.11. In this example, the input pattern is queried for a match with 0, 1, or the wildcard

**Listing 12.11** `constPattern.fsx`:  
Constant patterns match to constants.

```
1 type Medal = Gold | Silver | Bronze
2 let intToMedal (x : int) : Medal =
3     match x with
4         0 -> Gold
5         | 1 -> Silver
6         | _ -> Bronze
7
8 printfn "%A" (intToMedal 0)
```

---

```
1 $ fsharp --nologo constPattern.fsx && mono constPattern.exe
2 Gold
```

pattern. Any simple literal type constants may be used in the constant pattern, such as 8, 23y, 1010u, 1.2, "hello world", 'c', and false. Here we also use the wildcard pattern. Note that matching is performed in a lazy manner and stops at the first matching case from the top. Thus, although the wildcard pattern matches everything, its case expression is only executed if none of the previous patterns match the input.

Constants can also be pre-bound by the [`<Literal>`] attribute for value-bindings. This is demonstrated in Listing 12.12. The attribute is used to identify the value-

**Listing 12.12** `literalPattern.fsx`:  
A variant of constant patterns is literal patterns.

```
1 [<Literal>]
2 let TheAnswer = 42
3 let whatIsTheQuestion (x : int) : string =
4     match x with
5         TheAnswer -> "We will need to build a bigger machine..."
6         | _ -> "Don't know that either"
7
8 printfn "%A" (whatIsTheQuestion 42)
```

---

```
1 $ fsharp --nologo literalPattern.fsx && mono
   literalPattern.exe
2 "We will need to build a bigger machine..."
```

binding `TheAnswer` to be used, as if it were a simple literal type. Literal patterns must be either uppercase or module prefixed identifiers.

### 12.3 Variable Patterns

A *variable pattern* is a single lower-case letter identifier. Variable pattern identifiers are assigned the value and type of the input pattern. Combinations of constant and variable patterns are also allowed in conjunction with with records and arrays. This is demonstrated in Listing 12.13. In this example, the value identifier `n` has the

**Listing 12.13** `variablePattern.fsx`:

Variable patterns are useful for, e.g., extracting and naming fields

```
1 let (name, age) = ("Jon", 50)
2 let getAgeString (age : int) : string =
3     match age with
4     | 0 -> "a newborn"
5     | 1 -> "1 year old"
6     | n -> (string n) + " years old"
7
8 printfn "%s is %s" name (getAgeString age)
-----
1 $ fsharpc --nologo variablePattern.fsx && mono
   variablePattern.exe
2 Jon is 50 years old
```

function of a named wildcard pattern. Hence, the case could as well have been `| _ -> (string age) + "years old"`, since `age` is already defined in this scope. However, variable patterns syntactically act as an argument to an anonymous function and thus act to isolate the dependencies. They are also very useful together with guards, see Section 12.4.

### 12.4 Guards

A *guard* is a pattern used together with `match`-expressions including the `when`-keyword, as shown in Listing 12.5. Here guards are used to iteratively carve out subset of integers to assign different strings to each set. The guard expression in `<pat> when <guardExpr> -> <caseExpr>` is any expression evaluating to a Boolean, and the case expression is only executed for the matching case.

**Listing 12.14** guardPattern.fsx:

Guard expressions can be used with other patterns to restrict matches.

```

1 let getAgeString (age : int) : string =
2     match age with
3     | n when n < 1 -> "infant"
4     | n when n < 13 -> "child"
5     | n when n < 20 -> "teen"
6     | _ -> "adult"
7
8 printfn "A person aged %d is a/an %s" 50 (getAgeString 50)

```

---

```

1 $ fsharp --nologo guardPattern.fsx && mono guardPattern.exe
2 A person aged 50 is a/an adult

```

**12.5 List Patterns**

Lists have a concatenation pattern associated with them. The “::” cons-operator is used to match the head and the rest of a list, and “[ ]” is used to match an empty list, which is also sometimes called the nil-case. This is very useful when recursively processing lists, as shown in Listing 12.15. In the example, the function `sumList`

**Listing 12.15** listPattern.fsx:

Recursively parsing a list with list patterns.

```

1 let rec sumList (lst : int list) : int =
2     match lst with
3     | n :: rest -> n + (sumList rest)
4     | [] -> 0
5
6 let rec sumThree (lst : int list) : int =
7     match lst with
8     | [a; b; c] -> a + b + c
9     | _ -> sumList lst
10
11 let aList = [1; 2; 3]
12 printfn "The sum of %A is %d, %d" aList (sumList aList)
    (sumThree aList)

```

---

```

1 $ fsharp --nologo listPattern.fsx && mono listPattern.exe
2 The sum of [1; 2; 3] is 6, 6

```

uses the cons operator to match the head of the list with `n` and the tail with `rest`. The pattern `n :: tail` also matches `3 :: []`, and in that case `tail` would be assigned the value `[]`. When `lst` is empty, then it matches with “[ ]”. List patterns can also be matched explicitly named elements, as demonstrated in the `sumThree` function. The elements to be matched can be any mix of constants and variables.

It is also possible to match on a series of cons-operators. For example `elm0 :: elm1 :: rest` would match a list with at least two elements, where the first will be bound to `elm1`, the second to `elm2`, and the remainder to `rest`.

## 12.6 Array, Record, and Discriminated Union Patterns

*Array*, *record*, and *discriminated union patterns* are direct extensions on constant, variable, and wildcard patterns. Listing 12.16 gives examples of array patterns. In

**Listing 12.16** `arrayPattern.fsx`:

Using variable patterns to match on size and content of arrays.

```

1 let arrayToString (x : int []) : string =
2     match x with
3         [|1;_;-|] -> "3 elements, first of is 1"
4         | [|x;1;-|] -> "3 elements, first is " + (string x) + "
          Second 1"
5         | x -> "A general array"
6
7 printfn "%s" (arrayToString [|1; 1; 1|])
8 printfn "%s" (arrayToString [|3; 1; 1|])
9 printfn "%s" (arrayToString [|1|])

```

---

```

1 $ fsharp -nologo arrayPattern.fsx && mono arrayPattern.exe
2 3 elements, first of is 1
3 3 elements, first is 3 Second 1
4 A general array

```

the function `arrayToString`, the first case matches arrays of 3 elements where the first is the integer 1, the second case matches arrays of 3 elements where the second is a 1 and names the first `x`, and the final case matches all arrays and works as a default match case. As demonstrated, the cases are treated from first to last, and only the expression of the first case that matches is executed.

For record patterns, we use the field names to specify matching criteria. This is demonstrated in Listing 12.17. Here, the record type `Address` is created, and in the function `getZip`, a variable pattern `z` is created for naming zip values, and the remaining fields are ignored. Since the fields are named, the pattern match need not mention the ignored fields, and the example match is equivalent to `{zip = z} -> z`. The curly brackets are required for record patterns.

Discriminated union patterns are similar. For discriminated unions with arguments, the arguments can be matched as constants, variables, or wildcards. A demonstration is given in Listing 12.18. In the `project-function`, three-dimensional vectors are



**Listing 12.17** recordPattern.fsx:

Variable patterns for records to match on field values.

```

1 type Address = {street : string; zip : int; country : string}
2 let contact : Address = {
3     street = "Universitetsparken 1";
4     zip = 2100;
5     country = "Denmark"}
6 let getZip (adr : Address) : int =
7     match adr with
8     {street = _; zip = z; country = _} -> z
9
10 printfn "The zip-code is: %d" (getZip contact)

```

---

```

1 $ fsharp --nologo recordPattern.fsx && mono recordPattern.exe
2 The zip-code is: 2100

```

**Listing 12.18** unionPattern.fsx:

Matching on discriminated union types.

```

1 type vector =
2     Vec2D of float * float
3     | Vec3D of float * float * float
4
5 let project (vec : vector) : vector =
6     match vec with
7     Vec3D (a, b, _) -> Vec2D (a, b)
8     | v -> v
9
10 let v = Vec3D (1.0, -1.2, 0.9)
11 printfn "%A -> %A" v (project v)

```

---

```

1 $ fsharp --nologo unionPattern.fsx && mono unionPattern.exe
2 Vec3D (1.0, -1.2, 0.9) -> Vec2D (1.0, -1.2)

```

projected to two dimensions by removing the third element. Two-dimensional vectors are unchanged. The example uses the wildcard pattern to emphasize that the third element of three-dimensional vectors is ignored. Named arguments can also be matched, in which case “;” is used instead of “,” to delimit the fields in the match.

## 12.7 Disjunctive and Conjunctive Patterns

Patterns may be combined using the “/” and “&” lexemes. These patterns are called disjunctive and conjunctive patterns, respectively, and work similarly to their logical operator counter parts, “||” and “&&”.

*Disjunctive patterns* require at least one pattern to match, as illustrated in Listing 12.19. Here one or more cases must match for the final case expression, and

**Listing 12.19** `disjunctivePattern.fsx`:  
Patterns can be combined logically as ‘or’ syntax structures.

```
1 let vowel (c : char) : bool =
2     match c with
3         'a' | 'e' | 'i' | 'o' | 'u' | 'y' -> true
4         | _ -> false
5
6 String.iter (fun c -> printf "%A " (vowel c)) "abcdefg"
-----
1 $ fsharpc --nologo disjunctivePattern.fsx && mono
   disjunctivePattern.exe
2 true false false false true false false
```

thus, any vowel results in the value `true`. Everything else is matched with the wildcard pattern.

For *conjunctive patterns*, all patterns must match, which is illustrated in Listing 12.20. In this case, we separately check the elements of a pair for the constant value 1 and

**Listing 12.20** `conjunctivePattern.fsx`:  
Patterns can be combined logically as ‘and’ syntax structures.

```
1 let is11 (v : int * int) : bool =
2     match v with
3         (1,_) & (_,1) -> true
4         | _ -> false
5
6 printfn "%A" (List.map is11 [(0,0); (0,1); (1,0); (1,1)])
-----
1 $ fsharpc --nologo conjunctivePattern.fsx && mono
   conjunctivePattern.exe
2 [false; false; false; true]
```

return true only when both elements are 1. In many cases, conjunctive patterns can be replaced by more elegant matches, e.g., using tuples, and in the above example a single case `(1,1) -> true` would have been simpler. Nevertheless, conjunctive patterns are used together with active patterns, to be discussed below.

## 12.8 Active Patterns

The concept of patterns is extendable to functions. Such functions are called *active patterns*, and active patterns come in two flavors: regular and option types. The active pattern cases are constructed as function bindings, but using a special notation. They all take the pattern input as last argument, and may take further preceding arguments. The syntax for active patterns is one of,

**Listing 12.21:** Syntax for binding active patterns to expressions.

```
1 let (|<caseName>|_|) [ <arg> [<arg> ... ] ] <inputArgument>
    = <expr>
2 let (|<caseName>|<caseName>|...|<caseName>|) <inputArgument> =
    <expr>
```

When using the `(|<caseName>|_|)` variants, then the active pattern function must return an option type. `(|<caseName>|<caseName>|...|<caseName>|)` is the multi-case variant and must return a `Fsharp.Core.Choice` type. All other variants can return any type. There are no restrictions on arguments `<arg>`, and `<inputArgument>` is the input pattern to be matched. Notice in particular that the multi-case variant only takes one argument and cannot be combined with the option-type syntax. Below we will demonstrate by example how the various patterns are used.

The single case, `(|<caseName>|_|)`, matches all and is useful for extracting information from complex types, as demonstrated in Listing 12.22. Here we define a record to represent two-dimensional vectors and two different single case active patterns. Note that in the binding of the active pattern functions in line 2 and 3, the argument is the input expression `match <inputExpr> with ...`, see Listing 12.5. However, the argument for the cases in line 6 and 9 are names bound to the output of the active pattern function.

Both `Cartesian` and `Polar` match a vector record, but they dismantle the contents differently. For an alternative solution using `Class` types, see Section 23.1.

More complicated behavior is obtainable by supplying additional arguments to the single case. This is demonstrated in Listing 12.23. Here we supply an offset, which should be subtracted prior to calculating lengths and angles. Notice in line 8 that the argument is given prior to the result binding.

Active pattern functions return option types are called *partial pattern functions*. The option type allows for specifying mismatches, as illustrated in Listing 12.24. In the example, we use the `(|<caseName>|_|)` variant to indicate that the active pattern returns an option type. Nevertheless, the result binding `res` in line 6 uses the underlying value of `Some`. And in contrast to the two previous examples of single case

**Listing 12.22** activePattern.fsx:

Single case active pattern for deconstructing complex types.

```

1 type vec = {x : float; y : float}
2 let (|Cartesian|) (v : vec) = (v.x, v.y)
3 let (|Polar|) (v : vec) = (sqrt(v.x*v.x + v.y * v.y), atan2
  v.y v.x)
4 let printCartesian (p : vec) : unit =
5     match p with
6     | Cartesian (x, y) -> printfn "%A:\n Cartesian (%A, %A)"
  p x y
7 let printPolar (p : vec) : unit =
8     match p with
9     | Polar (a, d) -> printfn "%A:\n Polar (%A, %A)" p a d
10
11 let v = {x = 2.0; y = 3.0}
12 printCartesian v
13 printPolar v

```

---

```

1 $ fsharpc --nologo activePattern.fsx && mono activePattern.exe
2 { x = 2.0
3   y = 3.0 }:
4 Cartesian (2.0, 3.0)
5 { x = 2.0
6   y = 3.0 }:
7 Polar (3.605551275, 0.9827937232)

```

patterns, the value `None` results in a mismatch. Thus in this case, if the denominator is `0.0`, then `Div res` does not match but the wildcard pattern does.

*Multicase active patterns* work similarly to discriminated unions without arguments. An example is given in Listing 12.25. In this example, we define three cases in line 1. The result of the active pattern function must be one of these cases. For the `match`-expression, the match is based on the output of the active pattern function, hence in line 8, the case expression is executed when the result of applying the active pattern function to the input expression `i` is `Gold`. In this case, a solution based on discriminated unions would probably be clearer.

**Listing 12.23** activeArgumentsPattern.fsx:

All but the multi-case active pattern may take additional arguments.

```

1 type vec = {x : float; y : float}
2 let (|Polar|) (o : vec) (v : vec) =
3     let x = v.x - o.x
4     let y = v.y - o.y
5     (sqrt(x*x + y * y), atan2 y x)
6 let printPolar (o : vec) (p : vec) : unit =
7     match p with
8     | Polar o (a, d) -> printfn "%A:\n Cartesian (%A, %A)" p
9         a d
10
11 let v = {x = 2.0; y = 3.0}
12 let offset = {x = 1.0; y = 1.0}
13 printPolar offset v

```

---

```

1 $ fsharp --nologo activeArgumentsPattern.fsx && mono
   activeArgumentsPattern.exe
2 { x = 2.0
3   y = 3.0 }:
4 Cartesian (2.236067977, 1.107148718)

```

**Listing 12.24** activeOptionPattern.fsx:

Option type active patterns mismatch on None results.

```

1 let (|Div|_|) (e,d) = if d <> 0.0 then Some (e/d) else None
2
3 let safeDiv (p : float * float) =
4     match p with
5     | (0.0, 0.0) -> printfn "Div %A = undefined" p
6     | Div res -> printfn "Div %A = %A" p res
7     | _ -> printfn "Div %A = infinity" p
8
9 List.iter safeDiv [(1.0,1.0); (0.0,1.0); (1.0,0.0); (0.0,0.0)]

```

---

```

1 $ fsharp --nologo activeOptionPattern.fsx && mono
   activeOptionPattern.exe
2 Div (1.0, 1.0) = 1.0
3 Div (0.0, 1.0) = 0.0
4 Div (1.0, 0.0) = infinity
5 Div (0.0, 0.0) = undefined

```

**Listing 12.25** activeMultiCasePattern.fsx:

Multi-case active patterns have a syntactical structure similar to discriminated unions.

```
1 let (|Gold|Silver|Bronze|) inp =
2     if inp = 0 then Gold
3     elif inp = 1 then Silver
4     else Bronze
5
6 let intToMedal (i : int) =
7     match i with
8     | Gold -> printfn "%d: It's gold!" i
9     | Silver -> printfn "%d: It's silver." i
10    | Bronze -> printfn "%d: It's no more than bronze." i
11
12 List.iter intToMedal [0..3]
```

---

```
1 $ fsharp --nologo activeMultiCasePattern.fsx && mono
   activeMultiCasePattern.exe
2 0: It's gold!
3 1: It's silver.
4 2: It's no more than bronze.
5 3: It's no more than bronze.
```

## 12.9 Static and Dynamic Type Pattern

Input patterns can also be matched on type. For *static type matching*, the matching is performed at compile time and indicated using the “:” lexeme followed by the type name to be matched. Static type matching is further used as input to the type inference performed at compile time to infer non-specified types, as illustrated in Listing 12.26. Here the head of the list `n` in the list pattern is explicitly matched as

**Listing 12.26 staticTypePattern.fsx:**

Static matching on type binds the type of other values by type inference.

```
1 let rec sum lst =
2     match lst with
3         (n : int) :: rest -> n + (sum rest)
4         | [] -> 0
5
6 printfn "The sum is %d" (sum [0..3])
```

---

```
1 $ fsharp --nologo staticTypePattern.fsx && mono
   staticTypePattern.exe
2 The sum is 6
```

an integer, and the type inference system thus concludes that `lst` must be a list of integers.

In contrast to static type matching, *dynamic type matching* is performed at runtimes and indicated using the “:?” lexeme followed by a type name. Dynamic type patterns allow for matching generic values at runtime. This is an advanced topic, which is included here for completeness. An example is given in Listing 12.27. In F#, all types

**Listing 12.27 dynamicTypePattern.fsx:**

Dynamic matching on type binds the type of other values by type inference.

```
1 let isString (x : obj) : bool =
2     match x with
3         :? string -> true
4         | _ -> false
5
6 let a = "hej"
7 printfn "Is %A a string? %b" a (isString a)
8 let b = 3
9 printfn "Is %A a string? %b" b (isString b)
```

---

```
1 $ fsharp --nologo dynamicTypePattern.fsx && mono
   dynamicTypePattern.exe
2 Is "hej" a string? true
3 Is 3 a string? false
```

are also objects whose type is denoted `obj`. Thus, the example uses the generic type when defining the argument to `isString`, and then dynamic type pattern matching for further processing. See Chapter 23 for more on objects. Dynamic type patterns are often used for analyzing exceptions, which is discussed in Section 13.1. While

- ★ dynamic type patterns are useful, they imply runtime checking, and **it is almost always better to prefer compile time over runtime type checking.**

## 12.10 Key concepts and terms in this chapter

Summary text about the key concepts from this chapter

- ...



## Chapter 13

# Handling Errors and Exceptions

### 13.1 Exceptions

Exceptions are runtime errors, such as division by zero. E.g., attempting integer division by zero halts execution and a long somewhat cryptic error message is written to screen, as illustrated in Listing 13.1. The error message contains much information.

**Listing 13.1: Division by zero halts execution with an error message.**

```
1 > 3 / 0;;  
2 System.DivideByZeroException: Attempted to divide by zero.  
3    at <StartupCode$FSI_0002>.FSI_0002.main@()
```

The first part, `System.DivideByZeroException: Attempted to divide by zero` is the error-name with a brief elaboration. Then follows a list libraries that were involved when the error occurred, and finally F# states that it **Stopped due to error**. `System.DivideByZeroException` is a built-in exception type, and the built-in integer division operator chooses to raise the exception when the undefined division by zero is attempted. Many times such errors can be avoided by clever program design. However, this is not always possible or desirable, which is why F# implements exception handling for graceful control.

Exceptions are a basic-type called *exn*, and F# has a number of built-in ones, a few of which are listed in Table 13.1.

Exceptions are handled by the `try`-keyword expressions. We say that an expression may *raise* or *cast* an exception and that the `try`-expression may *catch* and *handle* the exception by another expression.

Exceptions like in Listing 13.1 may be handled by `try-with` expressions, as demonstrated in Listing 13.2. In the example, when the division operator raises the `System.DivideByZeroException` exception, then `try-with` catches it and re-

Attribute	Description
<code>ArgumentException</code>	Arguments provided are invalid.
<code>DivideByZeroException</code>	Division by zero.
<code>NotFiniteNumberException</code>	floating point value is plus or minus infinity, or Not-a-Number (NaN).
<code>OverflowException</code>	Arithmetic or casting caused an overflow.
<code>IndexOutOfRangeException</code>	Attempting to access an element of an array using an index which is less than zero or equal or greater than the length of the array.

**Table 13.1** Some built-in exceptions. The prefix `System.` has been omitted for brevity.

#### Listing 13.2 exceptionDivByZero.fsx:

A division by zero is caught and a default value is returned.

```

1 let div enum denom =
2     try
3         enum / denom
4     with
5         | :? System.DivideByZeroException -> System.Int32.MaxValue
6
7 printfn "3 / 1 = %d" (div 3 1)
8 printfn "3 / 0 = %d" (div 3 0)

```

---

```

1 $ fsharp --nologo exceptionDivByZero.fsx && mono
   exceptionDivByZero.exe
2 3 / 1 = 3
3 3 / 0 = 2147483647

```

turns the value `System.Int32.MaxValue`. Division by zero is still an undefined operation, but with the exception system, the program is able to receive a message about this undefined situation and choose an appropriate action.

The `try` expressions comes in two flavors: `try-with` and `try-finally` expressions.

The `try-with` expression has the following syntax,

#### Listing 13.3: Syntax for the `try-with` exception handling.

```

1 try
2     <testExpr>
3 with
4     [ | ] <pat1> -> <exprHndl1>
5       | <pa2> -> <exprHndl2>
6       | <pat3> -> <exprHndl3>
7     ...

```

where `<testExpr>` is an expression which might raise an exception, `<patn>` is a pattern, and `<exprHndl>` is the corresponding exception handler. The value of the `try`-expression is either the value of `<testExpr>`, if it does not raise an exception, or the value of the exception handler `<exprHndl>` of the first matching pattern `<patn>`. The above is using lightweight syntax. Regular syntax omits newlines.

In Listing 13.2 *dynamic type matching* is used (see Section 12.9) using the “:?” lexeme, i.e., the pattern matches exception with type `System.DivideByZeroException` at runtime. The exception value may contain further information and can be accessed if named using the `as`-keyword, as demonstrated in Listing 13.4. Here the exception

**Listing 13.4** `exceptionDivByZeroNamed.fsx`:

Exception value is bound to a name. Compare to Listing 13.2.

```

1 let div enum denom =
2     try
3         enum / denom
4     with
5         | :? System.DivideByZeroException as ex ->
6             printfn "Error: %s" ex.Message
7             System.Int32.MaxValue
8
9 printfn "3 / 1 = %d" (div 3 1)
10 printfn "3 / 0 = %d" (div 3 0)

```

---

```

1 $ fsharp --nologo exceptionDivByZeroNamed.fsx && mono
   exceptionDivByZeroNamed.exe
2 3 / 1 = 3
3 Error: Attempted to divide by zero.
4 3 / 0 = 2147483647

```

value is bound to the name `ex`.

All exceptions may be caught as the dynamic type `System.Exception`, and F# implements a short-hand for catching an exception and binding its value to a name as demonstrated in Listing 13.5. Finally, the short-hand may be guarded with a *when*-guard, as demonstrated in Listing 13.6. The first pattern only matches the `System.Exception` exception when `enum` is 0, in which case the exception handler returns 0.

Thus, if you don't care about the type of exception, then you need only use the short-hand pattern matching and name binding demonstrated in Listing 13.5 and Listing 13.6, but if you would like to distinguish between types of exceptions, then you must use explicit type matching and possibly value binding demonstrated in Listing 13.2 and Listing 13.4

The *try-finally* expression has the following syntax,

**Listing 13.7:** Syntax for the *try-finally* exception handling.

```

1 try
2     <testExpr>
3 finally
4     <cleanupExpr>

```

**Listing 13.5** exceptionDivByZeroShortHand.fsx:

An exception of type `System.Exception` is bound to a name. Compare to Listing 13.4.

```

1 let div enum denom =
2     try
3         enum / denom
4     with
5         | ex -> printfn "Error: %s" ex.Message;
6             System.Int32.MaxValue
7
8 printfn "3 / 1 = %d" (div 3 1)
9 printfn "3 / 0 = %d" (div 3 0)

```

---

```

1 $ fsharp --nologo exceptionDivByZeroShortHand.fsx && mono
   exceptionDivByZeroShortHand.exe
2 3 / 1 = 3
3 Error: Attempted to divide by zero.
4 3 / 0 = 2147483647

```

**Listing 13.6** exceptionDivByZeroGuard.fsx:

An exception of type `System.Exception` is bound to a name and guarded. Compare to Listing 13.5.

```

1 let div enum denom =
2     try
3         enum / denom
4     with
5         | ex when enum = 0 -> 0
6         | ex -> System.Int32.MaxValue
7
8 printfn "3 / 1 = %d" (div 3 1)
9 printfn "3 / 0 = %d" (div 3 0)
10 printfn "0 / 0 = %d" (div 0 0)

```

---

```

1 $ fsharp --nologo exceptionDivByZeroGuard.fsx && mono
   exceptionDivByZeroGuard.exe
2 3 / 1 = 3
3 3 / 0 = 2147483647
4 0 / 0 = 0

```

The `try-finally` expression evaluates the `<cleanupExpr>` expression following evaluation of the `<testExpr>`, regardless of whether an exception is raised or not, as illustrated in Listing 13.8. Here, the `finally` branch is evaluated following the evaluation of the test expression regardless of whether the test expression raises an exception or not. However, if an exception is raised in a `try-finally` expression and there is no outer `try-with` expression, then execution stops without having evaluated the `finally` branch.

**Listing 13.8** exceptionDivByZeroFinally.fsx:  
The **finally** branch is executed regardless of an exception.

```

1 let div enum denom =
2     printf "Doing division:"
3     try
4         printf " %d %d." enum denom
5         enum / denom
6     finally
7         printfn " Division finished."
8
9 printfn "3 / 1 = %d" (try div 3 1 with ex -> 0)
10 printfn "3 / 0 = %d" (try div 3 0 with ex -> 0)

```

---

```

1 $ fsharp --nologo exceptionDivByZeroFinally.fsx && mono
   exceptionDivByZeroFinally.exe
2 Doing division: 3 1. Division finished.
3 3 / 1 = 3
4 Doing division: 3 0. Division finished.
5 3 / 0 = 0

```

Exceptions can be raised using the *raise*-function,

**Listing 13.9:** Syntax for the *raise* function that raises exceptions.

```

1 raise (<expr>)

```

An example of raising the `System.ArgumentException` is shown in Listing 13.10. In this example, division by zero is never attempted and instead an exception is raised

**Listing 13.10** raiseArgumentException.fsx:  
Raising the division by zero with customized message.

```

1 let div enum denom =
2     if denom = 0 then
3         raise (System.ArgumentException "Error: \"division by
4             0\"")
5     else
6         enum / denom
7 printfn "3 / 0 = %s" (try (div 3 0 |> string) with ex ->
   ex.Message)

```

---

```

1 $ fsharp --nologo raiseArgumentException.fsx && mono
   raiseArgumentException.exe
2 3 / 0 = Error: "division by 0"

```

which must be handled by the caller. Note that the type of `div` is `int -> int -> int` because `denom` is compared with an integer in the conditional statement. This contradicts the typical requirements for `if` statements, where every branch has to

return the same type. However, any code that explicitly raise exceptions are ignored, and the type is inferred by the remaining branches.

Programs may define new exceptions using the syntax,

**Listing 13.11:** Syntax for defining new exceptions.

```
1 exception <ident> of <typeId> {* <typeId>}
```

An example of defining a new exception and raising it is given in Listing 13.12. Here

**Listing 13.12** exceptionDefinition.fsx:

A user-defined exception is raised but not caught by outer construct.

```
1 exception DontLikeFive of string
2
3 let picky a =
4     if a = 5 then
5         raise (DontLikeFive "5 sucks")
6     else
7         a
8
9 printfn "picky %A = %A" 3 (try picky 3 |> string with ex ->
    ex.Message)
10 printfn "picky %A = %A" 5 (try picky 5 |> string with ex ->
    ex.Message)
-----
1 $ fsharpc --nologo exceptionDefinition.fsx && mono
    exceptionDefinition.exe
2 picky 3 = "3"
3 picky 5 = "Exception of type
    'ExceptionDefinition+DontLikeFive' was thrown."
```

an exception called `DontLikeFive` is defined, and it is raised in the function `picky`. The example demonstrates that catching the exception as a `System.Exception` as in Listing 13.5, the `Message` property includes information about the exception name but not its argument. To retrieve the argument `"5 sucks"`, we must match the exception with the correct exception name, as demonstrated in Listing 13.13.

F# includes the `failwith` function to simplify the most common use of exceptions. It is defined as `failwith : string -> exn` and takes a string and raises the built-in `System.Exception` exception. An example of its use is shown in Listing 13.14.

To catch the `failwith` exception, there are several choices. The exception casts a `System.Exception` exception, which may be caught using the `:?` pattern, as shown in Listing 13.15. However, this gives annoying warnings, since F# internally is built such that all exception match the type of `System.Exception`. Instead, it is better to either match using the wildcard pattern as in Listing 13.16, or use the built-in `Failure` pattern as in Listing 13.17. Notice how only the `Failure` pattern allows for the parsing of the message given to `failwith` as an argument.

**Listing 13.13** exceptionDefinitionNCatch.fsx:  
Catching a user-defined exception.

```

1 exception DontLikeFive of string
2
3 let picky a =
4     if a = 5 then
5         raise (DontLikeFive "5 sucks")
6     else
7         a
8
9 try
10    printfn "picky %A = %A" 3 (picky 3)
11    printfn "picky %A = %A" 5 (picky 5)
12 with
13 | DontLikeFive msg -> printfn "Exception caught with
    message: %s" msg

```

---

```

1 $ fsharp --nologo exceptionDefinitionNCatch.fsx && mono
    exceptionDefinitionNCatch.exe
2 picky 3 = 3
3 Exception caught with message: 5 sucks

```

**Listing 13.14** exceptionFailwith.fsx:  
An exception raised by failwith.

```

1 if true then failwith "hej"

```

---

```

1 $ fsharp --nologo exceptionFailwith.fsx && mono
    exceptionFailwith.exe
2
3 Unhandled Exception:
4 System.Exception: hej
5 at
6   <StartupCode$exceptionFailwith>.$ExceptionFailwith$fsx.main@
7   () [0x0000b] in <62028a4fddd05a03a74503834f8a0262>:0
6 [ERROR] FATAL UNHANDLED EXCEPTION: System.Exception: hej
7 at
8   <StartupCode$exceptionFailwith>.$ExceptionFailwith$fsx.main@
9   () [0x0000b] in <62028a4fddd05a03a74503834f8a0262>:0

```

Invalid arguments are such a common reason for failures, that a built-in function for handling them has been supplied in F#. The *invalidArg* takes 2 strings and raises the built-in *ArgumentException*, as shown in Listing 13.18. The *invalidArg* function raises an *System.ArgumentException*, as shown in Listing 13.19.

The *try* construction is typically used to gracefully handle exceptions, but there are times where you may want to pass on the bucket, so to speak, and re-raise the exception. This can be done with the *reraise*, as shown in Listing 13.20. The

**Listing 13.15 exceptionSystemException.fsx:**  
**Catching a failwith exception using type matching pattern.**

```

1 let _ =
2     try
3         failwith "Arrrrrg"
4     with
5         :? System.Exception -> printfn "So failed"

```

---

```

1 $ fsharp --nologo exceptionSystemException.fsx && mono
   exceptionSystemException.exe
2
3 exceptionSystemException.fsx(5,5): warning FS0067: This type
   test or downcast will always hold
4
5 exceptionSystemException.fsx(5,5): warning FS0067: This type
   test or downcast will always hold
6 So failed

```

**Listing 13.16 exceptionMatchWildcard.fsx:**  
**Catching a failwith exception using the wildcard pattern.**

```

1 let _ =
2     try
3         failwith "Arrrrrg"
4     with
5         _ -> printfn "So failed"

```

---

```

1 $ fsharp --nologo exceptionMatchWildcard.fsx && mono
   exceptionMatchWildcard.exe
2 So failed

```

reraise function is only allowed to be the final call in the expression of a `with` rule.

**Listing 13.17 exceptionFailure.fsx:**  
**Catching a failwith exception using the Failure pattern.**

```

1 let _ =
2     try
3         failwith "Arrrrrg"
4     with
5         Failure msg ->
6             printfn "The castle of %A" msg

```

---

```

1 $ fsharp --nologo exceptionFailure.fsx && mono
   exceptionFailure.exe
2 The castle of "Arrrrrg"

```



**Listing 13.18 exceptionInvalidArg.fsx:**  
 An exception raised by invalidArg. Compare with Listing 13.10.

```

1 if true then invalidArg "a" "is too much 'a'"
-----
1 $ fsharp --nologo exceptionInvalidArg.fsx && mono
  exceptionInvalidArg.exe
2
3 Unhandled Exception:
4 System.ArgumentException: is too much 'a'
5 Parameter name: a
6   at
7     <StartupCode$exceptionInvalidArg>.$ExceptionInvalidArg$fsx.main@
8     () [0x0000b] in <62028a57941e65a2a7450383578a0262>:0
7 [ERROR] FATAL UNHANDLED EXCEPTION: System.ArgumentException:
  is too much 'a'
8 Parameter name: a
9   at
10    <StartupCode$exceptionInvalidArg>.$ExceptionInvalidArg$fsx.main@
11    () [0x0000b] in <62028a57941e65a2a7450383578a0262>:0

```

**Listing 13.19 exceptionInvalidArgNCatch.fsx:**  
 Catching the exception raised by invalidArg.

```

1 let _ =
2   try
3     invalidArg "a" "is too much 'a'"
4   with
5     :? System.ArgumentException -> printfn "Argument is no
  good!"
-----
1 $ fsharp --nologo exceptionInvalidArgNCatch.fsx && mono
  exceptionInvalidArgNCatch.exe
2 Argument is no good!

```

**Listing 13.20 exceptionReraise.fsx:  
Reraising an exception.**

```
1 let _ =  
2     try  
3         failwith "Arrrrrg"  
4     with  
5         Failure msg ->  
6             printfn "The castle of %A" msg  
7             reraise()  
-----  
1 $ fsharp --nologo exceptionReraise.fsx && mono  
   exceptionReraise.exe  
2 The castle of "Arrrrrg"  
3  
4 Unhandled Exception:  
5 System.Exception: Arrrrrg  
6     at  
   <StartupCode$exceptionReraise>.$ExceptionReraise$fsx.main@  
   () [0x00041] in <62028a640317d799a7450383648a0262>:0  
7 [ERROR] FATAL UNHANDLED EXCEPTION: System.Exception: Arrrrrg  
8     at  
   <StartupCode$exceptionReraise>.$ExceptionReraise$fsx.main@  
   () [0x00041] in <62028a640317d799a7450383648a0262>:0
```

## 13.2 Option Types

At exceptions, it is not always obvious what should be returned. E.g., in the Listing 13.2, the exception is handled gracefully, but the return value is somewhat arbitrarily chosen to be the largest possible integer. Instead, we may use the *option type*. The option type is a wrapper that can be put around any type, and which extends the type with the special value *None*. All other values are preceded by the *Some* identifier. An example of rewriting Listing 13.2 to correctly represent the non-computable value is shown in Listing 13.21. The value of an option type

**Listing 13.21:** Option types can be used when the value in case of exceptions is unclear.

```
1 > let div enum denom =
2   try
3       Some (enum / denom)
4   with
5       | :? System.DivideByZeroException -> None;;
6 val div: enum: int -> denom: int -> int option
7
8 > let a = div 3 1;;
9 val a: int option = Some 3
10
11 > let b = div 3 0;;
12 val b: int option = None
```

can be extracted and tested for by its member functions, *IsNone*, *IsSome*, and *Value*, as illustrated in Listing 13.22. The *Value* member is not defined for *None*,

**Listing 13.22 option.fsx:**  
Simple operations on option types.

```
1 let a = Some 3;
2 let b = None;
3 printfn "%A %A" a b
4 printfn "%A %b %b" a.Value b.IsSome b.IsNone

-----

1 $ fsharp --nologo option.fsx && mono option.exe
2 Some 3 None
3 3 false true
```

thus it is advised to **prefer explicit pattern matching for extracting values from an option type**. An example is: `let get (opt : 'a option) (def : 'a) = match opt with Some x -> x | _ -> def`. Note also that `printf` prints the value *None* as `<null>`. This author hopes that future versions of the option type will have better visual representations of the *None* value. ★

Functions on option types are defined using the *option*-keyword. E.g., to define a function with explicit type annotation that always returns `None`, write `let f (x : 'a option) = None`.

F# includes an extensive `Option` module. It defines, among many other functions, `Option.bind` which implements `let bind f opt = match opt with None -> None | Some x -> f x`. The function `Option.bind` is demonstrated in Listing 13.23. The `Option.bind` is a useful tool for cascading functions that evaluates

**Listing 13.23: Using `Option.bind` to perform calculations on option types.**

```
1 > Option.bind (fun x -> Some (2*x)) (Some 3);;  
2 val it: int option = Some 6
```

to option types.

### 13.3 Programming Intermezzo: Sequential Division of Floats

The following problem illustrates cascading error handling:

**Problem 13.1**

Given a list of floats such as `[1.0; 2.0; 3.0]`, calculate the sequential division `1.0/2.0/3.0`.

A sequential division is safe if the list does not contain zero values. However, if any element in the list is zero, then error handling must be performed. An example using `failwith` is given in Listing 13.24. In this example, a recursive function is defined which updates an accumulator element, initially set to the neutral value `1.0`. Division by zero results in a `failwith` exception, wherefore we must wrap its use in a `try-with` expression.

Instead of using exceptions, we may use `Option.bind`. In order to use `Option.bind` for a sequence of non-option floats, we will define a division operator that reverses the order of operands. This is shown in Listing 13.25. Here the function `divideBy` takes two non-option arguments and returns an option type. Thus, `Option.bind (divideBy 2.0) (Some 1.0)` is equal to `Some 0.5`, since `divideBy 2.0` is a function that divides any float argument by `2.0`. Iterating `Option.bind (divideBy 3.0) (Some 0.5)`, we calculate `Some 0.1666666667` or `Some (1.0/6.0)`, as expected. In Listing 13.25, this is written as a single `let`-binding using piping. Since `Option.bind` correctly handles the distinction between `Some` and `None` values, such piping sequences correctly handle possible errors, as shown in Listing 13.25.

**Listing 13.24 seqDiv.fsx:**  
 Sequentially dividing a list of numbers.

```

1 let rec seqDiv acc lst =
2     match lst with
3     | [] -> acc
4     | elm::rest when elm <> 0.0 -> seqDiv (acc/elm) rest
5     | _ -> failwith "Division by zero"
6
7 try
8     printfn "%A" (seqDiv 1.0 [1.0; 2.0; 3.0])
9     printfn "%A" (seqDiv 1.0 [1.0; 0.0; 3.0])
10 with
11     Failure msg -> printfn "%s" msg

```

---

```

1 $ fsharpc --nologo seqDiv.fsx && mono seqDiv.exe
2 0.1666666667
3 Division by zero

```

**Listing 13.25 seqDivOption.fsx:**  
 Sequentially dividing a sequence of numbers using `Option.bind`. Compare with Listing 13.24.

```

1 let divideBy denom enum =
2     if denom = 0.0 then
3         None
4     else
5         Some (enum/denom)
6
7 let success =
8     Some 1.0
9     |> Option.bind (divideBy 2.0)
10    |> Option.bind (divideBy 3.0)
11 printfn "%A" success
12
13 let fail =
14     Some 1.0
15     |> Option.bind (divideBy 0.0)
16     |> Option.bind (divideBy 3.0)
17 printfn "%A; isNone: %b" fail fail.IsNone

```

---

```

1 $ fsharpc --nologo seqDivOption.fsx && mono seqDivOption.exe
2 Some 0.1666666667
3 None; isNone: true

```

The sequential application can be extended to lists, using `List.foldBack`, as demonstrated in Listing 13.26. Since `List.foldBack` processes the list from the right, the list of integers has been reversed. Notice how `divideByOption` is the function spelled out in each piping step of Listing 13.25.

**Listing 13.26 seqDivOptionAdv.fsx:**

Sequentially dividing a list of numbers, using `Option.bind` and `List.foldBack`. Compare with Listing 13.25.

```
1 let divideBy denom enum =
2     if denom = 0.0 then
3         None
4     else
5         Some (enum/denom)
6 let divideByOption x acc =
7     Option.bind (divideBy x) acc
8
9 let success = List.foldBack divideByOption [3.0; 2.0; 1.0]
10    (Some 1.0)
11 printfn "%A" success
12
13 let fail = List.foldBack divideByOption [3.0; 0.0; 1.0] (Some
14    1.0)
15 printfn "%A; isNone: %A" fail fail.IsNone
```

---

```
1 $ fsharp --nologo seqDivOptionAdv.fsx && mono
   seqDivOptionAdv.exe
2 Some 0.1666666667
3 None; isNone: true
```

Exceptions and option type are systems to communicate errors up through a hierarchy of function calls. While exceptions favor imperative style programming, option types belong to functional style programming. Exceptions allow for a detailed report of the type of error to the caller, whereas option types only allow for flagging that an error has occurred.

## Chapter 14

# Working With Files

An important part of programming is handling data. A typical source of data is hard-coded bindings and expressions from libraries or the program itself, and the result is often shown on a screen as text output on the console. This is a good starting point when learning to program, and one which we have relied heavily upon in this book until now. However, many programs require more: We often need to ask a user to input data via, e.g., typing text on a keyboard, clicking with a mouse, or striking a pose in front of a camera. We also often need to load and save data to files, retrieve and deposit information from the internet, and visualize data graphically, as sounds, or by controlling electrical appliances. Graphical user interfaces will be discussed in Chapter 15, and here we will concentrate on working with the console, files, and the general concept of streams.

File and stream input and output are supported via built-in namespaces and classes. For example, the `printf` family of functions discussed in ?? is defined in the `Printf` module of the `Fsharp.Core` namespace, and it is used to put characters on the `stdout` stream, i.e., to print on the screen. Likewise, `ReadLine` discussed in ?? is defined in the `System.Console` class, and it fetches characters from the `stdin` stream, that is, reads the characters the user types on the keyboard until newline is pressed.

A *file* on a computer is a resource used to store data in and retrieve data from. Files are often associated with a physical device, such as a hard disk, but can also be a virtual representation in memory. Files are durable, such that other programs can access them independently, given certain rules for access. A file has a name, a size, and a type, where the type is related to the basic unit of storage such as characters, bytes, and words, (`char`, `byte`, and `int32`). Often data requires a conversion between the internal format to and from the format stored in the file. E.g., floating point numbers are sometimes converted to a UTF8 string using `fprintf` in order to store them in a file in a human-readable form, and interpreted from UTF8 when retrieving them at a later point from the file. Files have a low-level structure, which varies from device

to device, and the low-level details are less relevant for the use of the file and most often hidden for the user. Basic operations on files are *creation*, *opening*, *reading from*, *writing to*, *closing*, and *deleting*.

A *stream* is similar to files in that they are used to store data in and retrieve data from, but streams only allow for handling of data one element at a time, like the readout of a thermometer: we can make temperature readings as often as we like, making notes and thus saving a history of temperatures, but we cannot access the future. Hence, streams are in principle without an end, and thus have infinite size, and data from streams are programmed locally by considering the present and previous elements. In contrast, files are finite in size and allow for global operations on all the file's data. Files may be considered a stream, but the opposite is not true.

## 14.1 Command Line Arguments

Compiled programs may be started from the console with one or more arguments. E.g., if we have made a program called `prog`, then arguments may be passed as `mono prog arg1 arg2 ...`. To read the arguments in the program, we must define a function with the *EntryPoint* attribute, and this function must be of type `string array -> int`.

**Listing 14.1:** Defining an entry point function with arguments from the console.

```
1  [<EntryPoint>]
2  let <funcIdent> <arg> =
3      <bodyExpr>
```

`<funcIdent>` is the function's name, `<arg>` is the name of an array of strings, and `<bodyExpr>` is the function body. Return value 0 implies a successful execution of the program, while a non-zero value means failure. The entry point function can only be in the rightmost file in the list of files given to `fsharpc`. An example is given in Listing 14.2. An example execution with arguments is shown in Listing 14.3.

**Listing 14.2** `commandLineArgs.fsx`:  
Interacting with a user with `ReadLine` and `WriteLine`.

```
1  [<EntryPoint>]
2  let main args =
3      printfn "Arguments passed to function : %A" args
4      0 // Signals that program terminated successfully
```

In Bash, the return value is called the *exit status* and can be tested using Bash's `if` statements, as demonstrated in Listing 14.4. Also in Bash, the exit status of the last



**Listing 14.3: An example dialogue of running Listing 14.2.**

```

1 $ fsharp --nologo CommandLineArgs.fsx
2 $ mono CommandLineArgs.exe Hello World
3 Arguments passed to function : [|"Hello"; "World"|]

```

**Listing 14.4: Testing return values in Bash when running Listing 14.2.**

```

1 $ fsharp --nologo CommandLineArgs.fsx
2 $ if mono CommandLineArgs.exe Hello World; then echo
   "success"; else echo "failure"; fi
3 Arguments passed to function : [|"Hello"; "World"|]
4 success

```

executed program can be accessed using the `$?` built-in environment variable. In Windows, this same variable is called `%errorlevel%`.

## 14.2 Interacting With the Console

From a programming perspective, the console is a stream: A program may send new data to the console, but cannot return to previously sent data and make changes. Likewise, the program may retrieve input from the user, but cannot go back and ask the user to have input something else, nor can we peek into the future and retrieve what the user will input in the future. The console uses three built-in streams in `System.Console`, listed in Table 14.1. On the console, the standard output

Stream	Description
<code>stdout</code>	Standard output stream used to display regular output. It typically streams data to the console.
<code>stderr</code>	Standard error stream used to display warnings and errors, typically streams to the same place as <code>stdout</code> .
<code>stdin</code>	Standard input stream used to read input, typically from the keyboard input.

**Table 14.1** Three built-in streams in `System.Console`.

and error streams are displayed as text, and it is typically not possible to see a distinction between them. However, command-line interpreters such as Bash can, and it is possible from the command-line to filter output from programs according to these streams. However, a further discussion on this is outside the scope of this text. In `System.Console` there are many functions supporting interaction with the console, and the most important ones are shown in Table 14.2. Note that you must supply the empty argument `“C”` to the `Read` functions in order to run most of the functions instead of referring to them as values. A demonstration of the use of `Write`, `WriteLine`, and `ReadLine` is given in Listing 14.5. The functions `Write` and `WriteLine` act as `printfn` without a formatting string. These functions have

Function	Description
<code>Write: string -&gt; unit</code>	Write to the console. E.g., <code>System.Console.Write "Hello world"</code> . Similar to <code>printf</code> .
<code>WriteLine: string -&gt; unit</code>	As <code>Write</code> , but followed by a newline character, e.g., <code>WriteLine "Hello world"</code> . Similar to <code>printfn</code> .
<code>Read: unit -&gt; int</code>	Wait until the next key is pressed, and read its value. The key pressed is echoed to the screen.
<code>ReadKey: bool -&gt; System.ConsoleKeyInfo</code>	As <code>Read</code> , but returns more information about the key pressed. When given the value <code>true</code> as argument, then the key pressed is not echoed to the screen. E.g., <code>ReadKey true</code> .
<code>ReadLine unit -&gt; string</code>	Read the next sequence of characters until newline from the keyboard, e.g., <code>ReadLine ()</code> .

**Table 14.2** Some functions for interacting with the user through the console in the `System.Console` class. Prefix “`System.Console.`” is omitted for brevity.

#### Listing 14.5 userDialogue.fsx:

Interacting with a user with `ReadLine` and `WriteLine`. The user typed “3.5” and “7.4”.

```

1 System.Console.WriteLine "To perform the multiplication of a
  and b"
2 System.Console.Write "Enter a: "
3 let a = float (System.Console.ReadLine ())
4 System.Console.Write "Enter b: "
5 let b = float (System.Console.ReadLine ())
6 System.Console.WriteLine ("a * b = " + string (a * b))

-----
1 $ fsharp --nologo userDialogue.fsx && mono userDialogue.exe
2 To perform the multiplication of a and b
3 Enter a: 3.5
4 Enter b: 7.4
5 a * b = 25.9

```

many overloaded definitions, the description of which is outside the scope of this book. **★ For writing to the console, `printf` is to be preferred.**

Often `ReadKey` is preferred over `Read`, since the former returns a value of type `System.ConsoleKeyInfo` which is a structure with three properties:

**Key:** A `System.ConsoleKey` enumeration of the key pressed. E.g., the character ‘a’ is `ConsoleKey.A`.

**KeyChar:** A unicode representation of the key.

**Modifiers:** A `System.ConsoleModifiers` enumeration of modifier keys shift, ctrl, and alt.

An example of a dialogue is shown in Listing 14.6.

**Listing 14.6 readKey.fsx:**

Reading keys and modifiers. The user pressed 'a', 'shift-a', and 'ctrl-a', and the program was terminated by pressing 'ctrl-c'. The 'alt-a' combination does not work on MacOS.

```

1 open System
2
3 printfn "Start typing"
4 while true do
5     let key = Console.ReadKey true
6     let shift =
7         if key.Modifiers = ConsoleModifiers.Shift then "SHIFT+"
8         else ""
9     let alt =
10        if key.Modifiers = ConsoleModifiers.Alt then "ALT+" else ""
11    let ctrl =
12        if key.Modifiers = ConsoleModifiers.Control then "CTRL+"
13        else ""
14    printfn "You pressed: %s%s%s%s" shift alt ctrl
15    (key.Key.ToString ())

```

---

```

1 $ fsharp --nologo readKey.fsx && mono readKey.exe
2 Start typing
3 You pressed: A
4 You pressed: SHIFT+A
5 You pressed: CTRL+A

```

## 14.3 Storing and Retrieving Data From a File

A file stored on the filesystem has a name, and it must be opened before it can be accessed and closed when finished. Opening files informs the operating system that your program is now going to use the file. While a file is open, the operating system will protect it depending on how the file is opened. E.g., if you are going to write to the file, then this typically implies that no one else may write to the file at the same time, since simultaneous writing to a file may leave the resulting file in an uncertain state. Sometimes the operating system will realize that a file that was opened by a program is no longer being used, e.g., since the program is no longer running, but **it is good practice always to release reserved files, e.g., by closing them as** ★

soon as possible, such that other programs may have access to it. On the other hand, it is typically safe for several programs to read the same file at the same time, but it is still important to close files after their use, such that the operating system can effectively manage the computer's resources. Reserved files are just one of the possible obstacles that you may meet when attempting to open a file. Other points of failure may be that the file does not exist, your program may not have sufficient rights for accessing it, or the device where the file is stored may have unreliable access.

- ★ Thus, **never assume that accessing files always works, but program defensively, e.g., by checking the return status of the file accessing functions and by `try` constructions.**

Data in files may have been stored in various ways, e.g., it may contain UTF8 encoded characters or sequences of floating point numbers stored as raw bits in chunks of 64 bits, or it may be a sequence of bytes that are later going to be interpreted as an image in jpeg or tiff format. To aid in retrieving the data, F# has a family of open functions, all residing in the `System.IO.File` class. These are described in Table 14.3.

System.IO.File	Description
<code>Open:</code> (path : string) * (mode : FileMode) -> FileStream	Request the opening of a file on path for reading and writing with access mode <code>FileMode</code> , see Table 14.4. Other programs are not allowed to access the file before this program closes it.
<code>OpenRead:</code> (path : string) -> FileStream	Request the opening of a file on path for reading. Other programs may read the file regardless of this opening.
<code>OpenText:</code> (path : string) -> StreamReader	Request the opening of an existing UTF8 file on path for reading. Other programs may read the file regardless of this opening.
<code>OpenWrite:</code> (path : string) -> FileStream	Request the opening of a file on path for writing with <code>FileMode.OpenOrCreate</code> . Other programs may not access the file before this program closes it.
<code>Create:</code> (path : string) -> FileStream	Request the creation of a file on path for reading and writing, overwriting any existing file. Other programs may not access the file before this program closes it.
<code>CreateText:</code> (path : string) -> StreamWriter	Request the creation of an UTF8 file on path for reading and writing, overwriting any existing file. Other programs may not access the file before this program closes it.

**Table 14.3** The family of `System.IO.File.Open` functions. See Table 14.4 for a description of `FileMode`, Tables 14.5 and 14.6 for a description of `FileStream`, Table 14.7 for a description of `StreamReader`, and Table 14.8 for a description of `StreamWriter`.

For the general `Open` function, you must also specify how the file is to be opened. This is done with a special set of values described in Table 14.4. An example of how a file is opened and later closed is shown in Listing 14.7. Notice how the example uses a defensive programming style, where the `try`-expression is used to return the

FileMode	Description
Append	Open a file and seek to its end, if it exists, or create a new file. Can only be used together with FileAccess.Write. May throw IOException and NotSupportedException exceptions.
Create	Create a new file. If a file with the given filename exists, then that file is deleted. May throw the UnauthorizedAccessException exception.
CreateNew	Create a new file, but throw the IOException exception if the file already exists.
Open	Open an existing file. System.IO.FileNotFoundException exception is thrown if the file does not exist.
OpenOrCreate	Open a file, if it exists, or create a new file.
Truncate	Open an existing file and truncate its length to zero. Cannot be used together with FileAccess.Read.

**Table 14.4** File mode values for the System.IO.Open function.

#### Listing 14.7 openFile.fsx:

Opening and closing a file, in this case, the source code of this same file.

```

1 let filename = "openFile.fsx"
2
3 let reader =
4     try
5         Some (System.IO.File.Open (filename,
6                                     System.IO.FileMode.Open))
7     with
8         _ -> None
9
10 if reader.IsSome then
11     printfn "The file %A was successfully opened." filename
12     reader.Value.Close ()

```

---

```

1 $ fsharp --nologo openFile.fsx && mono openFile.exe
2 The file "openFile.fsx" was successfully opened.

```

optional datatype, and further processing is made dependent on the success of the opening operation.

In F#, the distinction between files and streams is not very clear. F# offers built-in support for accessing files as bytes through the `System.IO.FileStream` class, and for characters in a particular encoding through the `System.IO.TextReader` and `System.IO.TextWriter`.

A successfully opened `System.IO.FileStream` file by, e.g., `System.IO.File.OpenRead` from Table 14.3, will result in an `FileStream` object. From this object we can extract information about the file, such as the permitted operations and more listed in Table 14.5. This information is important in order to restrict the operation that we will perform on the file. Some typical operations are listed in and 14.6. E.g., we may `Seek` a particular position in the file, but only within the range of legal positions from 0 until the length of the file. Most operating systems do not necessarily write information to files immediately after one of the `Write` functions, but will often for

Property	Description
CanRead	Gets a value indicating whether the current stream supports reading. (Overrides Stream.CanRead.)
CanSeek	Gets a value indicating whether the current stream supports seeking. (Overrides Stream.CanSeek.)
CanWrite	Gets a value indicating whether the current stream supports writing. (Overrides Stream.CanWrite.)
Length	Gets the length of a stream in bytes. (Overrides Stream.Length.)
Name	Gets the name of the FileStream that was passed to the constructor.
Position	Gets or sets the current position of this stream. (Overrides Stream.Position.)

**Table 14.5** Some properties of the System.IO.FileStream class.

Method	Description
Close ()	Closes the stream.
Flush ()	Causes any buffered data to be written to the file.
Read byte[] * int * int	Reads a block of bytes from the stream and writes the data in a given buffer.
ReadByte ()	Read a byte from the file and advances the read position to the next byte.
Seek int * SeekOrigin	Sets the current position of this stream to the given value.
Write byte[] * int * int	Writes a block of bytes to the file stream.
WriteByte byte	Writes a byte to the current position in the file stream.

**Table 14.6** Some methods of the System.IO.FileStream class.

optimization purposes collect information in a buffer that is to be written to a device in batches. However, sometimes it is useful to be able to force the operating system to empty its buffer to the device. This is called *flushing* and can be forced using the Flush function.

**Listing 14.8 readFile.fsx:**

An example of opening a text file and using the StreamReader properties and methods.

```

1 let printFile (reader : System.IO.StreamReader) =
2     while not(reader.EndOfStream) do
3         let line = reader.ReadLine ()
4         printfn "%s" line
5
6 let filename = "readFile.fsx"
7 let reader = System.IO.File.OpenText filename
8 printFile reader
9
-----
1 $ fsharp --nologo readFile.fsx && mono readFile.exe
2 let printFile (reader : System.IO.StreamReader) =
3     while not(reader.EndOfStream) do
4         let line = reader.ReadLine ()
5         printfn "%s" line
6
7 let filename = "readFile.fsx"
8 let reader = System.IO.File.OpenText filename
9 printFile reader

```

Text is typically streamed through the `StreamReader` and `StreamWriter`. These may be considered higher-order stream processing, since they include an added interpretation of the bits to strings. A `StreamReader` has methods similar to a `FileStream` object and a few new properties and methods, such as the `EndOfStream` property and `ReadToEnd` method, see Table 14.7. Likewise, a `StreamWriter` has

Property/Method	Description
<code>EndOfStream</code>	Check whether the stream is at its end.
<code>Close ()</code>	Closes the stream.
<code>Flush ()</code>	Causes any buffered data to be written to the file.
<code>Peek ()</code>	Reads the next character, but does not advance the position.
<code>Read ()</code>	Reads the next character.
<code>Read char[] * int * int</code>	Reads a block of bytes from the stream and writes the data in a given buffer.
<code>ReadLine ()</code>	Reads the next line of characters until a newline. Newline is discarded.
<code>ReadToEnd ()</code>	Reads the remaining characters until end-of-file.

**Table 14.7** Some methods of the `System.IO.StreamReader` class.

an added method for automatically flushing after every writing operation. A simple

Property/Method	Description
<code>AutoFlush : bool</code>	Gets or sets the auto-flush. If set, then every call to <code>Write</code> will flush the stream.
<code>Close ()</code>	Closes the stream.
<code>Flush ()</code>	Causes any buffered data to be written to the file.
<code>Write 'a</code>	Writes a basic type to the file.
<code>WriteLine string</code>	As <code>Write</code> , but followed by newline.

**Table 14.8** Some methods of the `System.IO.StreamWriter` class.

example of opening a text-file and processing it is given in Listing 14.8. Here the program reads the source code of itself, and prints it to the console.

## 14.4 Working With Files and Directories.

F# has support for managing files, summarized in the `System.IO.File` class and summarized in Table 14.9.

Function	Description
<code>Copy (src : string, dest : string)</code>	Copy a file from <code>src</code> to <code>dest</code> , possibly overwriting any existing file.
<code>Delete string</code>	Delete a file
<code>Exists string</code>	Checks whether the file exists
<code>Move (from : string, to : string)</code>	Move a file from <code>src</code> to <code>to</code> , possibly overwriting any existing file.

**Table 14.9** Some methods of the `System.IO.File` class.

In the `System.IO.Directory` class there are a number of other frequently used functions, summarized in Table 14.10.

Function	Description
<code>CreateDirectory string</code>	Create the directory and all implied sub-directories.
<code>Delete string</code>	Delete a directory.
<code>Exists string</code>	Check whether the directory exists.
<code>GetCurrentDirectory ()</code>	Get working directory of the program.
<code>GetDirectories (path : string)</code>	Get directories in path.
<code>GetFiles (path : string)</code>	Get files in path.
<code>Move (from : string, to : string)</code>	Move a directory and its content from <code>src</code> to <code>to</code> .
<code>SetCurrentDirectory : (path : string) -&gt; unit</code>	Set the current working directory of the program to path.

**Table 14.10** Some methods of the `System.IO.Directory` class.



In the `System.IO.Path` class there are a number of other frequently used functions summarized in Table 14.11.

Function	Description
<code>Combine string * string</code>	Combine two paths into a new path.
<code>GetDirectoryName (path: string)</code>	Extract the directory name from <code>path</code> .
<code>GetExtension (path: string)</code>	Extract the extension from <code>path</code> .
<code>GetFileName (path: string)</code>	Extract the name and extension from <code>path</code> .
<code>GetFileNameWithoutExtension (path : string)</code>	Extract the name without the extension from <code>path</code> .
<code>GetFullPath (path : string)</code>	Extract the absolute path from <code>path</code> .
<code>GetTempFileName ()</code>	Create a uniquely named and empty file on disk and return its full path.

**Table 14.11** Some methods of the `System.IO.Path` class.

## 14.5 Programming intermezzo: Name of Existing File Dialogue

A typical problem when working with files is

### Problem 14.1

ask the user for the name of an existing file.

Such dialogues often require the program to aid the user, e.g., by telling the user which files are available, and by checking that the filename entered is an existing file.

We will limit our request to the present directory and use `System.Console.ReadLine` to get input from the user. Our strategy will be twofold. Firstly we will query the filesystem for the existing files using `System.IO.Directory.GetFiles`, and print these to the screen. Secondly, we will use `System.IO.File.Exists` to ensure that a file exists with the entered filename. We use the `Exists` function rather than examining the array obtained with `GetFiles`, since files may have been added or removed, since the `GetFiles` was called. A solution is shown in Listing 14.9. Note that it is programmed using a `while`-loop and with a flag `fileExists` used to exit the loop. The solution has a caveat: What should be done if the user decides not to enter a filename at all. **Including a 'cancel'-option is a good style for any user interface, and should be offered when possible.** In a text-based dialogue, this would require us to use an input, which cannot be a filename, to ensure that all possible filenames and 'cancel'-option is available to the user. This problem has not been addressed in the code. ★

**Listing 14.9** `filenamedialogue.fsx`:  
Ask the user to input a name of an existing file.

```

1 let getAFileName () =
2     let mutable filename = ""
3     let mutable fileExists = false
4     while not(fileExists) do
5         System.Console.WriteLine("Enter Filename: ")
6         filename <- System.Console.ReadLine()
7         fileExists <- System.IO.File.Exists filename
8     filename
9
10 let listOfFiles = System.IO.Directory.GetFiles "."
11 printfn "Directory contains: %A" listOfFiles
12 let filename = getAFileName ()
13 printfn "You typed: %s" filename

```

## 14.6 Reading From the Internet

The internet is a global collection of computers that are connected in a network using the internet protocol suite TCP/IP. The internet is commonly used for transport of data such as emails and for offering services such as web pages on the World Wide Web. Web resources are identified by a *Uniform Resource Locator (URL)*, popularly known as a web page, and an URL contains information about where and how data from the web page is to be obtained. E.g.,

`https://en.wikipedia.org/wiki/F_Sharp_(programming_language)`

contains 3 pieces of information: The host uses the `https` protocol, `en.wikipedia.org` is its name, and `wiki/F_Sharp_(programming_language)` is the filename.

F#'s `System` namespace contains functions for accessing web pages as stream, as illustrated in Listing 14.10. To connect to a URL as a stream, we first need first format the URL string as a *Uniform Resource Identifiers (URI)*, which is a generalization of the URL concept, using the `System.Uri` function. Then we must initialize the request by the `System.Net.WebRequest` function, and the response from the host is obtained by the `GetResponse` method. Finally, we can access the response as a stream by the `GetResponseStream` method. In the end, we convert the stream to a `StreamReader`, such that we can use the methods from Table 14.7 to access the web page.

**Listing 14.10 webRequest.fsx:**  
 Downloading a web page and printing the first few characters.

```

1  /// Set up a url as a stream
2  let url2Stream url =
3      let uri = System.Uri url
4      let request = System.Net.WebRequest.Create uri
5      let response = request.GetResponse ()
6      response.GetResponseStream ()
7
8  /// Read all contents of a web page as a string
9  let readUrl url =
10     let stream = url2Stream url
11     let reader = new System.IO.StreamReader(stream)
12     reader.ReadToEnd ()
13
14  let url = "http://fsharp.org"
15  let a = 40
16
17  let html = readUrl url
18  printfn "Downloaded %A. First %d characters are: %A" url a
    html[0..a]
  
```

---

```

1  $ dotnet fsi webRequest.fsx
2
3
4  webRequest.fsx(4,19): warning FS0044: This construct is
    deprecated. WebRequest, HttpWebRequest, ServicePoint, and
    WebClient are obsolete. Use HttpClient instead.
5
6  Downloaded "http://fsharp.org". First 40 characters are:
    "<!DOCTYPE html>"
7  <html lang="en">
8  <head>
  
```

## 14.7 Resource Management

Streams and files are examples of computer resources that may be shared by several applications. Most operating systems allow for several applications to be running in parallel, and to avoid unnecessarily blocking and hogging of resources, all responsible applications must release resources as soon as they are done using them. F# has language constructions for automatic releasing of resources: the `use` binding and the `using` function. These automatically dispose of resources when the resource's name binding falls out of scope. Technically, this is done by calling the `Dispose` method on objects that implement the `System.IDisposable` interface. See Section 24.4 for more on interfaces.

The `use` keyword is similar to `let`:

**Listing 14.11: Use binding expression.**

```
1 use <valueIdent> = <bodyExpr> [in <expr>]
```

A `use` binding provides a binding between the `<bodyExpr>` expression to the name `<valueIdent>` in the following expression(s), and in contrast to `let`, it also adds a call to `Dispose()` on `<valueIdent>` if it implements `System.IDisposable`. See for example Listing 14.12. Here, `file` is an `System.IDisposable` object,

**Listing 14.12 useBinding.fsx:**

Using `use` instead of `let` releases disposable resources at end of scope.

```
1 open System.IO
2
3 let writeToFile (filename : string) (str : string) : unit =
4     use file = File.CreateText filename
5     file.Write str
6     // file.Dispose() is implicitly called here,
7     // implying that the file is closed.
8
9 writeToFile "use.txt" "Using 'use' closes the file, when out
    of scope."
```

and `file.Dispose()` is called automatically before `writeToFile` returns. This implies that the file is closed. Had we used `let` instead, then the file would first be closed when the program terminates.

The higher-order function `using` takes a disposable object and a function, executes the function on the disposable objects, and then calls `Dispose()` on the disposable object. This is illustrated in Listing 14.13 The main difference between `use` and

**Listing 14.13 using.fsx:**

The `using` function executes a function on an object and releases its disposable resources. Compare with Listing 14.12.

```
1 open System.IO
2
3 let writeToFile (str : string) (file : StreamWriter) : unit =
4     file.Write str
5
6 using (File.CreateText "use.txt") (writeToFile "Disposed
    after call.")
7 // Dispose() is implicitly called on the anonymous file
8 // handle, implying
9 // that the file is automatically closed.
```

`using` is that resources allocated using `use` are disposed at the end of its scope, while `using` disposes the resources after the execution of the function in its argument. In spite of the added control of `using`, we **prefer `use` over `using` due to its simpler structure.**

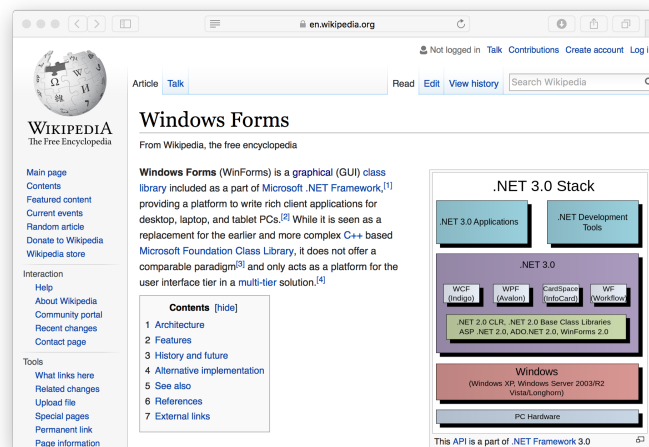
★

## Chapter 15

# Graphical User Interfaces

A *graphical user interface (GUI)* uses graphical elements such as windows, icons, and sound to communicate with the user, and a typical way to activate these elements is through a pointing device such as the mouse or by touch. Some of these elements may themselves be textual, and thus most operating systems offer access to a *command-line interface (CLI)* in a window alongside other interface types.

An example of a graphical user interface is a web-browser, shown in Figure 15.1. The program presents information to the user in terms of text and images, has active



**Fig. 15.1** A web-browser is a graphical user interface for accessing a web-server and interacting with its services. Here the browser is showing the page [https://en.wikipedia.org/wiki/Windows_Forms](https://en.wikipedia.org/wiki/Windows_Forms) at time of writing.

areas that may be activated by clicking, allows the user to go other web-pages by typing a URL or following hyperlinks, and can generate new pages through search queries.

F# includes a number of implementations of graphical user interfaces, and at time of writing, both *GTK+* and *WinForms 2.0* are supported on both the Microsoft .Net and the Mono platform. WinForms can be used without extra libraries during compilation, and therefore will be the subject of the following chapter.

WinForms is a set of libraries that simplifies many common tasks for applications, and in this chapter, we will focus on the graphical user interface part of WinForms. A *form* is a visual interface used to communicate information with the user, typically a window. Communication is done through *controls*, which are elements that display information or accept input. Examples of controls are a box with text, a button, and a menu. When the user gives input to a control element, this generates an *event* which you can write code to react to. WinForms is designed for *event-driven programming*, meaning that at runtime, most time is spent on waiting for the user to give input. See Chapter 16 for more on event-driven programming.

Designing easy-to-use graphical user interfaces is a challenging task. This chapter will focus on examples of basic graphical elements and how to program these in WinForms.

## 15.1 Opening a Window

The namespaces *System.Windows.Forms* and *System.Drawing* are central for programming graphical user interfaces with WinForms. *System.Windows.Forms* includes code for generating forms, controls, and handling events. *System.Drawing* is used for low-level drawing, and it gives access to the *Windows Graphics Device Interface (GDI+)*, which allows you to create and manipulate graphics objects targeting several platforms, such as screens and paper. All controls in *System.Windows.Forms* in Mono are drawn using *System.Drawing*.

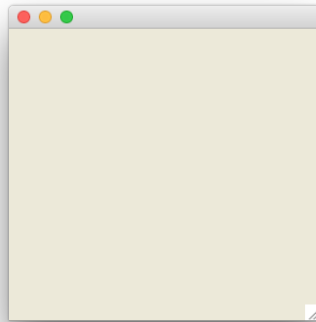
- ★ To display a graphical user interface on the screen, the first thing to do is open a window, which acts as a reserved screen-space for our output. In WinForms, windows are called forms. Code for opening a window is shown in Listing 15.1, and the result is shown in Figure 15.2. Note that the present version of WinForms on MacOs only works with the 32-bit implementation of mono, *mono32*, as demonstrated in the example. The `new System.Windows.Forms.Form ()` creates an object (See Chapter 23), but does not display the window on the screen. We use the optional `new` keyword, since the form is an *IDisposable* object and may be implicitly disposed of. I.e., it is recommended to **instantiate *IDisposable* objects using `new` to contrast them with other object types**. Executing `System.Windows.Forms.Application.Run` is applied to the object, then the control is handed over to the WinForms' *event-loop*, which continues until the window is closed by, e.g., pressing the icon designated by the operating system. On

**Listing 15.1** winforms/openWindow.fsx:

Create the window and turn over control to the operating system. See Figure 15.2.

```
1 // Create a window
2 let win = new System.Windows.Forms.Form ()
3 // Start the event-loop.
4 System.Windows.Forms.Application.Run win

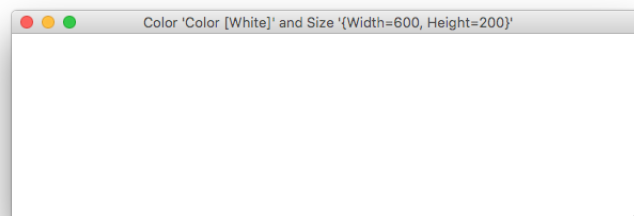
1 $ fsharpc --nologo openWindow.fsx && mono32 openWindow.exe
```



**Fig. 15.2** A window opened by Listing 15.1.

the Mac OSX, that is the red button in the top left corner of the window frame, and on Windows it is the cross on the top right corner of the window frame.

The window form has a long list of methods and properties. E.g., the background color may be set by `BackColor`, the title of the window may be set by `Text`, and you may get and set the size of the window with `Size`. This is demonstrated in Listing 15.2. These properties are *accessors*, implying that they act as mutable



**Fig. 15.3** A window with user-specified size and background color, see Listing 15.2.

**Listing 15.2** winforms/windowProperty.fsx:  
Create the window and change its properties. See Figure 15.3

```
1 // Prepare window form
2 let win = new System.Windows.Forms.Form ()
3
4 // Set some properties
5 win.BackColor <- System.Drawing.Color.White
6 win.Size <- System.Drawing.Size (600, 200)
7 win.Text <- sprintf "Color '%A' and Size '%A'" win.BackColor
   win.Size
8
9 // Start the event-loop.
10 System.Windows.Forms.Application.Run win
```

variables.

## 15.2 Drawing Geometric Primitives

The *System.Drawing.Color* is a structure for specifying colors as 4 channels: alpha, red, green, and blue. Some methods and properties for the Color structure is shown in Table 15.1. Each channel is an 8-bit unsigned integer. The alpha channel specifies the transparency of a color, where values 0–255 denote the range of fully transparent to fully opaque, and the remaining channels denote the amount of red, green, and blue, where 0 is none and 255 is full intensity. As a shorthand, colors are often referred to as a single 32-bit unsigned integer, whose bits are organized in groups of 8 bits as 0xAARRGGBB, where AA is the alpha channel's values 0x00–0xFF etc. Any color may be created using the *FromArgb* method, e.g., an opaque red is given by *System.Drawing.Color.FromArgb* (255, 255, 0, 0). There are also many build-in colors, e.g., the same red color is also a known color and may be obtained as *System.Drawing.Color.Red*. For a given color, the 4 alpha, red, green, and blue channels' values may be obtained as the A, R, G, and B members, see Listing 15.3

The namespace *System.Drawing* contains many useful functions and values. Listing 15.2 used *System.Drawing.Size* to specify a size by a pair of integers. Other important values and functions are *Point*, which specifies a coordinate as a pair of points; *Pen*, which specifies how to draw lines and curves; *Font*, which specifies the font of a string; *SolidBrush* and *TextureBrush*, used for filling geometric primitives, and *Bitmap*, which is a type of *Image*. These are summarized in Table 15.2.

The *System.Drawing.Graphics* is a class for drawing geometric primitives to a display device, and some of its methods are summarized in Table 15.3.



Method/Property	Description
Properties of an existing color structure	
A : byte	The value of the alpha channel.
R : byte	The value of the red channel.
G : byte	The value of the green channel.
B : byte	The value of the blue channel.
ToArgb : unit -> int	The 32-bit integer value of the color.
Static properties returning a color structure by its name.	
Black : Color	The ARGB value 0xFF000000.
Blue : Color	The ARGB value 0xFF0000FF.
Brown : Color	The ARGB value 0xFFA52A2A.
Gray : Color	The ARGB value 0xFF808080.
Green : Color	The ARGB value 0xFF00FF00.
Orange : Color	The ARGB value 0xFFFFA500.
Purple : Color	The ARGB value 0xFF800080.
Red : Color	The ARGB value 0xFFFF0000.
White : Color	The ARGB value 0xFFFFFFFF.
Yellow : Color	The ARGB value 0xFFFF0000.
Static methods for converting between color structures and integers representations.	
FromArgb : r:int * g:int * b:int -> Color	Create a color structure from red, green, and blue values.
FromArgb : a:int * r:int * g:int * b:int -> Color	Create a color structure from alpha, red, green, and blue values.
FromArgb : argb:int -> Color	Create a color structure from a single integer.

**Table 15.1** Some methods and properties of the System.Drawing.Color structure.

Constructor	Description
Bitmap(int, int)	Create a new empty Image of specified size.
Bitmap(Stream)	Create a Image from a System.IO.Stream or from a file specified by a filename.
Bitmap(string)	
Font(string, single)	Create a new font from the font's name and em-size.
Pen(Brush)	Create a pen to paint either with a brush or solid color and possibly with specified width.
Pen(Brush), single)	
Pen(Color)	
Pen(Color, single)	
Point(int, int)	Create an ordered pair of integers or singles specifying x- and y-coordinates in the plane.
Point(Size)	
PointF(single, single)	
Size(int, int)	Create an ordered pair of integers or singles specifying height and width in the plane.
Size(Point)	
SizeF(single, single)	
SizeF(PointF)	
SolidBrush(Color)	Create a Brush as a solid color or from an image to fill the interior of geometric shapes.
TextureBrush(Image)	

**Table 15.2** Basic geometrical structures in WinForms. Brush and Image are abstract classes.

**Listing 15.3** drawingColors.fsx:  
Defining colors and accessing their values.

```

1 // open namespace for brevity
2 open System.Drawing
3 // Define a color from ARGB
4 let c = Color.FromArgb (0xFF, 0x7F, 0xFF, 0xD4) //Aquamarine
5 printfn "The color %A is (%x, %x, %x, %x)" c c.A c.R c.G c.B
6 // Define a list of named colors
7 let colors =
8     [Color.Red; Color.Green; Color.Blue;
9      Color.Black; Color.Gray; Color.White]
10 for col in colors do
11     printfn "The color %A is (%x, %x, %x, %x)" col col.A col.R
        col.G col.B

```

---

```

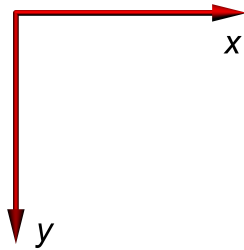
1 $ fsharp --nologo drawingColors.fsx && mono drawingColors.exe
2 The color Color [A=255, R=127, G=255, B=212] is (ff, 7f, ff,
    d4)
3 The color Color [Red] is (ff, ff, 0, 0)
4 The color Color [Green] is (ff, 0, 80, 0)
5 The color Color [Blue] is (ff, 0, 0, ff)
6 The color Color [Black] is (ff, 0, 0, 0)
7 The color Color [Gray] is (ff, 80, 80, 80)
8 The color Color [White] is (ff, ff, ff, ff)

```

Constructor	Description
DrawImage : Image * (Point []) -> unit	Draw an image at a specific point and size.
DrawImage : Image * (PointF []) -> unit	
DrawImage : Image * Point -> unit	Draw an image at a specific point.
DrawImage : Image * PointF -> unit	
DrawLines : Pen * (Point []) -> unit	Draw a series of lines between the <i>n</i> 'th and
DrawLines : Pen * (PointF []) -> unit	<i>n + 1</i> 'th points.
DrawString : string * Font * Brush * PointF -> unit	Draw a string at the specified point.

**Table 15.3** Basic geometrical structures in WinForms.

The location and shape of geometrical primitives are specified in a coordinate system, and WinForms operates with 2 coordinate systems: *screen coordinates* and *client coordinates*. Both coordinate systems have their origin in the top-left corner, with the first coordinate, *x*, increasing to the right, and the second, *y*, increasing down, as illustrated in Figure 15.4. The Screen coordinate system has its origin in the top-left corner of the screen, while the client coordinate system has its origin in the top-left corner of the drawable area of a form or a control, i.e., for a window, this will be the area without the window borders, scroll, and title bars. A control is a graphical object, such as a clickable button, will be discussed later. Conversion between client and screen coordinates is done with *System.Drawing.PointToClient* and *System.Drawing.PointToScreen*.



**Fig. 15.4** Coordinate systems in Winforms have the y axis pointing down.

Displaying graphics in WinForms is performed as the reaction to an event. E.g., windows are created by the program, moved, minimized, occluded by other windows, resized, etc., by the user or the program, and each action may require that the content of the window is refreshed. Thus, we must create a function that WinForms can call any time. This is known as a *call-back function*, and it is added to an existing form using the form's `Paint.Add` method. Due to the event-driven nature of WinForms, functions for drawing graphics primitives are only available when responding to an event, e.g., `System.Drawing.Graphics.DrawLine` draws a line in a window, and *it is only possible to call this function as part of an event handling*.

As an example, consider the problem of drawing a triangle in a window. For this we need to make a function that can draw a triangle not once, but at any amount of times as deemed necessary by the operating system. An example of such a program is shown in Listing 15.4. A walk-through of the code is as follows: First, we open the

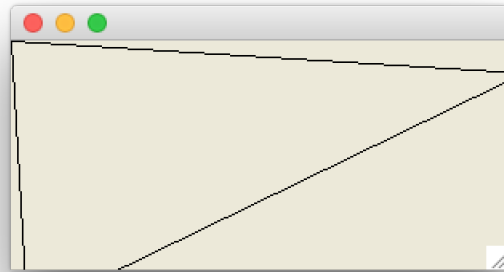
**Listing 15.4** winforms/triangle.fsx:  
Adding line graphics to a window. See Figure 15.5

```

1 // Open often used libraries, beware of namespace pollution!
2 open System.Windows.Forms
3 open System.Drawing
4
5 // Prepare window form
6 let win = new Form ()
7 win.Size <- Size (320, 170)
8
9 // Set paint call-back function
10 let paint (e : PaintEventArgs) : unit =
11     let pen = new Pen (Color.Black)
12     let points =
13         [|Point (0,0); Point (10,170); Point (320,20); Point
14            (0,0)|]
15     e.Graphics.DrawLine (pen, points)
16 win.Paint.Add paint
17
18 // Start the event-loop.
19 Application.Run win

```

two libraries that we will use heavily. This will save us some typing, but also pollute



**Fig. 15.5** Drawing a triangle using Listing 15.4.

our namespace. E.g., now `Point` and `Color` are existing types, and we cannot define our own identifiers with these names. Then we create the form with size  $320 \times 170$ , we add a paint call-back function, and we start the event-loop. The event-loop will call the paint function, whenever the system determines that the window's content needs to be refreshed. This function is to be called as a response to a paint event and takes a `System.Windows.Forms.PaintEventArgs` object, which includes the `System.Drawing.Graphics` object. The function `paint` chooses a pen and a set of points and draws a set of lines connecting the points.

The code in Listing 15.4 is not optimal. Despite the fact that the triangle spans the rectangle  $(0, 0)$  to  $(320, 170)$  and the window's size is set to  $(320, 170)$ , our window is too small and the triangle is clipped at the window border. The error is that we set the window's `Size` property, which determines the size of the window including top bar and borders. Alternatively, we may set the `ClientSize`, which determines the size of the drawable area, and this is demonstrated in Listing 15.5 and Figure 15.6.

- ★ Thus, **prefer the `ClientSize` over the `Size` property for internal consistency.**

Considering the program in Listing 15.4, we may identify a part that concerns the specification of the triangle, or more generally the graphical model, and some which concern system specific details. For future maintenance, it is often a good idea to

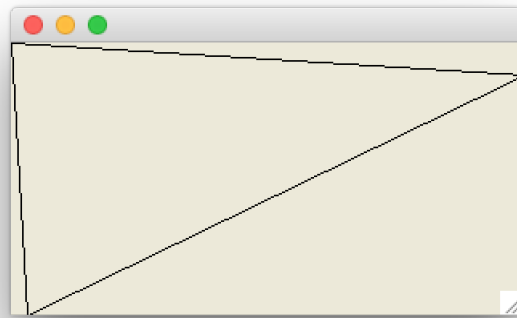
- ★ **separate the model from how it is viewed on a specific system.** E.g., it may be that at some point you decide that you would rather use a different library than WinForms. In this case, the general graphical model will be the same, but the specific details on initialization and event handling will be different. We think of the model and the viewing part of the code as top and bottom layers, respectively, and these are often connected with a connection layer. This *Model-View paradigm* is shown in Figure 15.7. While it is not easy to completely separate the general from the specific, it is often a good idea to strive for some degree of separation.

**Listing 15.5** winforms/triangleClientSize.fsx:  
Adding line graphics to a window. See Figure 15.6.

```

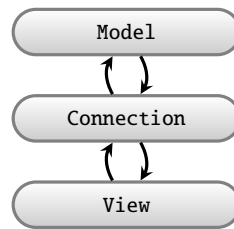
1 // Open often used libraries, beware of namespace pollution!
2 open System.Windows.Forms
3 open System.Drawing
4
5 // Prepare window form
6 let win = new Form ()
7 win.ClientSize <- Size (320, 170)
8
9 // Set paint call-back function
10 let paint (e : PaintEventArgs) : unit =
11     let pen = new Pen (Color.Black)
12     let points =
13         [|Point (0,0); Point (10,170); Point (320,20); Point
14            (0,0)|]
15     e.Graphics.DrawLine (pen, points)
16 win.Paint.Add paint
17
18 // Start the event-loop.
19 Application.Run win

```



**Fig. 15.6** Setting the `ClientSize` property gives a predictable drawing area, see Listing 15.5 for code.

In Listing 15.6, the program has been redesigned to follow the Model-View paradigm, where `view` contains most of the WinForms-specific code, and `model` contains most of the geometry, which could be reused with other graphical user interfaces. The model still uses the geometric primitives from WinForms for brevity, since a general implementation of geometric primitives avoiding WinForms would have a very similar interface. This program is longer, but there is a much better separation of *what* is to be displayed (model) from *how* it is to be done (view).



**Fig. 15.7** Separating model from view gives flexibility later.

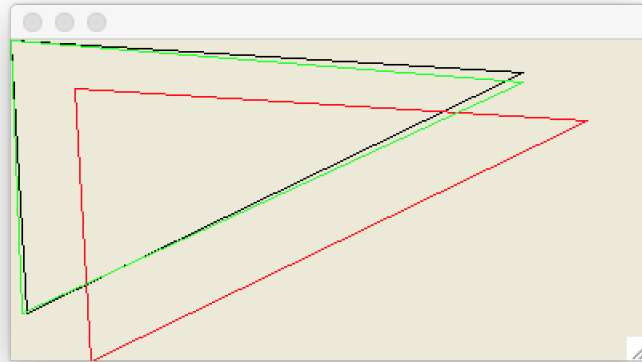
**Listing 15.6** winforms/triangleOrganized.fsx:

Improved organization of code for drawing a triangle. See Figure 15.8.

```

1 // Open often used libraries, beware of namespace pollution!
2 open System.Windows.Forms
3 open System.Drawing
4
5 ////////////// WinForm specifics ///////////////////
6 /// Setup a window form and return function which can
7   activate it
8 let view (sz : Size) (pen : Pen) (pts : Point []) : (unit ->
9   unit) =
10   let win = new System.Windows.Forms.Form ()
11   win.ClientSize <- sz
12   win.Paint.Add (fun e -> e.Graphics.DrawLine (pen, pts))
13   fun () -> Application.Run win // function as return value
14
15 ////////////// Model ///////////////////
16 // A black triangle, using winform primitives for brevity
17 let model () : Size * Pen * (Point []) =
18   let size = Size (320, 170)
19   let pen = new Pen (Color.FromArgb (0, 0, 0))
20   let lines =
21     [|Point (0,0); Point (10,170); Point (320,20); Point
22      (0,0)|]
23   (size, pen, lines)
24
25 ////////////// Connection ///////////////////
26 // Tie view and model together and enter main event loop
27 let (size, pen, lines) = model ()
28 let run = view size pen lines
29 run ()
  
```

To further our development of a general program for displaying graphics, consider the case where we are to draw another two triangles, that are a translation and rotations of the original, and where we would like to specify the color of each triangle individually. A simple extension of model in Listing 15.6 for generating many shapes of different colors is `model : unit -> Size * ((Point []) * Pen) list`, i.e., semantically augment each point array with a pen and return a list of such pairs. For this example, we also program translation and rotation transformations. See Listing 15.7 for the result. We update view accordingly to iterate through this



**Fig. 15.8** Better organization of the code for drawing a triangle, see Listing 15.6.

list as shown in Listing 15.8. Since we are using WinForms primitives in the model, the connection layer is trivial, as shown in Listing 15.9.

**Listing 15.7** winforms/transformWindows.fsx:  
Model of a triangle and simple transformations of it. See also Listing 15.8 and 15.9.

```

15 /////////////// Model ///////////////////
16 // A black triangle, using WinForm primitives for brevity
17 let model () : Size * ((Pen * (Point [])) list) =
18     /// Translate a primitive
19     let translate (d : Point) (arr : Point []) : Point [] =
20         let add (d : Point) (p : Point) : Point =
21             Point (d.X + p.X, d.Y + p.Y)
22         Array.map (add d) arr
23
24     /// Rotate a primitive
25     let rotate (theta : float) (arr : Point []) : Point [] =
26         let toInt = int << round
27         let rot (t : float) (p : Point) : Point =
28             let (x, y) = (float p.X, float p.Y)
29             let (a, b) = (x * cos t - y * sin t, x * sin t + y *
30                 cos t)
31             Point (toInt a, toInt b)
32         Array.map (rot theta) arr
33
34     let size = Size (400, 200)
35     let lines =
36         [|Point (0,0); Point (10,170); Point (320,20); Point
37             (0,0)|]
38     let black = new Pen (Color.FromArgb (0, 0, 0))
39     let red = new Pen (Color.FromArgb (255, 0, 0))
40     let green = new Pen (Color.FromArgb (0, 255, 0))
41     let shapes =
42         [(black, lines);
43          (red, translate (Point (40, 30)) lines);
44          (green, rotate (1.0 * System.Math.PI / 180.0) lines)]
45     (size, shapes)

```



**Listing 15.8 winforms/transformWindows.fsx:**

A view for lists of pairs of pen and point arrays. See also Listing 15.7 and 15.9.

```

1 // Open often used libraries, beware of namespace pollution!
2 open System.Windows.Forms
3 open System.Drawing
4
5 ////////////// WinForm specifics //////////////////
6 /// Setup a window form and return function to activate
7 let view (sz : Size) (shapes : (Pen * (Point [])) list) :
  (unit -> unit) =
8   let win = new Form ()
9   win.ClientSize <- sz
10  let paint (e : PaintEventArgs) ((p, pts) : (Pen * (Point
11   []))) : unit =
12   e.Graphics.DrawLine (p, pts)
13   win.Paint.Add (fun e -> List.iter (paint e) shapes)
14   fun () -> Application.Run win // function as return value

```

**Listing 15.9 winforms/transformWindows.fsx:**

Model of a triangle and simple transformations of it. See also Listing 15.7 and 15.8.

```

45 ////////////// Connection //////////////////
46 // Tie view and model together and enter main event loop
47 let (size, shapes) = model ()
48 let run = view size shapes
49 run ()

```

### 15.3 Programming Intermezzo: Hilbert Curve

A curve in 2 dimensions has a length but no width, and we can only visualize it by giving it a width. Thus, it came as a surprise to many when Giuseppe Peano in 1890 demonstrated that there exist curves which fill every point in a square. The method he used to achieve this was recursion:

#### Problem 15.1

consider a curve consisting of piecewise straight lines all with the same length but with varying angles  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$ , or  $270^\circ$  w.r.t. the horizontal axis. To draw this curve, we need 3 basic operations: Move forward ( $F$ ), turn right ( $R$ ), and turn left ( $L$ ). The turning is w.r.t. the present direction. A Hilbert Curve is a space-filling curve which can be expressed recursively as:

$$A \rightarrow LBFRAFARFBL, \quad (15.1)$$

$$B \rightarrow RAFLBFLFAR, \quad (15.2)$$

starting with  $A$ . For practical illustrations, we typically only draw space-filling curves to a specified depth of recursion, which is called the order of the curve. To keep track of the level of recursion, we introduce an index as:

$$A_{n+1} \rightarrow LB_n FRA_n F A_n RFB_n L,$$

$$B_{n+1} \rightarrow RA_n FLB_n FB_n LFA_n R,$$

for  $n > 0$  and  $A_0 \rightarrow \emptyset$  and  $B_0 \rightarrow \emptyset$ . Thus, the first-order curve is

$$A_1 \rightarrow LB_0 FRA_0 F A_0 RFB_0 L \rightarrow LFRFRFL,$$

and the second order curve is

$$\begin{aligned} A_2 &\rightarrow LB_1 FRA_1 F A_1 RFB_1 L \\ &\rightarrow LRFLFLFRFRFLFRFRFLFLFRFRFLFRFRFLFLFL. \end{aligned}$$

Since  $LR = RL = \emptyset$  the above simplifies to

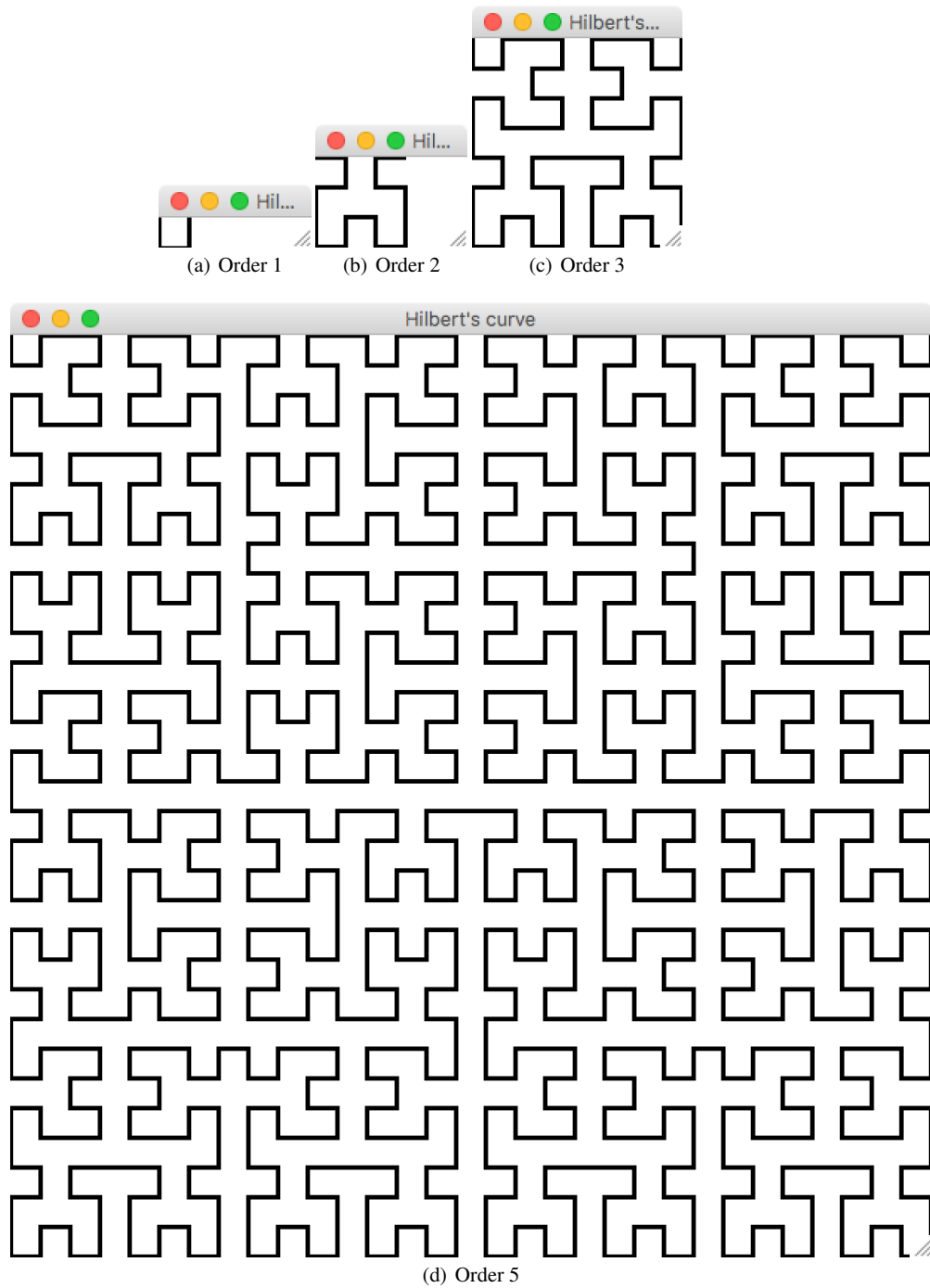
$$A_2 \rightarrow FLFLFRFFRFRFLFLFRFRFFRFLFLF$$

Make a program that given an order produces an image of the Hilbert curve.

Our strategy to solve this problem will be first to define the curves in terms of movement commands  $LRFL \dots$ . For this, we will define a discriminated union `type Command = F | L | R`. The movement commands can then be defined as a `Command list` type. The list for a specific order is a simple set of recursive functions in `F#` which we will call `A` and `B`.

To produce a graphical drawing of a command list, we must transform it into coordinates, and during the conversion, we need to keep track of both the present position and the present heading, since not all commands draw. This is a concept similar to Turtle Graphics, which is often associated with the Logo programming language from the 1960's. In Turtle graphics, we command a little robot - a turtle - which moves in 2 dimensions and can turn on the spot or move forward, and its track is the line being drawn. Thus we introduce a `type Turtle = {x : float; y : float; d : float}` record. Conversion of command lists to turtle lists is a fold programming structure, where the command list is read from left-to-right, building up an accumulator by adding each new element. For efficiency, we choose to prepend the new element to the accumulator. This we have implemented as the `addRev` function. Once the full list of turtles has been produced, then it is reversed.

Finally, the turtle list is converted to WinForms `Point` array, and a window of appropriate size is chosen. The resulting model part is shown in Listing 15.10. The view and connection parts are identical to Listing 15.8 and 15.9, and Figure 15.9 shows the result of using the program to draw Hilbert curves of orders 1, 2, 3, and 5.



**Fig. 15.9** Hilbert curves of orders 1, 2, 3, and 5 by code in Listing 15.10.

**Listing 15.10** winforms/hilbert.fsx:

Using simple turtle graphics to produce a list of points on a polygon. The code continues in Listing 15.11. The view and connection parts are identical to Listing 15.8 and 15.9.

```

15 // Turtle commands, type definitions must be in outermost
    scope
16 type Command = F | L | R
17 type Turtle = {x : float; y : float; d : float}
18
19 // A black Hilbert curve using WinForm primitives for brevity
20 let model () : Size * ((Pen * (Point [])) list) =
21     /// Hilbert recursion production rules
22     let rec A n : Command list =
23         if n > 0 then
24             [L]@B (n-1)@[F; R]@A (n-1)@[F]@A (n-1)@[R; F]@B
25             (n-1)@[L]
26         else
27             []
28     and B n : Command list =
29         if n > 0 then
30             [R]@A (n-1)@[F; L]@B (n-1)@[F]@B (n-1)@[L; F]@A
31             (n-1)@[R]
32         else
33             []
34     /// Convert a command to turtle record and prepend to list
35     let addRev (lst : Turtle list) (cmd : Command) (len :
36         float) : Turtle list =
37         let toInt = int << round
38         match lst with
39         | t::rest ->
40             match cmd with
41             | L -> {t with d = t.d + 3.141592/2.0}::rest // left
42             | R -> {t with d = t.d - 3.141592/2.0}::rest //
43             right
44             | F -> {t with x = t.x + len * cos t.d; // forward
45                     y = t.y + len * sin t.d}::lst
46             | _ -> failwith "Turtle list must be non-empty."
47
48     let maxPoint (p1 : Point) (p2 : Point) : Point =
49         Point (max p1.X p2.X, max p1.Y p2.Y)

```

**Listing 15.11** winforms/hilbert.fsx:  
Continued from Listing 15.10.

```
48 // Calculate commands for a specific order
49 let curve = A 5
50 // Convert commands to point array
51 let initTrtl = {x = 0.0; y = 0.0; d = 0.0}
52 let len = 20.0
53 let line =
54     List.fold (fun acc elm -> addRev acc elm len) [initTrtl]
55     curve // Convert command list to reverse turtle list
56     |> List.rev // Reverse list
57     |> List.map (fun t -> Point (int (round t.x), int (round
58         t.y))) // Convert turtle list to point list
59     |> List.toArray // Convert point list to point array
60 let black = new Pen (Color.FromArgb (0, 0, 0))
61 // Set size to as large as shape
62 let minVal = System.Int32.MinValue
63 let maxPoint = Array.fold maxPoint (Point (minVal, minVal))
64     line
65 let size = Size (maxPoint.X + 1, maxPoint.Y + 1)
66 (size, [(black, line)]) // return shapes as singleton list
```

## 15.4 Handling Events

In the previous section, we have looked at how to draw graphics using the `Paint` method of an existing form object. Forms have many other event handlers that we may use to interact with the user. Listing 15.12 demonstrates event handlers for moving and resizing a window, for clicking in a window, and for typing on the keyboard.

Listing 15.12 shows the output from an interaction with the program which is the

**Listing 15.12** `winforms/windowEvents.fsx`:  
Catching window, mouse, and keyboard events.

```

1  open System.Windows.Forms
2  open System.Drawing
3  open System
4
5  let win = new Form () // create a form
6
7  // Window event
8  let windowMove (e : EventArgs) =
9      printfn "Move: %A" win.Location
10     win.Move.Add windowMove
11
12     let windowResize (e : EventArgs) =
13         printfn "Resize: %A" win.DisplayRectangle
14         win.Resize.Add windowResize
15
16     // Mouse event
17     let mutable record = false; // records when button down
18     let mouseMove (e : MouseEventArgs) =
19         if record then printfn "MouseMove: %A" e.Location
20         win.MouseMove.Add mouseMove
21
22     let mouseDown (e : MouseEventArgs) =
23         printfn "MouseDown: %A" e.Location; (record <- true)
24         win.MouseDown.Add mouseDown
25
26     let mouseUp (e : MouseEventArgs) =
27         printfn "MouseUp: %A" e.Location; (record <- false)
28         win.MouseUp.Add mouseUp
29
30     let mouseClicked (e : MouseEventArgs) =
31         printfn "MouseClicked: %A" e.Location
32         win.MouseClick.Add mouseClicked
33
34     // Keyboard event
35     win.KeyPreview <- true
36     let keyPress (e : KeyPressEventArgs) =
37         printfn "KeyPress: %A" (e.KeyChar.ToString ())
38         win.KeyPress.Add keyPress
39
40     Application.Run win // Start the event-loop.

```

**Listing 15.13: Output from an interaction with the program in Listing 15.12.**

```

1 Move: {X=22,Y=22}
2 Move: {X=22,Y=22}
3 Move: {X=50,Y=71}
4 Resize: {X=0,Y=0,Width=307,Height=290}
5MouseDown: {X=144,Y=118}
6 MouseClick: {X=144,Y=118}
7 MouseUp: {X=144,Y=118}
8 MouseDown: {X=144,Y=118}
9 MouseUp: {X=144,Y=118}
10MouseDown: {X=96,Y=66}
11 MouseMove: {X=96,Y=67}
12 MouseMove: {X=97,Y=69}
13 MouseMove: {X=99,Y=71}
14 MouseMove: {X=103,Y=74}
15 MouseMove: {X=107,Y=77}
16 MouseMove: {X=109,Y=79}
17 MouseMove: {X=112,Y=81}
18 MouseMove: {X=114,Y=82}
19 MouseMove: {X=116,Y=84}
20 MouseMove: {X=117,Y=85}
21 MouseMove: {X=118,Y=85}
22 MouseClick: {X=118,Y=85}
23 MouseUp: {X=118,Y=85}
24 KeyPress: "a"
25 KeyPress: "b"
26 KeyPress: "c"

```

result of the following actions: moving the window, resizing the window, clicking the left mouse key, pressing and holding the down the left mouse key while moving the mouse, releasing the left mouse key, and typing “abc”. As demonstrated, some actions, like moving the mouse, result in a lot of events, and some, like the initial window moves results, are surprising. Thus, event-driven programming should take care to interpret the events robustly and carefully.

Common for all event-handlers is that they listen for an event, and when the event occurs, the functions that have been added using the `Add` method are called. This is also known as sending a message. Thus, a single event can give rise to calling zero or more functions.

Graphical user interfaces and other systems often need to perform actions that depend on specific lengths of time or a certain point in time. To measure length of time F# has the `System.Windows.Forms.Timer` class, which technically is an optimized of `System.Timers.Timer` for graphical user interfaces. The `Timer` class can be used to create an event after a specified duration of time. F# also has the `System.DateTime` class to specify points in time. An often used property is `System.DateTime.Now`, which returns a `DateTime` object for the date and time when the property is accessed. The use of these two classes is demonstrated in Listing 15.14 and Figure 15.10. In the code, a label has been created to show the present date and time. The label is a



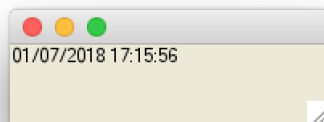
**Listing 15.14** winforms/clock.fsx:

Using `System.Windows.Forms.Timer` and `System.DateTime.Now` to update the display of the present date and time. See Figure 15.10 for the result.

```

1 open System.Windows.Forms
2 open System.Drawing
3 open System
4
5 let win = new Form () // make a window form
6 win.ClientSize <- Size (200, 50)
7
8 // make a label to show time
9 let label = new Label()
10 win.Controls.Add label
11 label.Width <- 200
12 label.Text <- string System.DateTime.Now // get present time
    and date
13
14 // make a timer and link to label
15 let timer = new Timer()
16 timer.Interval <- 1000 // create an event every 1000
    millisecond
17 timer.Enabled <- true // activate the timer
18 timer.Tick.Add (fun e -> label.Text <- string
    System.DateTime.Now)
19
20 Application.Run win // start event-loop

```



**Fig. 15.10** See Listing 15.14.

type of control, and it is displayed using the default font which is rather small. How to change this and other details on controls will be discussed in the next section.

In the example, the label is redrawn everytime the text is changed, such that the current value is correctly displayed on the screen. Sometimes it is necessary to force a control to redraw which can be done with the `Refresh()` method. Since a `Form` is also a type of control, it is common to trigger a redraw event for the top form, which in Listing 15.14 would be `win.Refresh()`. Thus, `Refresh()` and a `Timer` object can be used to produce animations.

## 15.5 Labels, Buttons, and Pop-up Windows

In WinForms, buttons, menus and other interactive elements are called *Controls*. A form is a type of control, and thus, programming controls are very similar to programming windows. Listing 15.15 shows a small program that displays a label and a button in a window, and when the button is pressed, then the label is updated. As the list-

**Listing 15.15** winforms/buttonControl.fsx:  
Create the button and an event, see also Figure 15.11.

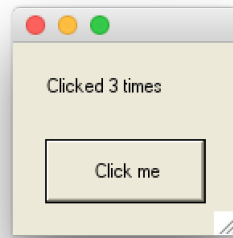
```

1  open System.Windows.Forms
2  open System.Drawing
3  open System
4
5  let win = new Form () // make a window form
6  win.ClientSize <- Size (140, 120)
7
8  // Create a label
9  let label = new Label()
10 win.Controls.Add label
11 label.Location <- new Point (20, 20)
12 label.Width <- 120
13 let mutable clicked = 0
14 let setLabel clicked =
15     label.Text <- sprintf "Clicked %d times" clicked
16 setLabel clicked
17
18 // Create a button
19 let button = new Button ()
20 win.Controls.Add button
21 button.Size <- new Size (100, 40)
22 button.Location <- new Point (20, 60)
23 button.Text <- "Click me"
24 button.Click.Add (fun e -> clicked <- clicked + 1; setLabel
25     clicked)
26 Application.Run win // Start the event-loop.
```

ing demonstrates, the button is created using the *System.Windows.Forms.Button* constructor, and it is added to the window's form's control list. The *Location* property controls its position w.r.t. the enclosing form. Other accessors are *Width*, *Text*, and *Size*.

*System.Windows.Forms* includes a long list of controls, some of which are summarized in Table 15.4. Examples are given in controls, shown in Listing 15.16 and Figure 15.12.

Some controls open separate windows for more involved dialogue with the user. Some examples are *MessageBox*, *OpenFileDialog*, and *SaveFileDialog*.



**Fig. 15.11** After pressing the button 3 times. See Listing 15.15.

Method/Property	Description
Button	A clickable button.
CheckBox	A clickable check box.
DateTimePicker	A box showing a date with a drop-down menu for choosing another.
Label	A displayable text.
ProgressBar	A box showing a progress bar.
RadioButton	A single clickable radio button. Can be paired with other radio buttons.
TextBox	A text area, which can accept input from the user.

**Table 15.4** Some types of `System.Windows.Forms.Control`.

`System.Windows.Forms.MessageBox` is used to have a simple but restrictive dialogue with the user, which is demonstrated in Listing 15.17 and Figure 15.13.

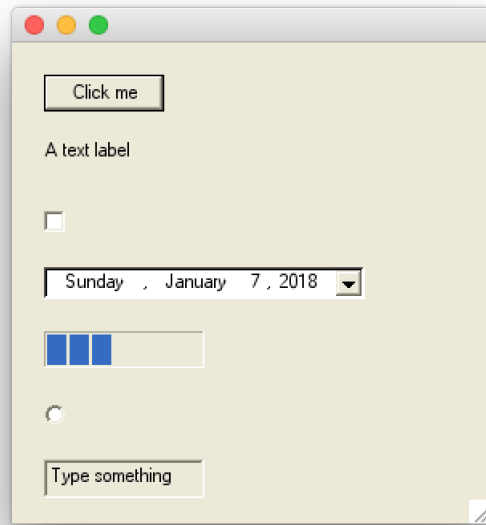
As an alternative to the YesNo response button, the message box also offers `AbortRetryIgnore`, `OK`, `OKCancel`, `RetryCancel`, and `YesNoCancel`. Note that all other windows of the process are blocked until the user closes the dialogue window.

With `System.Windows.Forms.OpenFileDialog`, you can ask the user to select an existing filename, as demonstrated in Listing 15.18 and Figure 15.14. Similarly to `OpenFileDialog`, `System.Windows.Forms.SaveFileDialog` asks for a file name, but if an existing file is selected, then the user will be asked to confirm the choice.

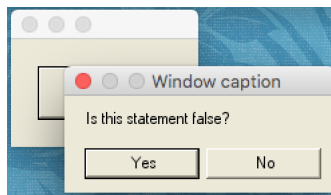
**Listing 15.16 winforms/controls.fsx:**

Examples of control elements added to a window form, see also Figure 15.12.

```
1 open System.Windows.Forms
2 open System.Drawing
3
4 let win = new Form () // Create a window
5 win.ClientSize <- Size (300, 300)
6
7 let button = new Button () // Make a button
8 win.Controls.Add button
9 button.Location <- new Point (20, 20)
10 button.Text <- "Click me"
11
12 let lbl = new Label () // Add a label
13 win.Controls.Add lbl
14 lbl.Location <- new Point (20, 60)
15 lbl.Text <- "A text label"
16
17 let chkbox = new CheckBox () // Add a check box
18 win.Controls.Add chkbox
19 chkbox.Location <- new Point (20, 100)
20
21 let pick = new DateTimePicker () // Add a date and time picker
22 win.Controls.Add pick
23 pick.Location <- new Point (20, 140)
24
25 let prgrss = new ProgressBar () // Show a progress bar
26 win.Controls.Add prgrss
27 prgrss.Location <- new Point (20, 180)
28 prgrss.Minimum <- 0
29 prgrss.Maximum <- 9
30 prgrss.Value <- 3
31
32 let rdbtn = new RadioButton () // Add a radio button
33 win.Controls.Add rdbtn
34 rdbtn.Location <- new Point (20, 220)
35
36 let txtbox = new TextBox () // Add a text input field
37 win.Controls.Add txtbox
38 txtbox.Location <- new Point (20, 260)
39 txtbox.Text <- "Type something"
40
41 Application.Run win // Show everything and start event-loop
```



**Fig. 15.12** Examples of control elements. See Listing 15.16.



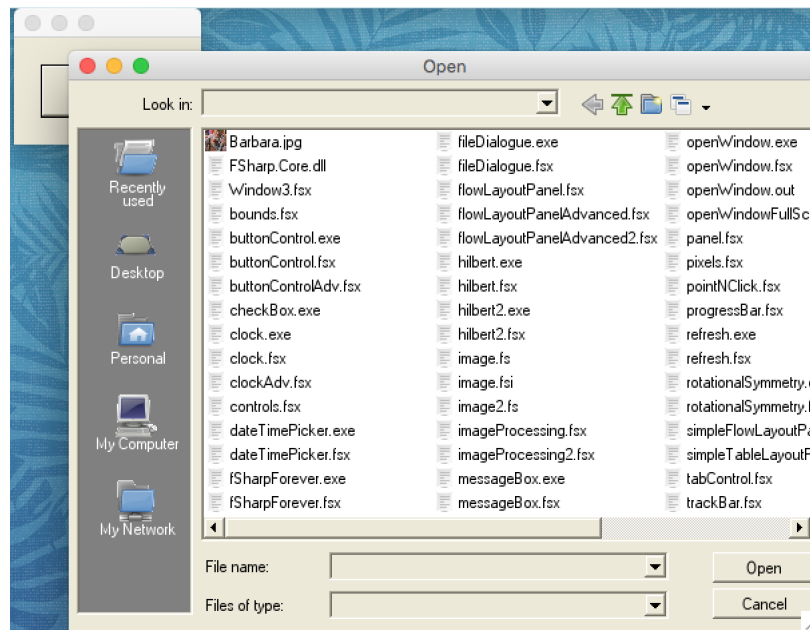
**Fig. 15.13** After pressing the “Click-me” button. See Listing 15.17.

**Listing 15.17 winforms/messageBox.fsx:**  
Create the MessageBox, see also Figure 15.13.

```
1 open System.Windows.Forms
2 open System.Drawing
3 open System
4
5 let win = new Form ()
6 win.ClientSize <- Size (140, 80)
7
8 let button = new Button ()
9 win.Controls.Add button
10 button.Size <- new Size (100, 40)
11 button.Location <- new Point (20, 20)
12 button.Text <- "Click me"
13 // Open a message box when button clicked
14 let buttonClicked (e : EventArgs) =
15     let question = "Is this statement false?"
16     let caption = "Window caption"
17     let boxType = MessageBoxButtons.YesNo
18     let response = MessageBox.Show (question, caption, boxType)
19     printfn "The user pressed %A" response
20 button.Click.Add buttonClicked
21
22 Application.Run win
```

**Listing 15.18 winforms/openFileDialog.fsx:**  
Create the OpenFileDialog, see also Figure 15.14.

```
1 open System.Windows.Forms
2 open System.Drawing
3 open System
4
5 let win = new Form ()
6 win.ClientSize <- Size (140, 80)
7
8 let button = new Button ()
9 win.Controls.Add button
10 button.Size <- new Size (100, 40)
11 button.Location <- new Point (20, 20)
12 button.Text <- "Click me"
13 // Open a message box when button clicked
14 let buttonClicked (e : EventArgs) =
15     let opendlg = new OpenFileDialog()
16     let okOrCancel = opendlg.ShowDialog()
17     printfn "The user pressed %A and selected %A" okOrCancel
18     opendlg.FileName
19 button.Click.Add buttonClicked
20
21 Application.Run win
```



**Fig. 15.14** Ask the user for a filename to read from. See Listing 15.18.

## 15.6 Organizing Controls

It is often useful to organize the controls in groups, and such groups are called *Panels* in WinForms. An example of creating a `System.Windows.Forms.Panel` that includes a `System.Windows.Forms.TextBox` and `System.Windows.Forms.Label` for getting user input is shown in Listing 15.19 and Figure 15.15. The label and

**Listing 15.19** winforms/panel.fsx:  
Create a panel, label, and text input controls.

```

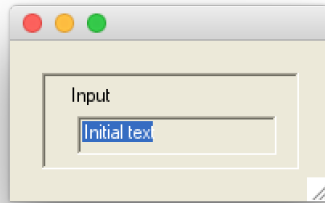
1  open System.Drawing
2  open System.Windows.Forms
3
4  let win = new Form () // Create a window form
5  win.ClientSize <- new Size (200, 100)
6
7  // Customize the Panel control
8  let panel = new Panel ()
9  panel.ClientSize <- new Size (160, 60)
10 panel.Location <- new Point (20,20)
11 panel.BorderStyle <- BorderStyle.Fixed3D
12 win.Controls.Add panel // Add panel to window
13
14 // Customize the Label and TextBox controls
15 let label = new Label ()
16 label.ClientSize <- new Size (120, 20)
17 label.Location <- new Point (15,5)
18 label.Text <- "Input"
19 panel.Controls.Add label // add label to panel
20
21 let textBox = new TextBox ()
22 textBox.ClientSize <- new Size (120, 20)
23 textBox.Location <- new Point (20,25)
24 textBox.Text <- "Initial text"
25 panel.Controls.Add textBox // add textbox to panel
26
27 Application.Run win // Start the event-loop

```

textbox are children of the panel, and the main advantage of using panels is that the coordinates of the children are relative to the top left corner of the panel. I.e., moving the panel will move the label and the textbox at the same time.

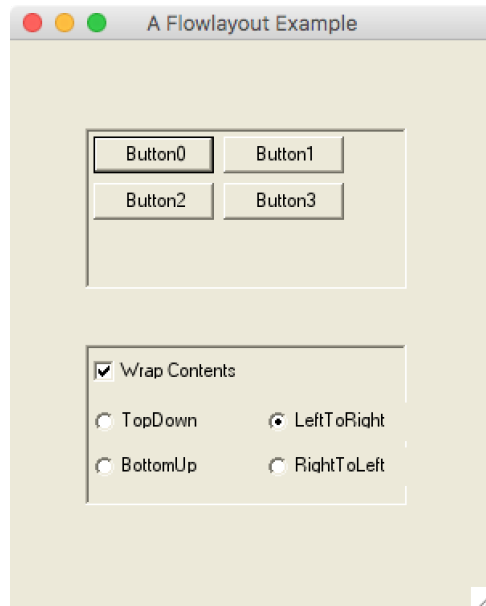
A very flexible panel is the `System.Windows.Forms.FlowLayoutPanel`, which arranges its objects according to the space available. This is useful for graphical user interfaces targeting varying device sizes, such as a computer monitor and a tablet, and it also allows the program to gracefully adapt when the user changes window size. A demonstration of `System.Windows.Forms.FlowLayoutPanel` together with `System.Windows.Forms.CheckBox` and `System.Windows.Forms.RadioButton` is given in Listing 15.20–15.21 and in Figure 15.16. The program illustrates how the button elements flow under four possible flow directions with `System.Windows.FlowDirection`,





**Fig. 15.15** A panel including a label and a text input field, see Listing 15.19.

and how `System.Windows.WrapContents` influences what happens to content that flows outside the panel's region. A walkthrough of the program is as follows. The



**Fig. 15.16** Demonstration of the `FlowLayoutPanel` panel, `CheckBox`, and `RadioButton` controls, see Listing 15.20–15.21.

goal is to make 2 areas, one giving the user control over display parameters, and another displaying the result of the user's choices. These are `FlowLayoutPanel` and `Panel`. In the `FlowLayoutPanel` there are four `Buttons` to be displayed in a region that is not tall enough for the buttons to be shown in vertical sequence and not wide enough to be shown in horizontal sequence. Thus the `FlowDirection` rules come into play, i.e., the buttons are added in sequence as they are named, and the default `FlowDirection.LeftToRight` arranges the `buttonList[0]` in the top left

**Listing 15.20 winforms/flowLayoutPanel.fsx:**  
**Create a FlowLayoutPanel with checkbox and radio buttons.**

```

1 open System.Windows.Forms
2 open System.Drawing
3
4 let flowLayoutPanel = new FlowLayoutPanel ()
5 let buttonLst =
6     [(new Button (), "Button0");
7      (new Button (), "Button1");
8      (new Button (), "Button2");
9      (new Button (), "Button3")]
10 let panel = new Panel ()
11 let wrapContentsCheckBox = new CheckBox ()
12 let initiallyWrapped = true
13 let radioButtonLst =
14     [(new RadioButton (), (3, 34), "TopDown",
15      FlowDirection.TopDown);
16      (new RadioButton (), (3, 62), "BottomUp",
17      FlowDirection.BottomUp);
18      (new RadioButton (), (111, 34), "LeftToRight",
19      FlowDirection.LeftToRight);
20      (new RadioButton (), (111, 62), "RightToLeft",
21      FlowDirection.RightToLeft)]
22
23 // customize buttons
24 for (btn, txt) in buttonLst do
25     btn.Text <- txt
26
27 // customize wrapContentsCheckBox
28 wrapContentsCheckBox.Location <- new Point (3, 3)
29 wrapContentsCheckBox.Text <- "Wrap Contents"
30 wrapContentsCheckBox.Checked <- initiallyWrapped
31 wrapContentsCheckBox.CheckedChanged.Add (fun _ ->
32     flowLayoutPanel.WrapContents <-
33     wrapContentsCheckBox.Checked)
34
35 // customize radio buttons
36 for (btn, loc, txt, dir) in radioButtonLst do
37     btn.Location <- new Point (fst loc, snd loc)
38     btn.Text <- txt
39     btn.Checked <- flowLayoutPanel.FlowDirection = dir
40     btn.CheckedChanged.Add (fun _ ->
41         flowLayoutPanel.FlowDirection <- dir)

```

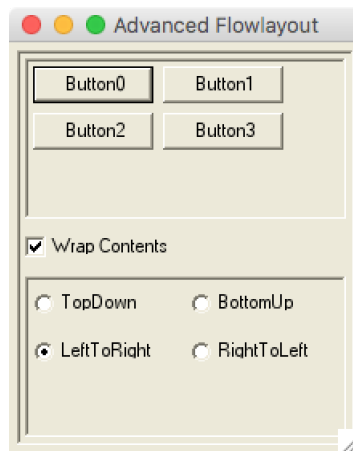
corner, and `buttonLst[1]` to its right. Other flow directions do it differently, and the reader is encouraged to experiment with the program.

The program in Listing 15.21 has not completely separated the semantic blocks of the interface and relies on explicit setting of coordinates of controls. This can be avoided by using nested panels. E.g., in Listing 15.22–15.23, the program has been rewritten as a nested set of `FlowLayoutPanel` in three groups: The button panel,

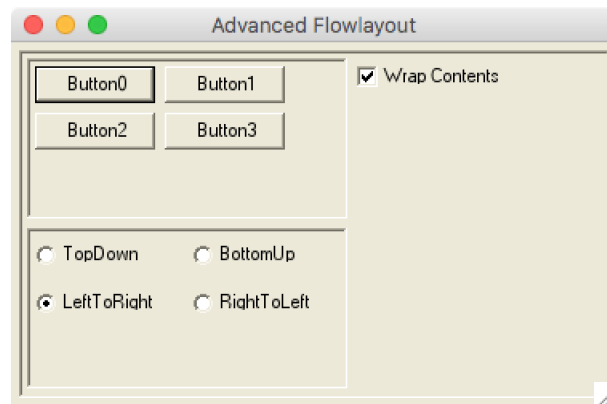
**Listing 15.21** winforms/flowLayoutPanel.fsx:  
Create a FlowLayoutPanel with checkbox and radio buttons. Continued from  
Listing 15.20.

```
36 // customize flowLayoutPanel
37 for (btn, txt) in buttonLst do
38     flowLayoutPanel.Controls.Add btn
39 flowLayoutPanel.Location <- new Point (47, 55)
40 flowLayoutPanel.BorderStyle <- BorderStyle.Fixed3D
41 flowLayoutPanel.WrapContents <- initiallyWrapped
42
43 // customize panel
44 panel.Controls.Add (wrapContentsCheckBox)
45 for (btn, loc, txt, dir) in radioButtonLst do
46     panel.Controls.Add (btn)
47 panel.Location <- new Point (47, 190)
48 panel.BorderStyle <- BorderStyle.Fixed3D
49
50 // Create a window, add controls, and start event-loop
51 let win = new Form ()
52 win.ClientSize <- new Size (302, 356)
53 win.Controls.Add flowLayoutPanel
54 win.Controls.Add panel
55 win.Text <- "A Flowlayout Example"
56 Application.Run win
```

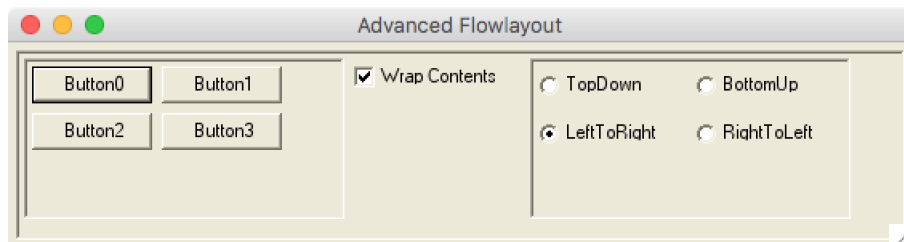
the checkbox, and the radio button panel. Adding a Resize event handler for the window to resize the outermost panel according to the outer window allows for the three groups to change position relative to each other. This results in three different views, all shown in Figure 15.17.



(a)



(b)



(c)

**Fig. 15.17** Nested `FlowLayoutPanel`, see Listing 15.22–15.23, allows for dynamic arrangement of content. Content flows when the window is resized.

**Listing 15.22 winforms/flowLayoutPanelAdvanced.fsx:  
Create nested FlowLayoutPanel.**

```

1 open System.Windows.Forms
2 open System.Drawing
3 open System
4
5 let win = new Form ()
6 let mainPanel = new FlowLayoutPanel ()
7 let mainPanelBorder = 5
8 let flowLayoutPanel = new FlowLayoutPanel ()
9 let buttonLst =
10     [(new Button (), "Button0");
11      (new Button (), "Button1");
12      (new Button (), "Button2");
13      (new Button (), "Button3")]
14 let wrapContentsCheckBox = new CheckBox ()
15 let panel = new FlowLayoutPanel ()
16 let initiallyWrapped = true
17 let radioButtonLst =
18     [(new RadioButton (), "TopDown", FlowDirection.TopDown);
19      (new RadioButton (), "BottomUp", FlowDirection.BottomUp);
20      (new RadioButton (), "LeftToRight",
21       FlowDirection.LeftToRight);
22      (new RadioButton (), "RightToLeft",
23       FlowDirection.RightToLeft)]
24
25 // customize buttons
26 for (btn, txt) in buttonLst do
27     btn.Text <- txt
28
29 // customize radio buttons
30 for (btn, txt, dir) in radioButtonLst do
31     btn.Text <- txt
32     btn.Checked <- flowLayoutPanel.FlowDirection = dir
33     btn.CheckedChanged.Add (fun _ ->
34         flowLayoutPanel.FlowDirection <- dir)
35
36 // customize flowLayoutPanel
37 for (btn, txt) in buttonLst do
38     flowLayoutPanel.Controls.Add btn
39 flowLayoutPanel.BorderStyle <- BorderStyle.Fixed3D
40 flowLayoutPanel.WrapContents <- initiallyWrapped
41
42 // customize wrapContentsCheckBox
43 wrapContentsCheckBox.Text <- "Wrap Contents"
44 wrapContentsCheckBox.Checked <- initiallyWrapped
45 wrapContentsCheckBox.CheckedChanged.Add (fun _ ->
46     flowLayoutPanel.WrapContents <-
47     wrapContentsCheckBox.Checked)

```

**Listing 15.23** winforms/flowLayoutPanelAdvanced.fsx:  
Create nested FlowLayoutPanel. Continued from Listing 15.22.

```
44 // customize panel
45 // changing border style changes ClientSize
46 panel.BorderStyle <- BorderStyle.Fixed3D
47 let width = panel.ClientSize.Width / 2 - panel.Margin.Left -
    panel.Margin.Right
48 for (btn, txt, dir) in radioButtonLst do
49     btn.Width <- width
50     panel.Controls.Add (btn)
51
52 mainPanel.Location <- new Point (mainPanelBorder,
    mainPanelBorder)
53 mainPanel.BorderStyle <- BorderStyle.Fixed3D
54 mainPanel.Controls.Add flowLayoutPanel
55 mainPanel.Controls.Add wrapContentsCheckBox
56 mainPanel.Controls.Add panel
57
58 // customize window, add controls, and start event-loop
59 win.ClientSize <- new Size (220, 256)
60 let windowResize _ =
61     let size = win.DisplayRectangle.Size
62     mainPanel.Size <- new Size (size.Width - 2 *
        mainPanelBorder, size.Height - 2 * mainPanelBorder)
63 windowResize ()
64 win.Resize.Add windowResize
65 win.Controls.Add mainPanel
66 win.Text <- "Advanced Flowlayout"
67 Application.Run win
```

## Chapter 16

# The Event-driven Programming Paradigm

In *event-driven programming*, the flow of the program is determined by *events*, such as the user moving the mouse, an alarm going off, a message arriving from another program, or an exception being thrown, and is very common for programs with extensive interaction with a user, such as a graphical user interface. The events are monitored by *listeners*, and the programmer can set *handlers* which are *call-back functions* to be executed when an event occurs. In event-driven programs, there is almost always a main loop to which the program relinquishes control to when all handlers have been set up. Event-driven programs can be difficult to test, since they often rely on difficult-to-automate mechanisms for triggering events, e.g., testing a graphical user interface often requires users to point-and-click, which is very slow compared to automatic unit testing.





## Chapter 17

### Assemblies

...

However, it is ill-advised to design programs to be run in an interactive session, ★  
since the scripts need to be manually copied every time it is to be run, and since  
the starting state may be unclear.

Both the interpreter and the compiler translates the source code into a format which can be executed by the computer. While the compiler performs this translation once and stores the result in the executable file, the interpreter translates the code every time the code is executed. Thus, to run the program again with the interpreter, it must be retranslated as "`fsharpi gettingStartedStump.fsx`". In contrast, compiled code does not need to be recompiled to be run again, only re-executed using "`mono gettingStartedStump.exe`". On a MacBook Pro, with a 2.9 GHz Intel Core i5, the time the various stages take for this script are:

Command	Time
<code>fsharpi gettingStartedStump.fsx</code>	1.88s
<code>fsharpc gettingStartedStump.fsx</code>	1.90s
<code>mono gettingStartedStump.exe</code>	0.05s

I.e., executing the script with `fsharpi` is slightly faster than by first compiling it with `fsharpc` and then executing the result with `mono` ( $1.88s < 0.05s + 1.90s$ ), if the script were to be executed only once, but every future execution of the script using the compiled version requires only the use of `mono`, which is much faster than `fsharpi` ( $1.88s \gg 0.05s$ ).

Finally, the file containing `gettingStartedStump.tex` may be compiled into an executable file with the program `fsharpc`, and run using the program `mono` from the console. This is demonstrated in Listing 17.1.

**Listing 17.1: Compiling and executing a script.**

```
1 $ fsharp gettingStartedStump.fsx
2 F# Compiler for F# 4.1 (Open Source Edition)
3 Freely distributed under the Apache 2.0 Open Source License
4 $ mono gettingStartedStump.exe
5 3
```

The compiler reads `gettingStartedStump.fsx` and makes `gettingStartedStump.exe`, which can be run using `mono`.

Executing programs with the interpreted directly from a file and compiling and executing the program is much preferred for programming complete programs, since the starting state is well defined, and since this better supports *unit testing*, which is

★ a method for debugging programs. Thus, **prefer compiling over interpretation**.

## Chapter 18

# Organising Code in Libraries and Application Programs

In this chapter, we will focus on a number of ways to make the code available as *library* functions in F#. A library is a collection of types, values, and functions that an application program can use. A library does not perform calculations on its own.

F# includes several programming structures to organize code in libraries: Modules, namespaces, and classes. In this chapter, we will describe modules and namespaces. Classes will be described in detail in Chapter 23.

### 18.1 Modules

An F# *module*, not to be confused with a Common Language Infrastructure module (see Appendix D), is a programming structure used to organize type declarations, values, functions, etc.

Every implementation and script file in F# implicitly defines a module, and the module name is given by the filename. Consider the script file `Meta.fsx` shown in Listing 18.1. Here, we have implicitly defined a module with the name `Meta`. Another

**Listing 18.1 Meta.fsx:**  
A script file defining the `apply` function.

```
1 type floatFunction = float -> float -> float
2 let apply (f : floatFunction) (x : float) (y : float) : float
   = f x y
```

script file may now use this function, which is accessed using the “.” notation, i.e., `Meta.apply` will refer to this function in other programs. An application program could be as the one shown in Listing 18.3. In the example above, we have explicitly

**Listing 18.2 MetaApp.fsx:**  
Defining a script calling the module.

```
1 let add : Meta.floatFunction = fun x y -> x + y
2 let result = Meta.apply add 3.0 4.0
3 printfn "3.0 + 4.0 = %A" result
```

- used the module's type definition for illustration purposes. A shorter and possibly simpler program would have been to define `add` as `let add x y = x + y`, since F#'s type system will infer the implied type. However, **explicit definitions of types is recommended for readability**. Hence, an alternative to the above example's use of anonymous functions is: `let add (x: float) (y: float) : float = x + y`. To compile the module and the application program, we write as demonstrated in Listing 18.3. Since the F# compiler reads through the files once, the order of the

**Listing 18.3: Compiling both the module and the application code. Note that file order matters when compiling several files.**

```
1 $ fsharp --nologo Meta.fsx MetaApp.fsx && mono MetaApp.exe
2 3.0 + 4.0 = 7.0
```

filenames in the compile command is very important. Hence, the script containing the module and function definitions must be to the left of the script containing their use. Notice also that if not otherwise specified, the F# compiler produces an `.exe` file derived from the last filename in the list of filenames.

We may also explicitly define the module name using the `module` with the following syntax,

**Listing 18.4: Outer module.**

```
1 module <ident>
2 <script>
```

Here, the identifier `<ident>` is a name not necessarily related to the filename, and the script `<script>` is an expression. An example is given in Listing 18.20. Since

**Listing 18.5 MetaExplicit.fsx:**  
Explicit definition of the outermost module.

```
1 module Meta
2 type floatFunction = float -> float -> float
3 let apply (f : floatFunction) (x : float) (y : float) : float
   = f x y
```

- we have created a new file, where the module `Meta` is explicitly defined, we can use the same application program. This is demonstrated in Listing 18.6. Since `MetaExplicit.fsx` explicitly defines the module name, `apply` is not available to an application program as `MetaExplicit.apply`. **It is recommended that module names are defined explicitly, since filenames may change due to external**

**Listing 18.6: Changing the module definition to explicit naming has no effect on the application nor the compile command.**

```
1 $ fsharp --nologo MetaExplicit.fsx MetaApp.fsx && mono
  MetaApp.exe
2 3.0 + 4.0 = 7.0
```

**conditions.** In other words, filenames are typically set from the perspective of the filesystem. The user may choose to change names to suit a filesystem structure, or different platforms may impose different file naming conventions. Thus, direct linking of filenames with the internal workings of a program is a needless complication of structure.

The definitions inside a module may be accessed directly from an application program, omitting the “.”-notation, by use of the [open](#) keyword,

**Listing 18.7: Open module.**

```
1 open <ident>
```

We can modify `MetaApp.fsx`, as shown in Listing 18.9. In this case, the namespace

**Listing 18.8 MetaAppWOpen.fsx:**  
Avoiding the “.”-notation by the [open](#) keyword.

```
1 open Meta
2 let add : floatFunction = fun x y -> x + y
3 let result = apply add 3.0 4.0
4 printfn "3.0 + 4.0 = %A" result
```

of our previously defined module is included into the scope of the application functions, and its types, values, functions, etc. can be used directly, as shown in Listing 18.9. The [open](#)-keyword should be used sparingly, since including a library’s

**Listing 18.9: How the application program opens the module has no effect on the module code nor compile command.**

```
1 $ fsharp --nologo MetaExplicit.fsx MetaAppWOpen.fsx && mono
  MetaAppWOpen.exe
2 3.0 + 4.0 = 7.0
```

definitions into the application scope can cause surprising naming conflicts, because the user of a library typically has no knowledge of the inner workings of the library. E.g., the user may accidentally use code defined in the library, but with different type and functionality than intended, which the type system will use to deduce types in the application program, and therefore will either give syntax or runtime errors that are difficult to understand. This problem is known as *namespace pollution*, and for clarity, **it is recommended to use the [open](#)-keyword sparingly**. Note that for historical reasons, the phrase ‘namespace pollution’ is used to cover pollution both due to modules and namespaces. ★

Modules may also be nested, in which case the nested definitions must use the “=”-sign and must be appropriately indented.

**Listing 18.10: Nested modules.**

```
1 module <ident> = <script>
```

In lightweight syntax, a newline may be entered before the script `<script>`, and the script must be indented. An example is shown in Listing 18.11. In this case, `Meta` and

**Listing 18.11 nestedModules.fsx:**

Modules may be nested.

```
1 module Utilities
2 let PI = 3.1415
3 module Meta =
4     type floatFunction = float -> float -> float
5     let apply (f : floatFunction) (x : float) (y : float) :
6         float = f x y
7 module MathFcts =
8     let add : Meta.floatFunction = fun x y -> x + y
```

`MathFcts` are defined at the same level and said to be siblings, while `Utilities` is defined at a higher level. In this relation, the former two are said to be the children of the latter. Note that the nesting respects the lexical scope rules, such that the constant `PI` is directly accessible in both modules `Meta` and `MathFcts`, as is the module `Meta` in `MathFcts`, but not `MathFcts` in `Meta`. The “.”-notation is reused to index deeper into the module hierarchy, as the example in Listing 18.12 shows. Modules can be

**Listing 18.12 nestedModulesApp.fsx:**

Applications using nested modules require additional usage of the “.” notation to navigate the nesting tree.

```
1
2 let add : Utilities.Meta.floatFunction = fun x y -> x + y
3 let result = Utilities.Meta.apply Utilities.MathFcts.add 3.0
4     Utilities.PI
5 printfn "3.0 + 4.0 = %A" result
```

recursive using the `rec`-keyword, meaning that in our example we can make the outer module recursive, as demonstrated in Listing 18.13. The consequence is that the modules `Meta` and `MathFcts` are accessible in both modules, but compilation will now give a warning since soundness of the code will first be checked at runtime. In general, it is advised to **avoid programming constructions whose validity cannot be checked at compile-time.**

★

**Listing 18.13 nestedRecModules.fsx:**

Mutual dependence on nested modules requires the `rec` keyword in the module definition.

```

1 module rec Utilities
2   module Meta =
3     type floatFunction = float -> float -> float
4     let apply (f : floatFunction) (x : float) (y : float) :
      float = f x y
5   module MathFcts =
6     let add : Meta.floatFunction = fun x y -> x + y

```

## 18.2 Namespaces

An alternative way to structure code in modules is to use a *namespace*, which can only hold modules and type declarations and only works in compiled mode. Namespaces are defined as explicitly defined outer modules, using the `namespace` keyword in accordance with the following syntax.

**Listing 18.14: Namespace.**

```

1 namespace <ident>
2 <script>

```

An example is given in Listing 18.15. Notice that when organizing code in a

**Listing 18.15 namespace.fsx:**

Defining a namespace is similar to explicitly named modules.

```

1 namespace Utilities
2 type floatFunction = float -> float -> float
3 module Meta =
4   let apply (f : floatFunction) (x : float) (y : float) :
      float = f x y

```

namespace, the first line of the file, other than comments and compiler directives, must be the one starting with `namespace`.

As for modules, the content of a namespace is accessed using the “.” notation, as demonstrated in Listing 18.16. Likewise, the compilation is performed in the same

**Listing 18.16 namespaceApp.fsx:**

The “.”-notation lets the application program access functions and types in a namespace.

```

1 let add : Utilities.floatFunction = fun x y -> x + y
2 let result = Utilities.Meta.apply add 3.0 4.0
3 printfn "3.0 + 4.0 = %A" result

```

way as for modules, see Listing 18.17. Hence, from an application point of view, it is

**Listing 18.17:** Compilation of files including namespace definitions uses the same procedure as modules.

```
1 $ fsharpc --nologo namespace.fsx namespaceApp.fsx && mono  
  namespaceApp.exe  
2 3.0 + 4.0 = 7.0
```

not immediately possible to see that `Utilities` is defined as a namespace and not a module. However, in contrast to modules, namespaces may span several files. E.g., we may add a third file extending the `Utilities` namespace with the `MathFcts` module, as demonstrated in Listing 18.18. To compile, we now need to include all three files

**Listing 18.18** `namespaceExtension.fsx`:  
Namespaces may span several files. Here is shown an extra file which extends the `Utilities` namespace.

```
1 namespace Utilities  
2 module MathFcts =  
3   let add : floatFunction = fun x y -> x + y
```

in the right order, see Listing 18.19. The order matters: `namespaceExtension.fsx`

**Listing 18.19:** Compilation of namespaces defined in several files requires careful consideration of order, since the compiler reads once and only once through the files in the order they are given.

```
1 $ fsharpc --nologo namespace.fsx namespaceExtension.fsx  
  namespaceApp.fsx && mono namespaceApp.exe  
2 3.0 + 4.0 = 7.0
```

uses the definition of `floatFunction` in the file `namespace.fsx`. You can use extensions to extend existing namespaces included with the F# compiler.

Namespaces may also be nested. In contrast to modules, nesting is defined using the “.” notation. That is, to create a child namespace more of `Utilities`, we must use initially write `namespace Utilities.more`. Indentation is ignored in the `namespace` line, thus left-most indentation is almost always used. Namespaces follow lexical scope rules, and identically to modules, namespaces containing mutually dependent children can be declared using the `rec` keyword, e.g., `namespace rec Utilities`.

### 18.3 Compiled Libraries

Libraries may be distributed in compiled form as `.dll` files. This saves the user from having to recompile a possibly large library every time library functions needs to be compiled with an application program. In order to produce a library file



from `MetaExplicit.fsx` and then compile an application program, we first use the compiler's `-a` option to produce the `.dll`. A demonstration is given in Listing 18.20. This produces the file `MetaExplicit.dll`, which may be linked to an application

**Listing 18.20:** A stand-alone `.dll` file is created and used with special compile commands.

```
1 $ fsharpc --nologo -a MetaExplicit.fsx
```

by using the `-r` option during compilation, see Listing 18.21. A library can be

**Listing 18.21:** The library is linked to an application during compilation to produce runnable code.

```
1 $ fsharpc --nologo -r MetaExplicit.dll MetaApp.fsx && mono
  MetaApp.exe
2 3.0 + 4.0 = 7.0
```

the result of compiling a number of files into a single `.dll` file. `.dll`-files may be loaded dynamically in script files (`.fsx`-files) by using the `#r` directive, as illustrated in Listing 18.22. We may now omit the explicit mentioning of the library when

**Listing 18.22** `MetaHashApp.fsx`:  
The `.dll` file may be loaded dynamically in `.fsx` script files and in interactive mode. Nevertheless, this usage is not recommended.

```
1 #r "MetaExplicit.dll"
2 let add : Meta.floatFunction = fun x y -> x + y
3 let result = Meta.apply add 3.0 4.0
4 printfn "3.0 + 4.0 = %A" result
```

compiling, as shown in Listing 18.23. The `#r` directive is also used to include a

**Listing 18.23:** When using the `#r` directive, then the `.dll` file need not be explicitly included in the list of files to be compiled.

```
1 $ fsharpc --nologo MetaHashApp.fsx && mono MetaHashApp.exe
2 3.0 + 4.0 = 7.0
```

library in interactive mode. However, for the code to be compiled, the use of the `#r` directive requires that the filesystem path to the library is coded inside the script. As for module names, direct linking of filenames with the internal workings of a program is a needless complication of structure, and **it is recommended not to rely** ★  
**on the use of the `#r` directive.**

In the above listings we have compiled *script files* into libraries. However, F# has reserved the `.fs` filename suffix for library files, and such files are called *implementation files*. In contrast to script files, implementation files do not support the `#r` directive. When compiling a list of implementation and script files, all but the last file must explicitly define a module or a namespace.

Both script and implementation files may be augmented with *signature files*. A signature file contains no implementation, only type definitions. Signature files offer three distinct features:

1. Signature files can be used as part of the documentation of code, since type information is of paramount importance for an application programmer to use a library.
2. Signature files may be written before the implementation file. This allows for a higher-level programming design that focuses on *which* functions should be included and *how* they can be composed.
3. Signature files allow for access control. Most importantly, if a type definition is not available in the signature file, then it is not available to the application program. Such definitions are private and can only be used internally in the library code. More fine-grained control related to classes is available and will be discussed in Chapter 23.

Signature files can be generated automatically using the `--sig:<filename>` compiler directive. To demonstrate this feature, we will first move the definition of `add` to the implementation file, see Listing 18.28. A signature file may be automatically

**Listing 18.24 MetaWAdd.fs:**  
An implementation file including the add function.

```
1 module Meta
2 type floatFunction = float -> float -> float
3 let apply (f : floatFunction) (x : float) (y : float) : float
  = f x y
4 let add (x : float) (y : float) : float = x + y
```

generated, as shown in Listing 18.25. The warning can safely be ignored, since at this

**Listing 18.25: Automatic generation of a signature file at compile time.**

```
1 $ fsharp --nologo --sig:MetaWAdd.fsi -a MetaWAdd.fs
```

point it is not our intention to produce runnable code. The above listing has generated the signature file in Listing 18.26. We can generate a library using the automatically

**Listing 18.26 MetaWAdd.fsi:**  
An automatically generated signature file from `MetaWAdd.fs`.

```
1 module Meta
2 type floatFunction = float -> float -> float
3 val apply : f:floatFunction -> x:float -> y:float -> float
4 val add : x:float -> y:float -> float
```

generated signature file by writing `fsharp -a MetaWAdd.fsi MetaWAdd.fs`, which is identical to compiling the `.dll` file without the signature file. However, if

we remove, e.g., the type definition for `add` in the signature file, then this function becomes private to the module and cannot be accessed outside. Hence, using the signature file in Listing 18.27, and recompiling the `.dll` with Listing 18.24 does not generate errors. However, when using the newly created `MetaWAdd.dll` with

**Listing 18.27 MetaWAddRemoved.fsi:**  
Removing the type definition for `add` from `MetaWAdd.fsi`.

```
1 module Meta
2 type floatFunction = float -> float -> float
3 val apply : f:floatFunction -> x:float -> y:float -> float
```

**Listing 18.28: Automatic generation of a signature file at compile time.**

```
1 $ fsharpc --nologo -a MetaWAdd.fsi MetaWAdd.fs
```

an application that does not itself supply a definition of `add`, we get a syntax error, since `add` now is inaccessible to the application program. This is demonstrated in Listing 18.29 and 18.30.

**Listing 18.29 MetaWOAddApp.fsx:**  
A version of Listing 18.3 without a definition of `add`.

```
1 let result = Meta.apply add 3.0 4.0
2 printfn "3.0 + 4.0 = %A" result
```

**Listing 18.30: Automatic generation of a signature file at compile time.**

```
1 $ fsharpc --nologo -r MetaWAdd.dll MetaWAddRemoved.fsi
   MetaWOAddApp.fsx
2
3 MetaWOAddApp.fsx(1,25): error FS0039: The value or
   constructor 'add' is not defined.
4
5 MetaWAddRemoved.fsi(1,1): error FS0240: The signature file
   'Meta' does not have a corresponding implementation file.
   If an implementation file exists then check the 'module'
   and 'namespace' declarations in the signature and
   implementation files match.
```

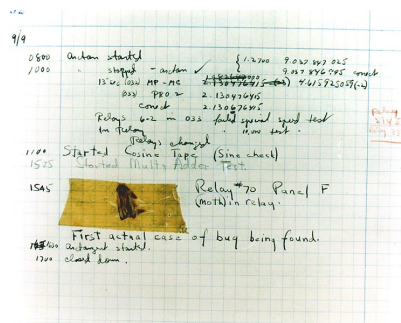
## 18.4 Debugging modules



## Chapter 19

### Testing Programs

A software bug is an error in a computer program that causes it to produce an incorrect result or behave in an unintended manner. The term 'bug' was used by Thomas Edison in 1878¹², but made popular in computer science by Grace Hopper, who found a moth interfering with the electronic circuits of the Harvard Mark II electromechanical computer and coined the term *bug* for errors in computer programs. The original bug is shown in Figure 19.1. Software is everywhere, and



**Fig. 19.1** The first computer bug, caught by Grace Hopper, U.S. Naval Historical Center Online Library Photograph NH 96566-KN.

errors therein have a huge economic impact on our society and can threaten lives³.

The ISO/IEC organizations have developed standards for software testing⁴. To illustrate basic concepts of software quality, consider a hypothetical route planning system. Essential factors of its quality are:

¹ [https://en.wikipedia.org/wiki/Software_bug](https://en.wikipedia.org/wiki/Software_bug)

² <http://edison.rutgers.edu/NamesSearch/DocImage.php3?DocId=LB003487>

³ [https://en.wikipedia.org/wiki/List_of_software_bugs](https://en.wikipedia.org/wiki/List_of_software_bugs)

⁴ ISO/IEC 9126, International standard for the evaluation of software quality, December 19, 1991, later replaced by ISO/IEC 25010:2011

**Functionality:** Does the software compile and run without internal errors. Does it solve the problem it was intended to solve? E.g., does the route planning software find a suitable route from point a to b?

**Reliability:** Does the software work reliably over time? E.g., does the route planning software work when there are internet dropouts?

**Usability:** Is the software easy and intuitive to use by humans? E.g., is it easy to enter addresses and alternative routes in the software's interface?

**Efficiency:** How many computer and human resources does the software require? E.g., does it take milliseconds or hours to find a requested route? Can the software run on a mobile platform with limited computer speed and memory?

**Maintainability:** In case of the discovery of new bugs, is it easy to test and correct the software? Is it easy to extend the software with new functionality? E.g., is it easy to update the map with updated roadmaps and new information? Can the system be improved to work both for car drivers and bicyclists?

**Portability:** Is it easy to port the software to new systems such as new server architecture and screen sizes? E.g., if the routing software originally was written for IOS devices, will it be easy to port to Android systems?

The above-mentioned concepts are ordered based on the requirements of the system. Functionality and reliability are perhaps the most important concepts, since if the software does not solve the specified problem, then the software design process has failed. However, many times the problem definition will evolve along with the software development process. But as a bare minimum, the software should run without internal errors and not crash under a well-defined set of circumstances. Furthermore, it is often the case that software designed for the general public requires a lot of attention to the usability of the software, since in many cases non-experts are expected to be able to use the software with little or no prior training. On the other hand, software used internally in companies will be used by a small number of people who become experts in using the software, and it is often less important that the software is easy to understand by non-experts. An example is text processing software like Microsoft Word versus Gnu Emacs and LaTeX. Word is designed to be used by non-experts for small documents such as letters and notes and relies heavily on interfacing with the system using click-interaction. On the other hand, Emacs and LaTeX are for experts for longer and professionally typeset documents and relies heavily on keyboard shortcuts and text-codes for typesetting document entities.

The purpose of *software testing* is to find bugs. When errors are found, then we engage in *debugging*, which is the process of diagnosing and correcting bugs. Once we have a failed software test, i.e., one that does not find any bugs, then we have strengthened our belief in the software, but it is important to note that software testing and debugging rarely removes all bugs, and with each correction or change

of software there is a fair risk new bugs being introduced. It is not exceptional that the testing-software is as large as the software being tested.

In this chapter, we will focus on two approaches to software testing which emphasize functionality: *white-box* and *black-box testing*. An important concept in this context is *unit testing*, where the program is considered in smaller pieces, called units, and for which accompanying programs for testing can be made which test these units automatically. Black-box testing considers the problem formulation and the program interface, and can typically be written early in the software design phase. In contrast, white-box testing considers the program text, and thus requires the program to be available. Thus, there is a tendency for black-box test programs to be more stable, while white-box testing typically is developed incrementally alongside the software development.

To illustrate software testing, we'll start with a problem:

**Problem 19.1**

iven any date in the Gregorian calendar, calculate the day of the week.

Facts about dates in the Gregorian calendar are:

- Combinations of dates and weekdays repeat themselves every 400 years.
- The typical length of the months January, February, . . . follow the knuckle rule, i.e., January belongs to the index knuckle, February to the space between the index and the middle finger, and August restarts or starts on the other hand. All knuckle months have 31 days, all spacing months have 30 days except February, which has 29 days on leap years and 28 days all other years.
- A leap year is a multiple of 4, except if it is also a multiple of 100 but not of 400.

Many solutions to the problem have been discovered, and here we will base our program on Gauss' method, which is based on integer division and calculates the weekday of the 1st of January of a given year. For any other date, we will count our way through the weeks from the previous 1st of January. The algorithm relies on an enumeration of weekdays starting with Sunday = 0, Monday = 1, . . . , and Saturday = 6. Our proposed solution is shown in Listing 19.1.

## 19.1 White-box Testing

*White-box testing* considers the text of a program. The degree to which the text of the program is covered in the test is called the *coverage*. Since our program is small,

**Listing 19.1 date2Day.fsx:**

A function that can calculate day-of-week from any date in the Gregorian calendar.

```

1 let januaryFirstDay (y : int) =
2     let a = (y - 1) % 4
3     let b = (y - 1) % 100
4     let c = (y - 1) % 400
5     (1 + 5 * a + 4 * b + 6 * c) % 7
6
7 let rec sum (lst : int list) j =
8     if 0 <= j && j < lst.Length then
9         lst[0] + sum lst[1..] (j - 1)
10    else
11        0
12
13 let date2Day d m y =
14     let dayPrefix =
15         ["Sun"; "Mon"; "Tues"; "Wednes"; "Thurs"; "Fri"; "Satur"]
16     let feb = if (y % 4 = 0) && ((y % 100 <> 0) || (y % 400 =
17         0)) then 29 else 28
18     let daysInMonth = [31; feb; 31; 30; 31; 30; 31; 31; 30; 31;
19         30; 31]
20     let dayOne = januaryFirstDay y
21     let daysSince = (sum daysInMonth (m - 2)) + d - 1
22     let weekday = (dayOne + daysSince) % 7;
23     dayPrefix[weekday] + "day"

```

we have the opportunity to ensure that all functions are called at least once, which is called *function coverage*, and we will also be able to test every branching in the program, which is called *branching coverage*. If both are fulfilled, we say that we have *statement coverage*. The procedure is as follows:

1. Decide which units to test: The program shown in Listing 19.1 has 3 functions, and we will consider these each as a unit, but we might as well just have chosen `date2Day` as a single unit. The important part is that the union of units must cover the whole program text, and since `date2Day` calls both `januaryFirstDay` and `sum`, designing test cases for the latter two is superfluous. However, we may have to do this anyway when debugging, and we may choose at a later point to use these functions separately, and in both cases, we will be able to reuse the testing of the smaller units.
2. Identify branching points: The function `januaryFirstDay` has no branching function, `sum` has one, and depending on the input values, two paths through the code may be used, and `date2Day` has one where the number of days in February is decided. Note that in order to test this, our test-date must be March 1 or later. In this example, there are only examples of *if*-branch points, but they may as well be loops and pattern matching expressions. In the Listing 19.2 it is shown that the branch points have been given a comment and a number.



**Listing 19.2 date2DayAnnotated.fsx:****In white-box testing, the branch points are identified.**

```

1 // Unit: januaryFirstDay
2 let januaryFirstDay (y : int) =
3     let a = (y - 1) % 4
4     let b = (y - 1) % 100
5     let c = (y - 1) % 400
6     (1 + 5 * a + 4 * b + 6 * c) % 7
7
8 // Unit: sum
9 let rec sum (lst : int list) j =
10     (* WB: 1 *)
11     if 0 <= j && j < lst.Length then
12         lst[0] + sum lst[1..] (j - 1)
13     else
14         0
15
16 // Unit: date2Day
17 let date2Day d m y =
18     let dayPrefix =
19         ["Sun"; "Mon"; "Tues"; "Wednes"; "Thurs"; "Fri";
20          "Satur"]
21     (* WB: 1 *)
22     let feb = if (y % 4 = 0) && ((y % 100 <> 0) || (y % 400
23                  = 0)) then 29 else 28
24     let daysInMonth = [31; feb; 31; 30; 31; 30; 31; 31; 30;
25                       31; 30; 31]
26     let dayOne = januaryFirstDay y
27     let daysSince = (sum daysInMonth (m - 2)) + d - 1
28     let weekday = (dayOne + daysSince) % 7;
29     dayPrefix[weekday] + "day"

```

3. For each unit, produce an input set that tests each branch: In our example, the branch points depend on a Boolean expression, and for good measure, we are going to test each term that can lead to branching. Using 't' and 'f' for **true** and **false**, we thus write as shown in Table 19.1. The impossible cases have been intentionally blank, e.g., it is not possible for  $j < 0$  and  $j > n$  for some positive value  $n$ .
4. Write a program that tests all these cases and checks the output, see Listing 19.3.

Notice that the output of the tests is organized such that they are enumerated per unit, hence we can rearrange as we like and still uniquely refer to a unit's test. Also, the output of the test program produces a list of tests that should return true or success or a similar positively loaded word, but without further or only little detail, such that we at a glance can identify any test that produced unexpected results.

Unit	Branch	Condition	Input	Expected output
januaryFirstDay	0	-	2016	5
sum	1	0 <= j && j < lst.Length		
	1a	t && t	[1; 2; 3] 1	3
	1b	f && t	[1; 2; 3] -1	0
	1c	t && f	[1; 2; 3] 10	0
	1d	f && f	-	-
date2Day	1	(y % 4 = 0) && ((y % 100 <> 0)    (y % 400 = 0))		
	-	t && (t    t)	-	-
	1a	t && (t    f)	8 9 2016	Thursday
	1b	t && (f    t)	8 9 2000	Friday
	1c	t && (f    f)	8 9 2100	Wednesday
	-	f && (t    t)	-	-
	1d	f && (t    f)	8 9 2015	Tuesday
	-	f && (f    t)	-	-
	-	f && (f    f)	-	-

**Table 19.1** Unit test

**Listing 19.3 date2DayWhiteTest.fsx:**

The tests identified by white-box analysis. The program from Listing 19.2 has been omitted for brevity.

```

1 printfn "White-box testing of date2Day.fsx"
2 printfn "  Unit: JanuaryFirstDay"
3 printfn "    Branch: 0 - %b" (JanuaryFirstDay 2016 = 5)
4
5 printfn "  Unit: sum"
6 printfn "    Branch: 1a - %b" (sum [1; 2; 3] 1 = 3)
7 printfn "    Branch: 1b - %b" (sum [1; 2; 3] -1 = 0)
8 printfn "    Branch: 1c - %b" (sum [1; 2; 3] 10 = 0)
9
10 printfn "  Unit: date2Day"
11 printfn "    Branch: 1a - %b" (date2Day 8 9 2016 =
    "Thursday")
12 printfn "    Branch: 1b - %b" (date2Day 8 9 2000 =
    "Friday")
13 printfn "    Branch: 1c - %b" (date2Day 8 9 2100 =
    "Wednesday")
14 printfn "    Branch: 1d - %b" (date2Day 8 9 2015 =
    "Tuesday")

```

---

```

1 $ dotnet fsi date2DayWhiteTest.fsx
2 White-box testing of date2Day.fsx
3   Unit: JanuaryFirstDay
4     Branch: 0 - true
5   Unit: sum
6     Branch: 1a - true
7     Branch: 1b - true
8     Branch: 1c - true
9   Unit: date2Day
10    Branch: 1a - true
11    Branch: 1b - true
12    Branch: 1c - true
13    Branch: 1d - true

```

After the white-box testing has failed to find errors in the program, we have some confidence in the program, since we have run every line at least once. It is, however, in no way a guarantee that the program is error free, which is why white-box testing is often accompanied with black-box testing to be described next.

## 19.2 Black-box Testing

In black-box testing, the program is considered a black box, and no knowledge is required about how a particular problem is solved. In fact, it is often useful not to have that knowledge at all. It is rarely possible to test all input to a program, so in black-box testing, the solution is tested for typical and extreme cases based on knowledge of the problem. The procedure is as follows:

1. Decide on the interface to use: It is useful to have an agreement with the software developers about what interface is to be used, e.g., in our case, the software developer has made a function `date2Day d m y` where `d`, `m`, and `y` are integers specifying the day, month, and year.
2. Make an overall description of the tests to be performed and their purpose:
  - 1 a consecutive week, to ensure that all weekdays are properly returned
  - 2 two set of consecutive days across boundaries that may cause problems: across a new year, and across a regular month boundary.
  - 3 a set of consecutive days across February-March boundaries for a leap and non-leap year
  - 4 four dates after February in a non-leap year, a non-multiple-of-100 leap year, a multiple-of-100-but-not-of-400 non-leap year, and a multiple-of-400 leap year.

Given no information about the program's text, there are other dates that one could consider as likely candidates for errors, but the above is judged to be a fair coverage.

3. Choose a specific set of input and expected output relations on the tabular form as shown in Table 19.2.
4. Write a program executing the tests, as shown in Listing 19.4 and 19.5. Notice

Test number	Input	Expected output
1a	1 1 2016	Friday
1b	2 1 2016	Saturday
1c	3 1 2016	Sunday
1d	4 1 2016	Monday
1e	5 1 2016	Tuesday
1f	6 1 2016	Wednesday
1g	7 1 2016	Thursday
2a	31 12 2014	Wednesday
2b	1 1 2015	Thursday
2c	30 9 2017	Saturday
2d	1 10 2017	Sunday
3a	28 2 2016	Sunday
3b	29 2 2016	Monday
3c	1 3 2016	Tuesday
3d	28 2 2017	Tuesday
3e	1 3 2017	Wednesday
4a	1 3 2015	Sunday
4b	1 3 2012	Thursday
4c	1 3 2000	Wednesday
4d	1 3 2100	Monday

**Table 19.2** Black-box testing

how the program has been made such that it is almost a direct copy of the table produced in the previous step.

A black-box test is a statement of what a solution should fulfill for a given problem. Hence, **it is a good idea to make a black-box test early in the software design phase, in order to clarify the requirements for the code to be developed and take an outside view of the code prior to developing it.** ★

After the black-box testing has failed to find errors in the program, we have some confidence in the program, since, from a user's perspective, the program produces sensible output in many cases. It is, however, in no way a guarantee that the program is error free.

## 19.3 Debugging by Tracing

Once an error has been found by testing, the *debugging* phase starts. The cause of a bug can either be that the chosen algorithm is the wrong one for the job, or the implementation of it has an error. In the debugging process, we have to keep an open mind and not rely on assumptions. A frequent source of errors is that the state of a program is different than expected, e.g., because the calculation performed is different than intended, or that the return of a library function is different than

**Listing 19.4 date2DayBlackTest.fsx:**

The tests identified by black-box analysis. The program from Listing 19.2 has been omitted for brevity.

```

28 let testCases = [
29     ("A complete week",
30      [(1, 1, 2016, "Friday");
31       (2, 1, 2016, "Saturday");
32       (3, 1, 2016, "Sunday");
33       (4, 1, 2016, "Monday");
34       (5, 1, 2016, "Tuesday");
35       (6, 1, 2016, "Wednesday");
36       (7, 1, 2016, "Thursday");]);
37     ("Across boundaries",
38      [(31, 12, 2014, "Wednesday");
39       (1, 1, 2015, "Thursday");
40       (30, 9, 2017, "Saturday");
41       (1, 10, 2017, "Sunday")]);
42     ("Across February boundary",
43      [(28, 2, 2016, "Sunday");
44       (29, 2, 2016, "Monday");
45       (1, 3, 2016, "Tuesday");
46       (28, 2, 2017, "Tuesday");
47       (1, 3, 2017, "Wednesday")]);
48     ("Leap years",
49      [(1, 3, 2015, "Sunday");
50       (1, 3, 2012, "Thursday");
51       (1, 3, 2000, "Wednesday");
52       (1, 3, 2100, "Monday")]);
53 ]
54
55 printfn "Black-box testing of date2Day.fsx"
56 for i = 0 to testCases.Length - 1 do
57     let (setName, testSet) = testCases[i]
58     printfn "    %d. %s" (i+1) setName
59     for j = 0 to testSet.Length - 1 do
60         let (d, m, y, expected) = testSet[j]
61         let day = date2Day d m y
62         printfn "        test %d - %b" (j+1) (day = expected)

```

**Listing 19.5: Output from Listing 19.4.**

```
1 $ dotnet fsi date2DayBlackTest.fsx
2 Black-box testing of date2Day.fsx
3   1. A complete week
4     test 1 - true
5     test 2 - true
6     test 3 - true
7     test 4 - true
8     test 5 - true
9     test 6 - true
10    test 7 - true
11   2. Across boundaries
12     test 1 - true
13     test 2 - true
14     test 3 - true
15     test 4 - true
16   3. Across Feburary boundary
17     test 1 - true
18     test 2 - true
19     test 3 - true
20     test 4 - true
21     test 5 - true
22   4. Leap years
23     test 1 - true
24     test 2 - true
25     test 3 - true
26     test 4 - true
```

introduce *Trace by hand* as a technique to simulate the execution of a program by hand. In the following section, tracing will refer to the Trace by hand method.

To understand the method of Tracing by hand, we will consider 3 imperative programs of gradually increasing complexity: a program using function call, a program including a `for`-loop, and a program with dynamic scope. In Section 8.4 we give a fourth example using recursion, a concept to be introduced in Chapter 8.

Tracing may seem tedious in the beginning, but in conjunction with strategically placed debugging `printfn` statements, it is a very valuable tool for debugging.

### 19.3.1 Tracing Function Calls

Consider the program in Listing 19.6. The program calls `testScope 2.0`, and by

**Listing 19.6** `lexicalScopeTracing.fsx`:  
Example of lexical scope and closure environment.

```
1 let testScope x =  
2   let a = 3.0  
3   let f z = a * z  
4   let a = 4.0  
5   f x  
6 printfn "%A" (testScope 2.0)  
  
1 $ dotnet fsi lexicalScopeTracing.fsx  
2 6.0
```

running the program, we see that the return-value is `6.0` and not `8.0`, as we had expected. Hence, we will use tracing to understand the result.

Tracing a program by hand means that we simulate its execution and, as part of that, keep track of the bindings, assignments closures, scopes, and input and output of the program. To do this, we need to consider the concept of *environments*.

Environments describe bindings available to the program at the present scope and at a particular time and place in the code. There is always an outer environment, called  $E_0$ , and each time we call a function or create a scope, we create a new environment. Only one environment can be active at a time, and it is updated as we simulate the execution of code with new bindings and temporary evaluations of expressions. Once a scope is closed, then its environment is deleted and a return-value is transported to its enclosing environment. In tracing, we note return-values explicitly. Likewise, output from, e.g., `printfn` is reported with a special notation.



To trace code, we make a table with 4 columns: Step, Line, Environment, and Bindings and evaluations. The Step column enumerates the steps performed. The Line column contains the program-line treated in a step *where* the present environment is updated. The Environment contains the name of the present environment, and Bindings ... shows *what* in the environment is updated.

The code in Listing 19.6 contains a function definition and a call, hence, the first lines of our table looks like,

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	testScope = ((x), testScope-body, ())
2	6	$E_0$	testScope 2.0 = ?

The elements of the table is to be understood as follows. Step 0 initializes the outer environment. In order for us to remember that the environment is empty, we write the unit value “()”. Reading the code from top to bottom, the first nonempty and non-comment line we meet is line 1, hence, in Step 1, we update the environment with the binding of a function to the name testScope. Since functions are values in F#, we note their bindings by their closures: a tuple of argument names, the function-body, and the values lexically available at the place of binding. See Section 4.2 for more information on closures. Following the function-binding, the printfn statement is called in line 6 to print the result testScope 2.0. However, before we can produce any output, we must first evaluate testScope 2.0. Since we do not yet know what this function evaluates to, in Step 2 we simply write the call with a question mark. The call causes the creation of a new environment, and we continue our table as follows,

Step	Line	Env.	Bindings and evaluations
3	1	$E_1$	((x = 2.0), testScope-body, ())

This means that we are going to execute the code in testScope-body. The function was called with 2.0 as argument, causing  $x = 2.0$ . Hence, the only binding available at the start of this environment is to the name x. In the testScope-body, we make 3 further bindings and a function call. First to a, then to f, then to another a, which will overshadow the previous binding, and finally we call f. Thus, our table is updated as follows,

Step	Line	Env.	Bindings and evaluations
4	2	$E_1$	a = 3.0
5	3	$E_1$	f = ((z), a * z, (a = 3.0, x = 2.0))
6	4	$E_1$	a = 4.0
7	5	$E_1$	f x = ?

Note that by lexical scope, the closure of f includes everything above its binding in  $E_1$ , and therefore we add  $a = 3.0$  and  $x = 2.0$  to the environment element in its

closure. This has consequences for the following call to `f` in line 5, which creates a new environment based on `f`'s closure and the value of its arguments. The value of `x` in Step 7 is found by looking in the previous steps for the last binding to the name `x` in  $E_1$ , which occurs in Step 3. Note that the binding to a name `x` in Step 5 is an internal binding in the closure of `f` and is irrelevant here. Hence, we continue the table as,

Step	Line	Env.	Bindings and evaluations
8	3	$E_2$	$((z = 2.0), a * z, (a = 3.0, x = 2.0))$

Executing the body of `f`, we initially have 3 bindings available: `z = 2.0`, `a = 3.0`, and `x = 2.0`. Thus, to evaluate the expression `a * z`, we use these bindings and write,

Step	Line	Env.	Bindings and evaluations
9	3	$E_2$	<code>a * z = 6.0</code>
10	3	$E_2$	<code>return = 6.0</code>

The 'return'-word is used to remind us that this is the value to replace the question mark with in Step 7. Here we will make a mental note and not physically replace the question mark with the calculated value. If you are ever in doubt which call is connected with which return value, seek upwards in the table from the return statement for the first question mark. Now we delete  $E_2$  and return to the enclosing environment,  $E_1$ . Here the function call was the last expression, hence the return-value from `testScope` will be equal to the return-value from `f`, and we write,

Step	Line	Env.	Bindings and evaluations
11	3	$E_1$	<code>return = 6.0</code>

Similarly, we delete  $E_1$  and return to the question mark in Step 2, which is replaced by the value 6.0. We can now finish the `printfn` statement and produce the output,

Step	Line	Env.	Bindings and evaluations
12	6	$E_0$	<code>output = "6.0\n"</code>

The return-value of a `printfn` statement is `()`, and since this line is the last of our program, we return `()` and end the program:

Step	Line	Env.	Bindings and evaluations
13	6	$E_0$	<code>return = ()</code>

The full table is shown for completeness in Table 19.3. Hence, we conclude that the program outputs the value 6.0, since the function `f` uses the first binding of

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	testScope = ((x), testScope-body, ())
2	6	$E_0$	testScope 2.0 = ?
3	1	$E_1$	((x = 2.0), testScope-body, ())
4	2	$E_1$	a = 3.0
5	3	$E_1$	f = ((z), a * z, (a = 3.0, x = 2.0))
6	4	$E_1$	a = 4.0
7	5	$E_1$	f x = ?
8	3	$E_2$	((z = 2.0), a * z, (a = 3.0, x = 2.0))
9	3	$E_2$	a * z = 6.0
10	3	$E_2$	return = 6.0
11	3	$E_1$	return = 6.0
12	6	$E_0$	output = "6.0\n"
13	6	$E_0$	return = ()

**Table 19.3** The complete table produced while tracing the program in Listing 19.6 by hand.

a = 3.0, and this is because the binding of f to the expression a * z creates a closure with a lexical scope. Thus, in spite that there is an overshadowing value of a, when f is called, this binding is ignored in the body of f. To correct this, we update the code as shown in Listing 19.7.

#### Listing 19.7 lexicalScopeTracingCorrected.fsx:

Tracing the code in Listing 19.6 by hand produced the table in Table 19.3, and to get the desired output, we correct the code as shown here.

```

1 let testScope x =
2     let a = 4.0
3     let f z = a * z
4     f x
5 printfn "%A" (testScope 2.0)
-----
1 $ dotnet fsi lexicalScopeTracingCorrected.fsx
2 8.0

```

## 19.3.2 Tracing Loops

Consider the program in Listing 19.8. The program includes a function for printing the sequence of the first  $N$  squares of integers. It uses a `for`-loop with a counting value. F# creates a new environment each time the loop body is executed. Thus, to trace this program, we mentally *unfold* the loop as shown in Listing 19.9. The unfolding contains 3 new scopes lines 3–7, lines 8–12, and lines 13–17 corresponding to the 3 times, the loop is repeated, and each scope starts by binding the counting value to the name `i`.

**Listing 19.8 printSquares.fsx:**

Print the squares of a sequence of positive integers.

```
1 let N = 3
2 let printSquares n =
3     for i = 1 to n do
4         let p = i * i
5         printfn "%d: %d" i p
6
7 printSquares N
```

---

```
1 $ fsharp --nologo printSquares.fsx && mono printSquares.exe
2 1: 1
3 2: 4
4 3: 9
```

**Listing 19.9 printSquaresUnfold.fsx:**

An unfolded version of Listing 19.8.

```
1 let N = 3
2 let printSquaresUnfold n =
3     (
4         let i = 1
5         let p = i * i
6         printfn "%d: %d" i p
7     )
8     (
9         let i = 2
10        let p = i * i
11        printfn "%d: %d" i p
12    )
13    (
14        let i = 3
15        let p = i * i
16        printfn "%d: %d" i p
17    )
18
19 printSquaresUnfold N
```

---

```
1 $ fsharp --nologo printSquaresUnfold.fsx && mono
   printSquaresUnfold.exe
2 1: 1
3 2: 4
4 3: 9
```

In the rest of this section, we will refer to the code in Listing 19.8. The first rows in our tracing-table looks as follows:

Step	Line	Env.	Bindings and evaluations
0	-	$E_0$	()
1	1	$E_0$	$N = 3$
2	2	$E_0$	$\text{printSquares} = ((n), \text{printSquares-body}, (N = 3))$
3	7	$E_0$	$\text{printSquares } N = ?$

Note that due to the lexical scope rule, the closure of `printSquares` includes `N` in its environment element. Calling `printSquares N` causes the creation of a new environment,

Step	Line	Env.	Bindings and evaluations
4	2	$E_1$	$((n = 3), \text{printSquares-body}, (N = 3))$

The first statement of `printSquares-body` is the `for`-loop. As our unfolding in Listing 19.9 demonstrated, each time the loop-body is executed, a new scope is created with a new binding to `i`. Reusing the notation from closures, we write

Step	Line	Env.	Bindings and evaluations
5	3	$E_1$	$\text{for } \dots = ?$

and create a new environment as if it had been a function,

Step	Line	Env.	Bindings and evaluations
6	3	$E_2$	$((i = 1), \text{for-body}, (n = 3, N = 3))$

As for functions, this denotes the bindings available at beginning of the execution of the `for`-body. The first line in the `for`-body is the binding of the value of an expression to `p`. The expression is `i*i`, and to calculate its value, we look in the `for`-loop's pseudo-closure where we find the  $i = 1$  binding. Hence,

Step	Line	Env.	Bindings and evaluations
7	4	$E_2$	$i * i = 1$
8	4	$E_2$	$p = 1$

The final step in the `for`-body is the `println`-statement. Its arguments we get from the updated, active environment  $E_2$  and write,

Step	Line	Env.	Bindings and evaluations
9	5	$E_2$	$\text{output} = "1 : 1 \backslash n"$

At this point, the `for`-loop has reached its last line,  $E_2$  is deleted, we create a new environment with the counter variable increased by 1, and repeat. Hence,

Step	Line	Env.	Bindings and evaluations
10	3	$E_3$	$((i = 2), \text{for-body}, (n = 3, N = 3))$
11	4	$E_3$	$i * i = 4$
12	4	$E_3$	$p = 4$
13	5	$E_3$	output = "2 : 4\n"

Again, we delete  $E_3$ , create  $E_4$  where  $i$  is incremented, and repeat,

Step	Line	Env.	Bindings and evaluations
14	3	$E_4$	$((i = 3), \text{for-body}, (n = 3, N = 3))$
15	4	$E_4$	$i * i = 9$
16	4	$E_4$	$p = 9$
17	5	$E_4$	output = "3 : 9\n"

Finally, incrementing  $i$  would mean that  $i > n$ , hence the **for**-loop ends and as all statements returns ()

Step	Line	Env.	Bindings and evaluations
18	3	$E_4$	return = ()

At this point, the environment  $E_4$  is deleted, and we return to the enclosing environment  $E_1$  and the statement or expression following Step 5. Since the **for**-loop is the last expression in the **printSquares** function, its return value is that of the **for**-loop,

Step	Line	Env.	Bindings and evaluations
19	3	$E_1$	return = ()

Returning to Step 3 and environment  $E_0$ , we have now calculated the return-value of **printSquares**  $N$  to be (), and since this line is the last of our program, we return () and end the program:

Step	Line	Env.	Bindings and evaluations
20	3	$E_0$	return = ()

### 19.3.3 Tracing Mutable Values

For mutable bindings, the scope is dynamic. For this, we need the concept of storage. Consider the program in Listing 19.10. To trace the dynamic behavior of this program, we add a second table to our hand tracing, which is initially empty and has the columns Step and Value to hold the Step number when the value was updated and the value stored. For Listing 19.10, the firsts 4 steps thus look like,

**Listing 19.10 dynamicScopeTracing.fsx:**  
**Example of lexical scope and closure environment.**

```

1 let testScope x =
2   let mutable a = 3.0
3   let f z = a * z
4   a <- 4.0
5   f x
6 printfn "%A" (testScope 2.0)

```

---

```

1 $ fsharp --nologo dynamicScopeTracing.fsx && mono
  dynamicScopeTracing.exe
2 8.0

```

Step	Line	Env.	Bindings and evaluations	Step	Value
0	-	$E_0$	()	0	-
1	1	$E_0$	testScope = ((x), body, ())		
2	6	$E_0$	testScope 2.0 = ?		
3	1	$E_1$	((x = 2.0), body, ())		

The mutable binding in line 2 creates an internal name and a dynamic storage location. The name *a* will be bound to a reference value, which we call  $\alpha_1$ , and which is a unique name shared between the two tables:

Step	Line	Env.	Bindings and evaluations	Step	Value
4	2	$E_1$	$a = \alpha_1$	4	$\alpha_1 = 3.0$

The following closure of *f* uses the reference-name instead of its value,

Step	Line	Env.	Bindings and evaluations	Step	Value
5	3	$E_1$	$f = ((z), a * z, (x = 2.0, a = \alpha_1))$	4	$\alpha_1 = 3.0$

In line 4, the value in the storage is updated by the assignment operator, which we denote as,

Step	Line	Env.	Bindings and evaluations	Step	Value
6	4	$E_1$	$a <- 4.0$	6	$\alpha_1 = 4.0$

Hence, when we evaluate the function *f*, its closure looks up the value of *a* by following the reference and finding the new value:

Step	Line	Env.	Bindings and evaluations	Step	Value
7	5	$E_1$	$f\ x = ?$	6	$\alpha_1 = 4.0$
8	5	$E_2$	$((z = 2.0), a * z, (x = 2.0, a = \alpha_1))$		
9	5	$E_2$	$a * z = 8.0$		
10	5	$E_2$	return = 8.0		
10	5	$E_1$	return = 8.0		
11	6	$E_0$	output = "8.0\n"		
12	6	$E_0$	return = ()		

For reference, the complete pair of tables is shown in Table 19.4. By comparing this

Step	Line	Env.	Bindings and evaluations	Step	Value
0	-	$E_0$	()	0	-
1	1	$E_0$	testScope = ((x), body, ())	4	$\alpha_1 = 3.0$
2	6	$E_0$	testScope 2.0 = ?	6	$\alpha_1 = 4.0$
3	1	$E_1$	((x = 2.0), body, ())		
4	2	$E_1$	$a = \alpha_1$		
5	3	$E_1$	$f = ((z), a * z, (x = 2.0, a = \alpha_1))$		
6	4	$E_1$	$a <- 4.0$		
7	5	$E_1$	$f\ x = ?$		
8	5	$E_2$	$((z = 2.0), a * z, (x = 2.0, a = \alpha_1))$		
9	5	$E_2$	$a * z = 8.0$		
10	5	$E_2$	return = 8.0		
10	5	$E_1$	return = 8.0		
11	6	$E_0$	output = "8.0\n"		
12	6	$E_0$	return = ()		

**Table 19.4** The complete table produced while tracing the program in Listing 19.10 by hand.

to the value-bindings in Listing 19.6, we see that the mutable values give rise to a different result due to the difference between lexical and dynamic scope.



## Chapter 20

### Mutable values

#### 20.1 Variables

Identifiers may be mutable, which means that it may be rebound to a new value. Mutable identifiers are specified using the *mutable* keyword with the following syntax:

**Listing 20.1:** Syntax for defining mutable values with an initial value.

```
1 let mutable <ident> = <expr> [in <expr>]
```

Changing the value of an identifier is called *assignment* and is done using the “<-” lexeme. Assignments have the following syntax:

**Listing 20.2:** Value reassignment for mutable variables.

```
1 <ident> <- <ident>
```

*Mutable values* is synonymous with the term *variable*. A variable is an area in the computer’s working memory associated with an identifier and a type, and this area may be read from and written to during program execution, see Listing 20.3 for an example. Here, an area in memory was denoted *x*, initially assigned the integer value 5, hence the type was inferred to be *int*. Later, this value of *x* was replaced with another integer using the “<-” lexeme. The “<-” lexeme is used to distinguish the assignment from the comparison operator. For example, the statement *a = 3* in Listing 20.4 is not an assignment but a comparison which is evaluated to be false. However, it is important to note that when the variable is initially defined, then the “=” operator must be used, while later reassignments must use the “<-” expression.

Assignment type mismatches will result in an error, as demonstrated in Listing 20.5. I.e., once the type of an identifier has been declared or inferred, it cannot be changed.

**Listing 20.3** mutableAssignReassingShort.fsx:

A variable is defined and later reassigned a new value.

```

1 let mutable x = 5
2 printfn "%d" x
3 x <- -3
4 printfn "%d" x

```

---

```

1 $ fsharp --nologo mutableAssignReassingShort.fsx && mono
   mutableAssignReassingShort.exe
2 5
3 -3

```

**Listing 20.4:** It is a common error to mistake “=” and “<-” lexemes for mutable variables.

```

1
2 > let mutable a = 0
3 a = 3;;
4 val mutable a: int = 0
5 val it: bool = false

```

**Listing 20.5** mutableAssignReassingTypeError.fsx:

Assignment type mismatching causes a compile-time error.

```

1 let mutable x = 5
2 printfn "%d" x
3 x <- -3.0
4 printfn "%d" x

```

---

```

1 $ fsharp --nologo mutableAssignReassingTypeError.fsx && mono
   mutableAssignReassingTypeError.exe
2
3 mutableAssignReassingTypeError.fsx(3,6): error FS0001: This
   expression was expected to have type
4     'int'
5 but here has type
6     'float'

```

A typical variable is a counter of type integer, and a typical use of counters is to increment them, see Listing 20.6 for an example. Using variables in expressions, as opposed to the left-hand-side of an assignment operation, reads the value of the variable. Thus, when using a variable as the return value of a function, then the value is copied from the local scope of the function to the scope from which it is called. This is demonstrated in Listing 20.7. In the example we see that the type is a value, and not mutable.

Variables implement dynamic scope, that is, the value of an identifier depends on *when* it is used. This is in contrast to lexical scope, where the value of an identifier

**Listing 20.6 mutableAssignIncrement.fsx:**  
Variable increment is a common use of variables.

```

1 let mutable x = 5 // Declare a variable x and assign the
    value 5 to it
2 printfn "%d" x
3 x <- x + 1 // Increment the value of x
4 printfn "%d" x

```

---

```

1 $ fsharpc --nologo mutableAssignIncrement.fsx && mono
    mutableAssignIncrement.exe
2 5
3 6

```

**Listing 20.7: Returning a mutable variable returns its value.**

```

1 > let g () =
2     let mutable y = 0
3     y
4 printfn "%d" (g ());;
5 0
6 val g: unit -> int
7 val it: unit = ()

```

depends on *where* it is defined. As an example, consider the script in Listing 4.16 which defines a function using lexical scope and returns the number 6.0, however, if a is made **mutable**, then the behavior is different, as shown in Listing 20.8. Here,

**Listing 20.8 dynamicScopeNFunction.fsx:**  
Mutual variables implement dynamic scope rules. Compare with Listing 4.16.

```

1 let testScope x =
2     let mutable a = 3.0
3     let f z = a * z
4     a <- 4.0
5     f x
6 printfn "%A" (testScope 2.0)

```

---

```

1 $ fsharpc --nologo dynamicScopeNFunction.fsx && mono
    dynamicScopeNFunction.exe
2 8.0

```

the response is 8.0, since the value of a changed before the function f was called.

## 20.2 Reference Cells

F# has a variation of mutable variables called *reference cells*. Reference cells have the built-in function `ref` and the operators “!” and “:=”, where `ref` creates a reference variable, and the “!” and the “:=” operators respectively reads and writes its value. An example of using reference cells is given in Listing 20.9. Reference cells

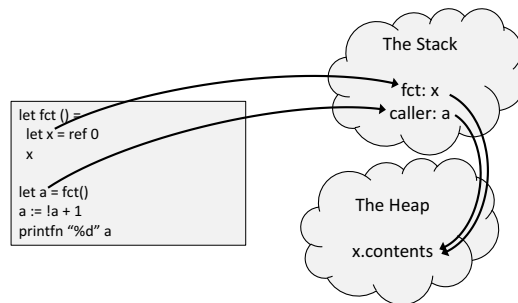
### Listing 20.9 refCell.fsx:

Reference cells are variants of mutable variables.

```
1 let x = ref 0
2 printfn "%d" !x
3 x := !x + 1
4 printfn "%d" !x

1 $ fsharp --nologo refCell.fsx && mono refCell.exe
2 0
3 1
```

are different from mutable variables, since their content is allocated on *The Heap*. The Heap is a global data storage that is not destroyed when a function returns, which is in contrast to the *call stack*, also known as *The Stack*. The Stack maintains all the local data for a specific instance of a function call, see Section 8.2 for more details. As a consequence, when a reference cell is returned from a function, then it is the reference to the location on The Heap, which is returned as a value. Since this points outside the local data area of the function, this location is still valid after the function returns, and the variable stored there is accessible to the caller. This is illustrated in Figure 20.1



**Fig. 20.1** A reference cell is a pointer to The Heap, and the content is not destroyed when its reference falls out of scope.

Reference cells may cause *side-effects*, where variable changes are performed across independent scopes. Some side-effects are useful, e.g., the `printf` family changes the content of the screen, and the screen is outside the scope of the caller. Another example of a useful side-effect is a counter shown in Listing 20.10. Here `incr` is

**Listing 20.10 refEncapsulation.fsx:****An increment function with a local state using a reference cell.**

```

1 let incr =
2   let counter = ref 0
3   fun () ->
4     counter := !counter + 1
5     !counter
6 printfn "%d" (incr ())
7 printfn "%d" (incr ())
8 printfn "%d" (incr ())

```

---

```

1 $ fsharp --nologo refEncapsulation.fsx && mono
   refEncapsulation.exe
2 1
3 2
4 3

```

an anonymous function with an internal state `counter`. At first glance, it may be surprising that `incr ()` does not return the value 1 at every call. The reason is that the value of the `incr` is the closure of the anonymous function `fun () -> counter := ...`, which is

$$\text{incr} : (\text{args}, \text{exp}, \text{env}) = ((), \left( \begin{smallmatrix} \text{counter} \\ \text{!counter} \end{smallmatrix} := \text{!counter} + 1 \right), (\text{counter} \rightarrow \text{ref } 0)). \quad (20.1)$$

Thus, `counter` is only initiated once at the initial binding, while every call of `incr ()` updates its value on The Heap. Such a programming structure is called *encapsulation*, since the `counter` state has been encapsulated in the anonymous function, and the only way to access it is by calling the same anonymous function. In general, it is advisable to **use encapsulation to hide implementation details** ★ **irrelevant to the user of the code.**

The `incr` example in Listing 20.10 is an example of a useful side-effect. An example to be avoided is shown in Listing 20.11. In the example, the function `updateFactor` changes a variable in the scope of the function `multiplyWithFactor`. The code style is prone to errors, since the computations are not local at the place of writing, i.e., in `multiplyWithFactor`, and if `updateFactor` were defined in a library, then the source code may not be available. Better style of programming is shown in Listing 20.12. Here, there can be no doubt in `multiplyWithFactor` that the value of `a` is changing. Side-effects do have their use, but should, in general, be avoided at almost all costs, and it is advised to **minimize the use of side effects.** ★

Reference cells give rise to an effect called *aliasing*, where two or more identifiers refer to the same data, as illustrated in Listing 20.13. Here, `a` is defined as a reference cell, and by defining `b` to be equal to `a`, we have created an alias. This can be very confusing since as the example shows, changing the value of `b` causes `a` to change

**Listing 20.11 refSideEffect.fsx:**

Intertwining independent scopes is typically a bad idea.

```

1 let updateFactor factor =
2     factor := 2
3
4 let multiplyWithFactor x =
5     let a = ref 1
6     updateFactor a
7     !a * x
8
9 printfn "%d" (multiplyWithFactor 3)

```

---

```

1 $ fsharpc --nologo refSideEffect.fsx && mono refSideEffect.exe
2 6

```

**Listing 20.12 refWithoutSideEffect.fsx:**

A solution similar to Listing 20.11 without side-effects.

```

1 let updateFactor () =
2     2
3
4 let multiplyWithFactor x =
5     let a = ref 1
6     a := updateFactor ()
7     !a * x
8
9 printfn "%d" (multiplyWithFactor 3)

```

---

```

1 $ fsharpc --nologo refWithoutSideEffect.fsx && mono
   refWithoutSideEffect.exe
2 6

```

- ★ as well. Aliasing is a variant of side-effects, and **aliasing should be avoided at all costs**.

**Listing 20.13 refCellAliasing.fsx:**

Aliasing can cause surprising results and should be avoided.

```

1 let a = ref 1
2 let b = a
3 printfn "%d, %d" !a !b
4 b := 2
5 printfn "%d, %d" !a !b

```

---

```

1 $ fsharpc --nologo refCellAliasing.fsx && mono
   refCellAliasing.exe
2 1, 1
3 2, 2

```

Since F# version 4.0, the compiler has automatically converted mutable variables to reference cells, where needed. E.g., Listing 20.10 can be rewritten using a mutable variable, as shown in Listing 20.14. Reference cells are preferred over mutable

**Listing 20.14 mutableEncapsulation.fsx:**

Local mutable content can be indirectly accessed outside its scope.

```
1 let incr =
2     let mutable counter = 0
3     fun () ->
4         counter <- counter + 1
5         counter
6 printfn "%d" (incr ())
7 printfn "%d" (incr ())
8 printfn "%d" (incr ())
```

---

```
1 $ fsharp --nologo mutableEncapsulation.fsx && mono
   mutableEncapsulation.exe
2 1
3 2
4 3
```

variables for encapsulation, in order to avoid confusion.

## 20.3 Arrays

One dimensional *arrays*, or just arrays for short, are mutable lists of the same type and follow a similar syntax as lists. Arrays can be stated as a *sequence expression*,

**Listing 20.15: The syntax for an array using the sequence expression.**

```
1 [| [<expr>; <expr>] |]
```

E.g., [|1; 2; 3|] is an array of integers, [|"This"; "is"; "an"; "array"|] is an array of strings, [(fun x -> x); (fun x -> x*x)|] is an array of functions, [|]| is the empty array. Arrays may also be given as ranges,

**Listing 20.16: The syntax for an array using the range expression.**

```
1 [|<expr> .. <expr> [|.. <expr>]|]
```

but arrays of *range expressions* must be of **<expr>** integers, floats, or characters. Examples are [|1 .. 5|], [| -3.0 .. 2.0|], and [|'a' .. 'z'|]. Range expressions may include a step size, thus, [|1 .. 2 .. 10|] evaluates to [|1; 3; 5; 7; 9|].

The array type is defined using the `array` keyword or alternatively the “[ ]” lexeme. Like strings and lists, arrays may be indexed using the “[ ]” notation. Arrays cannot be resized, but are mutable, as shown in Listing 20.17. Notice that in spite of

**Listing 20.17** `arrayReassign.fsx`:

Arrays are mutable in spite of the missing `mutable` keyword.

```
1 let square (a : int array) =
2     for i = 0 to a.Length - 1 do
3         a[i] <- a[i] * a[i]
4
5 let A = [| 1; 2; 3; 4; 5 |]
6 printfn "%A" A
7 square A
8 printfn "%A" A
```

---

```
1 $ dotnet fsi arrayReassign.fsx
2 [|1; 2; 3; 4; 5|]
3 [|1; 4; 9; 16; 25|]
```

the missing `mutable` keyword, the function `square` still has the *side-effect* of squaring all entries in `A`. F# implements arrays as chunks of memory and indexes arrays via address arithmetic. I.e., element  $i$  in an array, whose first element is in memory address  $\alpha$  and whose elements fill  $\beta$  addresses each, is found at address  $\alpha + i\beta$ . Hence, indexing has computational complexity of  $O(1)$ , but appending and prepending values to arrays and array concatenation requires copying the new and existing values to a fresh area in memory and thus has computational complexity  $O(n)$ , where  $n$  is the total number of elements. Thus, **indexing arrays is fast, but cons and concatenation is slow and should be avoided.**

Arrays support *slicing*, that is, indexing an array with a range result in a copy of the array with values corresponding to the range. This is demonstrated in Listing 20.18.

As illustrated, the missing start or end index imply from the first or to the last element, respectively.

Arrays do not have explicit operator support for appending and concatenation, instead the `Array` namespace includes an `Array.append` function, as shown in Listing 20.19.

Arrays are *reference types*, meaning that identifiers are references and thus suffer from aliasing, as illustrated in Listing 20.20.



**Listing 20.18:** Examples of array slicing. Compare with Listing 7.6 and Listing 3.27.

```

1  > let arr = [|'a' .. 'g'|];;
2  val arr: char[] = [|'a'; 'b'; 'c'; 'd'; 'e'; 'f'; 'g'|]
3
4
5  > arr[0];;
6  val it: char = 'a'
7
8  > arr[3];;
9  val it: char = 'd'
10
11 > arr[3..];;
12 val it: char[] = [|'d'; 'e'; 'f'; 'g'|]
13
14 > arr[..3];;
15 val it: char[] = [|'a'; 'b'; 'c'; 'd'|]
16
17 > arr[1..3];;
18 val it: char[] = [|'b'; 'c'; 'd'|]
19
20 > arr[*];;
21 val it: char[] = [|'a'; 'b'; 'c'; 'd'; 'e'; 'f'; 'g'|]

```

**Listing 20.19** arrayAppend.fsx:  
Two arrays are appended with `Array.append`.

```

1  let a = [|1; 2;|]
2  let b = [|3; 4; 5|]
3  let c = Array.append a b
4  printfn "%A, %A, %A" a b c

```

---

```

1  $ fsharp -n:nologo arrayAppend.fsx && mono arrayAppend.exe
2  [|1; 2|], [|3; 4; 5|], [|1; 2; 3; 4; 5|]

```

**Listing 20.20** arrayAliasing.fsx:  
Arrays are reference types and suffer from aliasing.

```

1  let a = [|1; 2; 3|];
2  let b = a
3  a[0] <- 0
4  printfn "a = %A, b = %A" a b;;

```

---

```

1  $ dotnet fsi arrayAliasing.fsx
2  a = [|0; 2; 3|], b = [|0; 2; 3|]

```

### 20.3.1 Array Properties and Methods

Some important properties and methods for arrays are:

**Clone():** 'T [].

Returns a copy of the array.

#### Listing 20.21: Clone

```
1
2 > let a = [|1; 2; 3|];
3 let b = a.Clone()
4 a[0] <- 0
5 printfn "a = %A, b = %A" a b;;
6 a = [|0; 2; 3|], b = [|1; 2; 3|]
7 val a: int[] = [|0; 2; 3|]
8 val b: obj = [|1; 2; 3|]
9 val it: unit = ()
```

**Length:** int.

Returns the number of elements in the array.

#### Listing 20.22: Length

```
1 > [|1; 2; 3|].Length;;
2 val it: int = 3
```

### 20.3.2 The Array Module

There are quite a number of built-in procedures for arrays in the `Array` module, some of which are summarized below.

**Array.append:** arr1:'T [] -> arr2:'T [] -> 'T [].

Creates a new array whose elements are a concatenated copy of `arr1` and `arr2`.

#### Listing 20.23: Array.append

**Array.contains:** elm:'T -> arr:'T [] -> bool.

Returns true if `arr` contains `elm`.

**Listing 20.24: Array.contains**

```
1 > Array.contains 3 [|1; 2; 3|];;
2 val it: bool = true
```

**Array.exists:** `f:('T -> bool) -> arr:'T [] -> bool.`

Returns true if any application of `f` evaluates to true when applied to the elements of `arr`.

**Listing 20.25: Array.exists**

```
1 > Array.exists (fun x -> x % 2 = 1) [|0 .. 2 .. 4|];;
2 val it: bool = false
```

**Array.filter:** `f:('T -> bool) -> arr:'T [] -> 'T [].`

Returns an array of elements from `arr` who evaluate to true when `f` is applied to them.

**Listing 20.26: Array.filter**

**Array.find:** `f:('T -> bool) -> arr:'T [] -> 'T.`

Returns the first element in `arr` for which `f` evaluates to true. The `KeyNotFoundException` exception is raised if no element is found. See Section 13.1 for more on exceptions.

**Listing 20.27: Array.find**

```
1 > Array.find (fun x -> x % 2 = 1) [|0 .. 9|];;
2 val it: int = 1
```

**Array.findIndex:** `f:('T -> bool) -> arr:'T [] -> int.`

Returns the index of the first element in `arr` for which `f` evaluates to true. If none are found, then the `System.Collections.Generic.KeyNotFoundException` exception is raised. See Section 13.1 for more on exceptions.

**Listing 20.28: Array.findIndex**

```
1 > Array.findIndex (fun x -> x = 'k') [|'a' .. 'z'|];;
2 val it: int = 10
```

**Array.fold:** `f:('S -> 'T -> 'S) -> elm:'S -> arr:'T [] -> 'S.`

Updates an accumulator iteratively by applying `f` to each element in `arr`. The initial value of the accumulator is `elm`. For example, when `arr` consists of `n+1` elements `Array.fold` calculates:

$$f \dots (f (f \text{ elm arr}[0]) \text{ arr}[1]) \dots \text{ arr}[n].$$

**Listing 20.29: Array.fold**

```

1 > let addSquares acc elm = acc + elm*elm
2 Array.fold addSquares 0 [|0 .. 9|];;
3 val addSquares: acc: int -> elm: int -> int
4 val it: int = 285

```

**Array.foldBack:** `f:('T -> 'S -> 'S) -> arr:'T [] -> elm:'S -> 'S`.  
 Updates an accumulator iteratively backwards by applying `f` to each element in `arr`. The initial value of the accumulator is `elm`. For example, when `arr` consists of `n+1` elements `Array.foldBack` calculates:

```
f arr[0] (f arr[1] (...(f arr[n] elm) ...)).
```

**Listing 20.30: Array.foldBack**

```

1 > let addSquares elm acc = acc + elm*elm
2 Array.foldBack addSquares [|0 .. 9|] 0;;
3 val addSquares: elm: int -> acc: int -> int
4 val it: int = 285

```

**Array.forall:** `f:('T -> bool) -> arr:'T [] -> bool`.  
 Returns true if `f` evaluates to true for every element in `arr`.

**Listing 20.31: Array.forall**

```

1 > Array.forall (fun x -> (x % 2 = 1)) [|0 .. 9|];;
2 val it: bool = false

```

**Array.init:** `m:int -> f:(int -> 'T) -> 'T []`.  
 Create an array with `m` elements and whose value is the result of applying `f` to the index of the element.

**Listing 20.32: Array.init**

```

1 > Array.init 10 (fun i -> i * i);;
2 val it: int[] = [|0; 1; 4; 9; 16; 25; 36; 49; 64; 81|]

```

**Array.isEmpty:** `arr:'T [] -> bool`.  
 Returns true if `arr` is empty.

**Listing 20.33: Array.isEmpty**

```

1 > Array.isEmpty [|]|;
2 val it: bool = true

```

**Array.iter:** `f:('T -> unit) -> arr:'T [] -> unit`.  
 Applies `f` to each element of `arr`.

**Listing 20.34: Array.iter**

```
1 > Array.iter (fun x -> printfn "%A " x) [|0; 1; 2|];;
2 0
3 1
4 2
5 val it: unit = ()
```

**Array.map:** `f:('T -> 'U) -> arr:'T [] -> 'U []`.

Creates a new array whose elements are the results of applying `f` to each of the elements of `arr`.

**Listing 20.35: Array.map**

**Array.ofList:** `lst:'T list -> 'T []`.

Creates an array whose elements are copied from `lst`.

**Listing 20.36: Array.ofList**

```
1 > Array.ofList [|1; 2; 3|];;
2 val it: int[] = [|1; 2; 3|]
```

**Array.rev:** `arr:'T [] -> 'T []`.

Creates a new array whose elements are identical to `arr` but in reverse order.

**Listing 20.37: Array.rev**

```
1 > Array.rev [|1; 2; 3|];;
2 val it: int[] = [|3; 2; 1|]
```

**Array.sort:** `arr:'T[] -> 'T []`.

Creates a new array with the same elements as in `arr` but in sorted order

**Listing 20.38: Array.sort**

**Array.toList:** `arr:'T [] -> 'T list`.

Creates a new list whose elements are copied from `arr`.

**Listing 20.39: Array.toList**

```
1 > Array.toList [|1; 2; 3|];;
2 val it: int list = [1; 2; 3]
```

**Array.unzip:** `arr:('T1 * 'T2) [] -> 'T1 [] * 'T2 []`.

Returns a pair of arrays of all the first elements and all the second elements of `arr`, respectively.

**Listing 20.40: Array.unzip**

```

1 > Array.unzip [| (1, 'a'); (2, 'b'); (3, 'c') |];;
2 val it: int[] * char[] = ([|1; 2; 3|], [|'a'; 'b'; 'c'|])

```

`Array.zip: arr1:'T1 [] -> arr2:'T2 [] -> ('T1 * 'T2) []`.

Returns a list of pairs, where elements in `arr1` and `arr2` are iteratively paired.

**Listing 20.41: Array.zip**

## 20.4 Multidimensional Arrays

*Multidimensional arrays* can be created as arrays of arrays (of arrays . . . ). These are known as *jagged arrays*, since there is no inherent guarantee that all sub-arrays are of the same size. The example in Listing 20.42 is a jagged array of increasing width. Indexing arrays of arrays is done sequentially, in the sense that in the above example,

**Listing 20.42 arrayJagged.fsx:**

An array of arrays. When row lengths are of non-equal elements, then it is a jagged array.

```

1 let arr = [| [|1|]; [|1; 2|]; [|1; 2; 3|] |]
2
3 for row in arr do
4     for elm in row do
5         printf "%A " elm
6     printf "\n"

```

---

```

1 $ fsharpc --nologo arrayJagged.fsx && mono arrayJagged.exe
2 1
3 1 2
4 1 2 3

```

the number of outer arrays is `a.Length`, `a[i]` is the *i*'th array, the length of the *i*'th array is `a[i].Length`, and the *j*'th element of the *i*'th array is thus `a[i][j]`. Often 2-dimensional rectangular arrays are used, which can be implemented as a jagged array, as shown in Listing 20.43. Note that the `for-in` cannot be used in `pownArray`, e.g.,

```
for row in arr do for elm in row do elm <- pown elm p done done,
```

since the iterator value `elm` is not mutable, even though `arr` is an array.

**Listing 20.43** `arrayJaggedSquare.fsx`:  
A rectangular array.

```

1 let pownArray (arr : int array array) p =
2     for i = 1 to arr.Length - 1 do
3         for j = 1 to arr[i].Length - 1 do
4             arr[i][j] <- pown arr[i][j] p
5
6 let printArrayOfArrays (arr : int array array) =
7     for row in arr do
8         for elm in row do
9             printf "%3d " elm
10            printf "\n"
11
12 let A = [| [| 1 .. 4 |]; [| 1 .. 2 .. 7 |]; [| 1 .. 3 .. 10 |] |]
13 pownArray A 2
14 printArrayOfArrays A

```

---

```

1 $ dotnet fsi arrayJaggedSquare.fsx
2
3
4 arrayJaggedSquare.fsx(4,25): warning FS3369: The syntax
   'expr1[expr2]' is ambiguous when used as an argument. See
   https://aka.ms/fsharp-index-notation. If you intend
   indexing or slicing then you must use 'expr1.[expr2]' in
   argument position. If calling a function with multiple
   curried arguments, add a space between them, e.g.
   'someFunction expr1 [expr2]'.
5
6
7
8 arrayJaggedSquare.fsx(4,20): error FS0003: This value is not
   a function and cannot be applied.

```

Square arrays of dimensions 2 to 4 are so common that F# has built-in modules for their support. Here, we will describe `Array2D`. The workings of `Array3D` and `Array4D` are very similar. A generic `Array2D` has type 'T [, ]', and it is indexed also using the `[, ]` notation. The `Array2D.length1` and `Array2D.length2` functions are supplied by the `Array2D` module for obtaining the size of an array along the first and second dimension. Rewriting the with jagged array example in Listing 20.43 to use `Array2D` gives a slightly simpler program, which is shown in Listing 20.44. Note that the `printf` supports direct printing of the 2-dimensional array. `Array2D` arrays support slicing. The “*” lexeme is particularly useful to obtain all values along a dimension. This is demonstrated in Listing 20.45. Note that in almost all cases, slicing produces a sub-rectangular 2 dimensional array, except for `arr[1,*]`, which is an array, as can be seen by the single “[”. In contrast, `A[1..1,*]` is an `Array2D`. Note also that `printfn` typesets 2 dimensional arrays as `[ [ ... ] ]` and not `[ [ [ ... ] ] ]`, which can cause confusion with lists of lists.

**Listing 20.44** array2D.fsx:  
Creating a 3 by 4 rectangular array of integers.

```

1 let arr = Array2D.create 3 4 0
2 for i = 0 to (Array2D.length1 arr) - 1 do
3   for j = 0 to (Array2D.length2 arr) - 1 do
4     arr[i,j] <- j * Array2D.length1 arr + i
5 printfn "%A" arr

```

```

1 $ dotnet fsi array2D.fsx
2 [[0; 3; 6; 9]
3  [1; 4; 7; 10]
4  [2; 5; 8; 11]]

```

**Listing 20.45:** Examples of Array2D slicing. Compare with Listing 20.44.

```

1 > let arr = Array2D.init 3 4 (fun i j -> i + 10 * j);;
2 val arr: int[,] = [[0; 10; 20; 30]
3                   [1; 11; 21; 31]
4                   [2; 12; 22; 32]]
5
6 > arr[2,3];;
7 val it: int = 32
8
9 > arr[1..,3..];;
10 val it: int[,] = [[31]
11                  [32]]
12
13 > arr[..1,*];;
14 val it: int[,] = [[0; 10; 20; 30]
15                  [1; 11; 21; 31]]
16
17 > arr[1,*];;
18 val it: int[] = [|1; 11; 21; 31|]
19
20 > arr[1..1,*];;
21 val it: int[,] = [[1; 11; 21; 31]]

```

Multidimensional arrays have the same properties and methods as arrays, see Section 20.3.1.



### 20.4.1 The Array2D Module

There are quite a number of built-in procedures for arrays in the `Array2D` namespace, some of which are summarized below.

`copy: arr:'T [,] -> 'T [,]`.

Creates a new array whose elements are copied from `arr`.

#### Listing 20.46: Array2D.copy

```
1 > let a = Array2D.init 3 4 (fun i j -> i + 10 * j)
2 let b = Array2D.copy a;;
3 val a: int[,] = [[0; 10; 20; 30]
4                  [1; 11; 21; 31]
5                  [2; 12; 22; 32]]
6 val b: int[,] = [[0; 10; 20; 30]
7                  [1; 11; 21; 31]
8                  [2; 12; 22; 32]]
```

`create: m:int -> n:int -> v:'T -> 'T [,]`.

Creates an `m` by `n` array whose elements are set to `v`.

#### Listing 20.47: Array2D.create

```
1 > Array2D.create 2 3 3.14;;
2 val it: float[,] = [[3.14; 3.14; 3.14]
3                    [3.14; 3.14; 3.14]]
```

`init: m:int -> n:int -> f:(int -> int -> 'T) -> 'T [,]`.

Creates an `m` by `n` array whose elements are the result of applying `f` to the index of an element.

#### Listing 20.48: Array2D.init

```
1
2 > Array2D.init 3 4 (fun i j -> i + 10 * j);;
3 val it: int[,] = [[0; 10; 20; 30]
4                  [1; 11; 21; 31]
5                  [2; 12; 22; 32]]
```

`iter: f:('T -> unit) -> arr:'T [,] -> unit`.

Applies `f` to each element of `arr`.

**Listing 20.49: Array2D.iter**

```

1 > let arr = Array2D.init 3 4 (fun i j -> i + 10 * j)
2 Array2D.iter (fun elm -> printf "%A " elm) arr
3 printfn "";
4 0 10 20 30 1 11 21 31 2 12 22 32
5 val arr: int[,] = [[0; 10; 20; 30]
6                    [1; 11; 21; 31]
7                    [2; 12; 22; 32]]
8 val it: unit = ()

```

**length1:** arr:'T [,] -> int.

Returns the length the first dimension of arr.

**Listing 20.50: Array2D.length1**

**length2:** arr:'T [,] -> int.

Returns the length of the second dimension of arr.

**Listing 20.51: Array2D.forall length2**

```

1 > let arr = Array2D.create 2 3 0.0 in Array2D.length2
   arr;;
2 val it: int = 3

```

**map:** f:( 'T -> 'U) -> arr:'T [,] -> 'U [,].

Creates a new array whose elements are the results of applying f to each of the elements of arr.

**Listing 20.52: Array2D.map**

```

1 > let arr = Array2D.init 3 4 (fun i j -> i + 10 * j)
2 Array2D.map (fun x -> x * x) arr;;
3 val arr: int[,] = [[0; 10; 20; 30]
4                    [1; 11; 21; 31]
5                    [2; 12; 22; 32]]
6 val it: int[,] = [[0; 100; 400; 900]
7                    [1; 121; 441; 961]
8                    [4; 144; 484; 1024]]

```

## Chapter 21

# While and For Loops

Non-recursive functions encapsulate code and allow for control of execution flow. That is, if a piece of code needs to be executed many times, then we can encapsulate it in the body of a function and call this function several times. In this chapter, we will look at more general control of flow via loops and conditional execution. Recursion is another mechanism for controlling flow, but this is deferred to Chapter 8.

Many programming constructs need to be repeated, and F# contains many structures for repetition. A *while*-loop has the following syntax:

**Listing 21.1:** While loop.

```
1 while <condition> do <expr> [done]
```

The *condition* `<condition>` is an expression that evaluates to true or false. A while-loop repeats the `<expr>` expression as long as the condition is true. Using lightweight syntax, the block following the `do` keyword up to and including the `done` keyword may be replaced by a newline and indentation.

The program in Listing 21.5 is an example of a while-loop which counts from 1 to 10. The variable `i` is customarily called the counter variable. The counting is

**Listing 21.2** countWhile.fsx:  
Count to 10 with a counter variable.

```
1 let mutable i = 1 in while i <= 10 do printf "%d " i; i <- i
  + 1 done;
2 printf "\n"

-----

1 $ fsharp --nologo countWhile.fsx && mono countWhile.exe
2 1 2 3 4 5 6 7 8 9 10
```

done by performing the following computation: In line 1, the counter variable is first

given an initial value of 1. Then execution enters the while-loop and examines the condition. Since  $1 \leq 10$ , the condition is true, and execution enters the body of the loop. The body prints the value of the counter to the screen and increases the counter by 1. Then execution returns to the top of the while-loop. Now the condition is  $2 \leq 10$ , which is also true, and so execution enters the body and so on until the counter has reached the value 11, in which case the condition  $11 \leq 10$  is false, and execution continues in line 2.

In lightweight syntax, this would be as shown in Listing 21.3. Notice that although the

**Listing 21.3** `countWhileLightweight.fsx`:  
Count to 10 with a counter variable using lightweight syntax.

```
1 let mutable i = 1
2 while i <= 10 do
3     printf "%d " i
4     i <- i + 1
5 printf "\n"

-----
1 $ fsharpc --nologo countWhileLightweight.fsx && mono
   countWhileLightweight.exe
2 1 2 3 4 5 6 7 8 9 10
```

expression following the condition is preceded with a `do` keyword, and `do <expr>` is a `do`-binding, the keyword `do` is mandatory.

Counters are so common that a special syntax has been reserved for loops using counters. These are called *for-to*-loops. For-loops come in several variants, and here we will focus on the one using an explicit counter. Its syntax is:

**Listing 21.4:** For loop.

```
1 for <ident> = <firstExpr> to <lastExpr> do <bodyExpr> [done]
```

A for-loop initially binds the counter identifier `<ident>` to be the value `<firstExpr>`. Then execution enters the body, and `<bodyExpr>` is evaluated. Once done, the counter is increased, and execution evaluates `<bodyExpr>` once again. This is repeated as long as the counter is not greater than `<lastExpr>`. As for while-loops, when using lightweight syntax the block following the `do` keyword up to and including the `done` keyword may be replaced by a newline and indentation.

The counting example from Listing 21.2 using a *for*-loop is shown in Listing 21.5. As this interactive script demonstrates, the identifier `i` takes all the values between 1 and 10, but in spite of its changing state, it is not mutable. Note also that the return value of the *for* expression is “()”, like the `printf` functions. The lightweight equivalent is shown in Listing 21.6.

**Listing 21.5** count.fsx:  
Counting from 1 to 10 using a *for*-loop.

```
1 for i = 1 to 10 do printf "%d " i done
2 printfn ""

-----

1 $ fsharpc --nologo count.fsx && mono count.exe
2 1 2 3 4 5 6 7 8 9 10
```

**Listing 21.6** countLightweight.fsx:  
Counting from 1 to 10 using a *for*-loop using the lightweight syntax.

```
1 for i = 1 to 10 do
2     printf "%d " i
3 printfn ""

-----

1 $ fsharpc --nologo countLightweight.fsx && mono
   countLightweight.exe
2 1 2 3 4 5 6 7 8 9 10
```

Counting backwards is sufficiently common that F# has a *for-downto* structure, which works exactly like a *for-to*-loop except that the counter is decreased by 1 in each iteration. An example of this is shown in Listing 21.7.

**Listing 21.7** countLightweightBackwards.fsx:  
Counting from 10 to 1 using a *for-downto*-loop using the lightweight syntax.

```
1 for i = 10 downto 1 do
2     printf "%d " i
3 printfn ""

-----

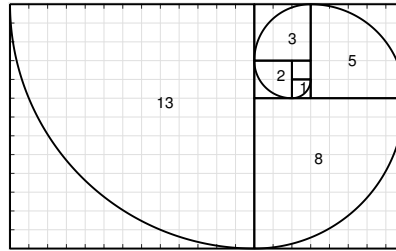
1 $ fsharpc --nologo countLightweightBackwards.fsx && mono
   countLightweightBackwards.exe
2 10 9 8 7 6 5 4 3 2 1
```

To further compare *for*- and *while*-loops, consider the following problem.

**Problem 21.1**

rite a program that calculates the  $n$ 'th Fibonacci number.

Fibonacci numbers is a sequence of numbers starting with 1, 1, and where the next number is calculated as the sum of the previous two. Hence the first ten numbers are: 1, 1, 2, 3, 5, 8, 13, 21, 34, 55. Fibonacci numbers are related to Golden spirals shown in Figure 21.1. Often the sequence is extended with a preceding number 0, to be 0, 1, 1, 2, 3, ..., which we will do here as well.



**Fig. 21.1** The Fibonacci spiral is an approximation of the golden spiral. Each square has side lengths of successive Fibonacci numbers, and the curve in each square is the circular arc with a radius of the square it is drawn in.

We could solve this problem with a `for`-loop, as shown in Listing 21.8. The basic

**Listing 21.8** `fibFor.fsx`:

The  $n$ 'th Fibonacci number calculated using a `for`-loop.

```

1 let fib n =
2   let mutable pair = (0, 1)
3   for i = 2 to n do
4     pair <- (snd pair, (fst pair) + (snd pair))
5     snd pair
6
7 printfn "fib(1) = %d" (fib 1)
8 printfn "fib(2) = %d" (fib 2)
9 printfn "fib(3) = %d" (fib 3)
10 printfn "fib(10) = %d" (fib 10)

```

---

```

1 $ fsharp --nologo fibFor.fsx && mono fibFor.exe
2 fib(1) = 1
3 fib(2) = 1
4 fib(3) = 2
5 fib(10) = 55

```

idea of the solution is that if we are given the  $(n - 1)$ 'th and  $(n - 2)$ 'th numbers, the  $n$ 'th number is trivial to compute. And assuming that `fib(1)` and `fib(2)` are given, then it is trivial to calculate `fib(3)`. For `fib(4)`, we only need `fib(3)` and `fib(2)`, hence we may disregard `fib(1)`. Thus, we realize that we can cyclicly update the previous, current, and next values by shifting values until we have reached the desired `fib(n)`. This is implement in Listing 21.8 as the function `fib`, which takes an integer `n` as argument and returns the  $n$ 'th Fibonacci number. The function does this iteratively using a `for`-loop, where `i` is the counter value, and `pair` is the pair of the  $i - 1$ 'th and  $i$ 'th Fibonacci numbers. In the body of the loop, the  $i$ 'th and  $i + 1$ 'th numbers are assigned to `pair`. The `for`-loop automatically updates `i` for next iteration. When  $n < 2$  the body of the `for`-loop is not evaluated, and 1 is returned. This is of course wrong for  $n < 1$ , but we will ignore this for now.

Listing 21.9 shows a program similar to Listing 21.8 using a `while`-loop instead of `for`-loop. The programs are almost identical. In this case, the `for`-loop is to

**Listing 21.9 fibWhile.fsx:**  
 The  $n$ 'th Fibonacci number calculated using a while-loop.

```

1 let fib (n : int) : int =
2     let mutable pair = (0, 1)
3     let mutable i = 1
4     while i < n do
5         pair <- (snd pair, fst pair + snd pair)
6         i <- i + 1
7     snd pair
8
9 printfn "fib(1) = %d" (fib 1)
10 printfn "fib(2) = %d" (fib 2)
11 printfn "fib(3) = %d" (fib 3)
12 printfn "fib(10) = %d" (fib 10)

```

---

```

1 $ fsharp --nologo fibWhile.fsx && mono fibWhile.exe
2 fib(1) = 1
3 fib(2) = 1
4 fib(3) = 2
5 fib(10) = 55

```

be preferred, since more lines of code typically mean more chances of making a mistake. However, while-loops are somewhat easier to argue correctness about.

The correctness of `fib` in Listing 21.9 can be proven using a *loop invariant*. An *invariant* is a statement that is always true at a particular point in a program, and a loop invariant is a statement which is true at the beginning and end of a loop. In line 4 in Listing 21.9, we may state the invariant: The variable `pair` is the pair of the  $i - 1$ 'th and  $i$ 'th Fibonacci numbers. This is provable by induction:

Base case: Before entering the while loop, `i` is 1, `pair` is (0, 1). Thus, the invariant is true.

Induction step: Assuming that `pair` is the  $i - 1$ 'th and  $i$ 'th Fibonacci numbers, the body first assigns a new value to `pair` as the  $i$ 'th and  $i + 1$ 'th Fibonacci numbers, then increases `i` by one such that at the end of the loop the `pair` again contains the  $i - 1$ 'th and  $i$ 'th Fibonacci numbers.

Thus, since our invariant is true for the first case, and any iteration following an iteration where the invariant is true, is also true, then it is true for all iterations.

Thus we know that the second value in `pair` holds the value of the  $i$ 'th Fibonacci number, and since we further may prove that  $i = n$  when line 7 is reached, then it is proven that `fib` returns the  $n$ 'th Fibonacci number.

While-loops also allow for logical structures other than for-loops, such as the case when the number of iteration cannot easily be decided when entering the loop. As

an example, consider a slight variation of the above problem, where we wish to find the largest Fibonacci number less or equal some number. A solution to this problem is shown in Listing 21.10. The strategy here is to iteratively calculate Fibonacci

**Listing 21.10 fibWhileLargest.fsx:****Search for the largest Fibonacci number less than a specified number.**

```
1 let largestFibLeq n =  
2   let mutable pair = (0, 1)  
3   while snd pair <= n do  
4     pair <- (snd pair, fst pair + snd pair)  
5     fst pair  
6  
7   for i = 1 to 10 do  
8     printfn "largestFibLeq(%d) = %d" i (largestFibLeq i)
```

---

```
1 $ fsharp --nologo fibWhileLargest.fsx && mono  
   fibWhileLargest.exe  
2 largestFibLeq(1) = 1  
3 largestFibLeq(2) = 2  
4 largestFibLeq(3) = 3  
5 largestFibLeq(4) = 3  
6 largestFibLeq(5) = 5  
7 largestFibLeq(6) = 5  
8 largestFibLeq(7) = 5  
9 largestFibLeq(8) = 8  
10 largestFibLeq(9) = 8  
11 largestFibLeq(10) = 8
```

numbers until we've found one larger than the argument *n*, and then return the previous. This could not be calculated with a for-loop.



## 21.1 Programming Intermezzo: Automatic Conversion of Decimal to Binary Numbers

Using loops and conditional expressions, we are now able to solve the following problem:

### Problem 21.2

Given an integer on decimal form, write its equivalent value on the binary form.

To solve this problem, consider odd numbers: They all have the property that the least significant bit is 1, e.g.,  $1_2 = 1$ ,  $101_2 = 5$ , in contrast to even numbers such as  $110_2 = 6$ . Division by 2 is equal to right-shifting by 1, e.g.,  $1_2/2 = 0.1_2 = 0.5$ ,  $101_2/2 = 10.1_2 = 2.5$ ,  $110_2/2 = 11_2 = 3$ . Thus, through dividing by 2 and checking the remainder, we may sequentially read off the least significant bit. This leads to the algorithm shown in Listing 21.11. In the code, the states *v* and *str* are

### Listing 21.11 dec2bin.fsx:

Using integer division and remainder to write any positive integer in binary form.

```

1 let dec2bin n =
2   if n < 0 then
3     "Illegal value"
4   elif n = 0 then
5     "0b0"
6   else
7     let mutable v = n
8     let mutable str = ""
9     while v > 0 do
10      str <- (string (v % 2)) + str
11      v <- v / 2
12    "0b" + str
13
14
15 printfn "%4d -> %s" -1 (dec2bin -1)
16 printfn "%4d -> %s" 0 (dec2bin 0)
17 for i = 0 to 3 do
18   printfn "%4d -> %s" (pown 10 i) (dec2bin (pown 10 i))

```

---

```

1 $ fsharp --nologo dec2bin.fsx && mono dec2bin.exe
2 -1 -> Illegal value
3 0 -> 0b0
4 1 -> 0b1
5 10 -> 0b1010
6 100 -> 0b1100100
7 1000 -> 0b111101000

```

iteratively updated until *str* finally contains the desired solution.

To prove that Listing 21.11 calculates the correct sequence, we use induction. First we realize that for  $v < 1$ , the while-loop is skipped, and the result is trivially true. We will concentrate on line 9 in Listing 21.11 and will prove the following loop invariant: The string `str` contains all the bits of `n` to the right of the bit pattern remaining in variable `v`.

Base case  $n = 000 \dots 000x$ : If  $n$  only uses the lowest bit, then  $n = 0$  or  $n = 1$ . If  $n = 0$ , then it is trivially correct. Considering the case  $n = 1$ : Before entering into the loop, `v` is 1, and `str` is the empty string, so the invariant is true. The condition of the while-loop is  $1 > 0$ , so execution enters the loop. Since integer division of 1 by 2 gives 0 with remainder 1, `str` is set to `"1"` and `v` to 0. Now we reexamine the while-loop's condition,  $0 > 0$ , which is false, so we exit the loop. At this point, `v` is 0 and `str` is `"1"`, so all bits have been shifted from `n` to `str`, and none are left in `v`. Thus the invariant is true. Finally, the program returns `"0b1"`.

Induction step: Consider the case of  $n > 1$ , and assume that the invariant is true when entering the loop, i.e., that  $m$  bits already have been shifted to `str` and that  $n > 2^m$ . In this case, `v` contains the remaining bits of `n`, which is the integer division  $v = n / 2^m$ . Since  $n > 2^m$ , `v` is non-zero, and the loop conditions is true, so we enter the loop body. In the loop body we concatenate the rightmost bit of `v` to the left of `str` using `v % 2`, and right-shift `v` one bit to the right with `v <- v / 2`. Thus, when returning to the condition the invariant is true, since the right-most bit in `v` has been shifted to `str`. This continues until all bits have been shifted to `str` and `v = 0`, in which case the loop terminates, and `"0b"+str` is returned.

Thus we have proven that `dec2bin` correctly converts integers to strings representing binary numbers.

## Chapter 22

# The Imperative Programming paradigm

*Imperative programming* is a paradigm for programming states. In imperative programming, the focus is on how a problem is to be solved, as a list of *statements* that affects *states*. In F#, states are mutable and immutable values, and they are affected by functions and procedures. An imperative program is typically identified as using:

### Mutable values

Mutable values are holders of states, they may change over time, and thus have a dynamic scope.

### Procedures

Procedures are functions that returns “()”, as opposed to functions that transform data. They are the embodiment of side-effects.

### Side-effects

Side-effects are changes of state that are not reflected in the arguments and return values of a function. The `printf` is an example of a procedure that uses side-effects to communicate with the terminal.

### Loops

The `for`- and `while`-loops typically use an iteration value to update some state, e.g., `for`-loops are often used to iterate through a list and summarize its contents.

Mono state or stateless programs, as *functional programming*, can be seen as a subset of imperative programming and is discussed in Chapter 11. *Object-oriented programming* is an extension of imperative programming, where statements and states are grouped into classes. For a discussion on object-oriented programming, see Chapter 25.

An imperative program is like a Turing machine, a theoretical machine introduced by Alan Turing in 1936 [10]. Almost all computer hardware is designed for *machine*

*code*, which is a common term used for many low-level computer programming languages, and almost all machine languages follow the imperative programming paradigm.

A prototypical example is a baking recipe, e.g., to make a loaf of bread, do the following:

1. Mix yeast with water.
2. Stir in salt, oil, and flour.
3. Knead until the dough has a smooth surface.
4. Let the dough rise until it has doubled its size.
5. Shape dough into a loaf.
6. Let the loaf rise until double size.
7. Bake in the oven until the bread is golden brown.

Each line in this example consists of one or more statements that are to be executed, and while executing them, states such as the size of the dough and the color of the bread changes. Some execution will halt execution until certain conditions of these states are fulfilled, e.g., the bread will not be put into the oven for baking before it has risen sufficiently.

## **22.1 Imperative Design**

Programming is the act of solving a problem by writing a program to be executed on a computer. The imperative programming paradigm focuses on states. To solve a problem, you could work through the following list of actions:

1. Understand the problem. As Pólya described it, see Chapter 1, the first step in any solution is to understand the problem. A good trick to check whether you understand the problem, is to briefly describe it in your own words.
2. Identify the main values, variables, functions, and procedures needed. If the list of procedures is large, then you most likely should organize them in modules.

3. For each function and procedure, write a precise description of what it should do. This can conveniently be performed as an in-code comment for the procedure, using the F# XML documentation standard.
4. Make mockup functions and procedures using the intended types, but do not necessarily compute anything sensible. Run through examples in your mind, using this mockup program to identify any obvious oversights.
5. Write a suite of unit tests that tests the basic requirements for your code. The unit tests should be runnable with your mockup code. Writing unit tests will also allow you to evaluate the usefulness of the code pieces as seen from an application point of view.
6. Replace the mockup functions in a prioritized order, i.e., write the must-have code before you write the nice-to-have code, while regularly running your unit tests to keep track of your progress.
7. Evaluate the code in relation to the desired goal, and reiterate earlier actions as needed until the task has been sufficiently completed.
8. Complete your documentation both in-code and outside to ensure that the intended user has sufficient knowledge to effectively use your program and to ensure that you or a fellow programmer will be able to maintain and extend the program in the future.



## Chapter 23

# Classes and Objects

*Object-oriented programming* is a programming paradigm that focuses on objects such as a persons, places, things, events, and concepts relevant for the problem.

Object-oriented programming has a rich language for describing objects and their relations, which can seem overwhelming at first, and they will be explained in detail in this and following chapters. Here is a brief overview: The main programming structures are called a *classes* and *objects*. It is useful to think of classes as user defined types and objects as values of such types. However, there is more to classes and objects than types and values. Objects may contain both data and code, and it is sometimes useful to draw the corresponding class definition as shown in Figure 23.1. In this illustration, objects of type `aClass` will each contain an `int` and a pair of a

aClass
// The object's values (properties) aValue : int anotherValue : float*bool
// The object's functions (methods) aMethod: () -> int anotherMethod: float -> float

**Fig. 23.1** A class is sometimes drawn as a figure.

float and a boolean, and each object has two functions associated with them. The values stored in each object may differ, but the types are fixed by the class definition. It is common to call an object's values *properties* and an object's functions *methods*. In short, properties and methods are collectively called *members*. When an object is created, memory is set aside on *The Heap* to each object's property. Creating an object is commonly called *instantiation*. The members serve as the interface to each object, and each instantiated object will have the same type of members as all objects of that class, but their content may differ.

Object-oriented programming is an extension of data types, in the sense that objects contain both data and functions in a similar manner as a module, but object-oriented

programming emphasizes the semantic unity of the data and functions. Thus, objects are often *models* of real-world entities, and object-oriented programming leads to a particular style of programming analysis and design called *object-oriented analysis and design* to be discussed in Chapter 25.

## 23.1 Constructors and Members

A class is defined using the `type` keyword. Note that there are *always* parentheses after the class name to distinguish it from a regular type definition. The basic syntax for a class definition is as follows:

Listing 23.1: Syntax for simple class definitions.

```
1 type <classIdent> ({<arg>}) [as <selfIdent>]
2   {let <binding> | do <statement>}
3   {member <memberDef>}
```

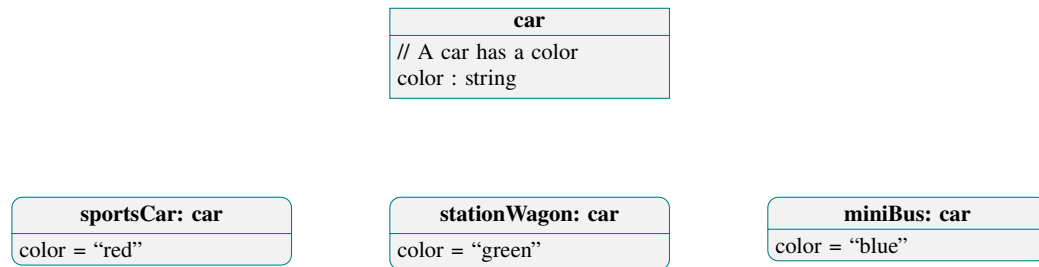
The first line is the header of the class, where the `<classIdent>` is the name of the class, `<arg>` are its optional arguments, and `<selfIdent>` is an optional *self identifier*. The body of a class consists of the constructor and the member section. The header and the constructor section is often collectively called the *constructor*, and the body of the constructor consist of optional `let`-bindings and `do`-statements. Note that the `do`-statements in a class definition *must* use the `do`-keyword. The member section consisting of all the optional member definitions, where each definition use the `member`-keyword.

The header and constructor section is commonly called the *constructor*, and the constructor is executed at instantiation. In contrast to many other languages, the constructor is always stated as the initial code of a class definition. The values and variables in the constructor are called *fields*, while functions are just called *functions*.

Members are declared using the `member`-keyword, which defines values and functions that are accessible from outside the class using the `“.”`-notation. In this manner, the members define the *interface* between the internal bindings in the constructor and an application program. Member values are called *properties*, and member functions are called *methods*. Note that members are immutable. The body of a member has access to the arguments, the constructor’s bindings, and to all class members, regardless of the member’s lexicographical order. In contrast, members are not available in the constructor unless the self identifier has been declared in the header using the keyword `as`, e.g., `type classMutable(name : string) as this = ....`

Consider the example in Figure 23.2. Here we have defined a class `car`, instantiated three objects, and bound them to the names `sportsCar`, `stationWagon`, and





**Fig. 23.2** A class `car` is instantiated three times and bound to the names `sportsCar`, `stationWagon`, and `miniBus`, and each object's properties are set to different values.

`miniBus`. Each object has been given different values for the `color` property. In F# this could look like the code in Listing 23.2. In the example, the class `car` is

**Listing 23.2** `car.fsx`:

Defining a class `car`, and making three instances of it. See also Figure 23.2.

```

1 type car (aColor : string) =
2     // Member section
3     member this.color = aColor
4
5 let sportsCar = car ("red")
6 let stationWagon = car ("green")
7 let miniBus = car ("blue")
8 printfn "%s %s %s" sportsCar.color stationWagon.color
   miniBus.color

```

---

```

1 $ fsharp --nologo car.fsx && mono car.exe
2 red green blue

```

defined in lines 1–3. Its header includes one string argument, `aColor`. The body of the constructor is empty, and the member section consists of lines 2–3. The class defines one property `color : string`. Note that when referring to a member inside an object, then we must use a *self identifier*. Here we use `this` as the self identifier, and as the example shows, we need not declare it in the class' header. A self identifier refers to the memory set aside to the particular instance of an object. It is common among other programming languages to use `this` as self identifier. F# is very flexible regarding what name can be used for the self-identifier, and the member section could as well have been `self.value`, `__.value`, or anything else, and it need not be the same in every member definition. Nevertheless, **consistency in the name used as self-identifier is strongly encouraged, preferably using a name that reflects the nature of the reference, such as `this` or `me`**. The objects are instantiated in lines 5–7, and the value of their properties are accessed in line 8. In many languages, objects are instantiated using the `new` keyword, but in F# this is optional. I.e., `let sportsCar = car ("red")` is identical to `let sportsCar = new car ("red")`. Note that both the self identifier and member access uses the `."` notation. ★

A more advanced implementation of a car class might include notions of a fuel gauge, fuel economy, and the ability to update the fuel gauge as the car is driven. An example of an implementation of this is given In Listing 23.3. Here in line 1,

**Listing 23.3 class.fsx:**

**Extending Listing 23.2 with fields and methods.**

```

1 type car (econ : float, fuel : float) =
2   // Constructor body section
3   let mutable fuelLeft = fuel // liters in the tank
4   do printfn "Created a car (%.1f, %.1f)" econ fuel
5   // Member section
6   member this.fuel = fuelLeft
7   member this.drive distance =
8     fuelLeft <- fuelLeft - econ * distance / 100.0
9
10  let sport = car (8.0, 60.0)
11  let economy = car (5.0, 45.0)
12  sport.drive 100.0
13  economy.drive 100.0
14  printfn "Fuel left after 100km driving:"
15  printfn " sport: %.1f" sport.fuel
16  printfn " economy: %.1f" economy.fuel

```

---

```

1 $ fsharpc --nologo class.fsx && mono class.exe
2 Created a car (8.0, 60.0)
3 Created a car (5.0, 45.0)
4 Fuel left after 100km driving:
5   sport: 52.0
6   economy: 40.0

```

the constructor has 2 arguments: the fuel economy parameter and the initial amount of fuel in the tank. Thus, we are able to create 2 different cars with different fuel economy, as shown in lines 10–11. The amount of fuel left in each car object is stored in the mutable field `fuelLeft`. This is an example of a state of an object: It can be accessed outside the object by the `fuel` property, and it can be updated by the `drive` method.

Field names and functions defined in the constructor do not use the self identifier and cannot be accessed outside an object using the “.” notation. However, they are available in both the constructor and the member section following the regular scope rules. Fields are a common way to hide implementation details, and they are *private* to the object or class in contrast to members that are *public*.

## 23.2 Accessors

Methods are most often used as an interface between the fields of an object and the application program. Consider the example in Listing 23.4. In the example, the

**Listing 23.4** classAccessor.fsx:

Accessor methods interface with internal bindings.

```

1 type aClass () =
2     let mutable v = 1
3     member this.setValue (newValue : int) : unit =
4         v <- newValue
5     member this.getValue () : int = v
6
7 let a = aClass ()
8 printfn "%d" (a.getValue ())
9 a.setValue (2)
10 printfn "%d" (a.getValue ())

```

---

```

1 $ fsharp --nologo classAccessor.fsx && mono classAccessor.exe
2 1
3 2

```

data contained in objects of type `aClass` is stored in the mutable field `v`. Since only members can be accessed from an application, it is not possible to retrieve or change the data of these object of class `aClass` directly. We could have programmed `v` as a member instead, i.e., `member this.v = 1`, however, often we are in a situation, where there is a range of possible choices of data representation, details of which we do wish to share with an application program. E.g., implementation details of arrays are not important for our ability to use them in applications. What matters is that the members that work on the array elements are well defined and efficient. Thus, the example demonstrates how we can build two simple methods `setValue` and `getValue` to set and get the data stored `v`. By making a distinction between the internal representation and how members give access to the data, we retain the possibility to change the internal representation without having to reprogram all the application programs. Analogously, we can change the engine in a car from one type to another without having to change the car's interaction with the driver and the road: steering wheel, pedals, wheels etc.

Such functions are called *accessors*. Internal states with setters and getters are a typical construction, since they allow for complicated computations when states are read to and written from, and gives the designer of the class the freedom to change the internal representation while keeping the interface the same. Accessors are so common that F# includes a special syntax for them: Classes can be made to act like variables using `member...with...and` keywords and the special function bindings `get()` and `set()`, as demonstrated in Listing 23.5. The expression defining

**Listing 23.5 classGetSet.fsx:**

Members can act as variables with the built-in get and set functions.

```

1 type aClass () =
2     let mutable v = 0
3     member this.value
4     with get () = v
5     and set (a) = v <- a
6
7 let a = aClass ()
8 printfn "%d" a.value
9 a.value<-2
10 printfn "%d" a.value

```

---

```

1 $ fsharp --nologo classGetSet.fsx && mono classGetSet.exe
2 0
3 2

```

get: () -> 'a and set: 'a -> (), where 'a is any type, can be any usual expression. The application calls the get and set as if the property were a mutable value. If set is omitted, then the property acts as a value rather than a variable, and values cannot be assigned to it in the application program.

Setters and getters are so common that F# has a short-hand for this using **member val value = 0 with get, set**, which creates the internal mutable value value, but this is discouraged in this text.

Defining an *Item* property with extended get and set makes objects act as indexed variables, as demonstrated in Listing 23.6. Higher dimensional indexed properties

**Listing 23.6 classGetSetIndexed.fsx:**

Properties can act as indexed variables with the built-in get and set functions.

```

1 type aClass (size : int) =
2     let arr = Array.create<int> size 0
3     member this.Item
4     with get (ind : int) = arr[ind]
5     and set (ind : int) (p : int) = arr[ind] <- p
6
7 let a = aClass (3)
8 printfn "%A" a
9 printfn "%d %d %d" a[0] a[1] a[2]
10 a[1] <- 3
11 printfn "%d %d %d" a[0] a[1] a[2]

```

---

```

1 $ dotnet fsi classGetSetIndexed.fsx
2 FSI_0001+aClass
3 0 0 0
4 0 3 0

```

are defined by adding more indexing arguments to the definition of `get` and `set`, such as demonstrated in Listing 23.7.

**Listing 23.7** `classGetSetHigherIndexed.fsx`:  
Getters and setters for higher dimensional index variables.

```
1 type aClass (rows : int, cols : int) =
2     let arr = Array2D.create<int> rows cols 0
3     member this.Item
4         with get (i : int, j : int) = arr[i,j]
5             and set (i : int, j : int) (p : int) = arr[i,j] <- p
6
7 let a = aClass (3, 3)
8 printfn "%A" a
9 printfn "%d %d %d" a[0,0] a[0,1] a[2,1]
10 a[0,1] <- 3
11 printfn "%d %d %d" a[0,0] a[0,1] a[2,1]
```

---

```
1 $ dotnet fsi classGetSetHigherIndexed.fsx
2 FSI_0001+aClass
3 0 0 0
4 0 3 0
```

### 23.3 Objects are Reference Types

- Objects are reference type values, implying that copying objects copies their references, not their values, and their content is stored on *The Heap*, see Section 20.2. Consider the example in Listing 23.8. Thus, the binding to `b` in line 6 is an alias to `a`, not a copy, and changing object `a` also changes `b`! This is a common cause of error, and you should **think of objects as arrays**. For this reason, it is often seen that classes implement a copy function returning a new object with copied values, as shown in Listing 23.9. In the example, we see that since `b` now is a copy, we do not change it by changing `a`. This is called a *copy constructor*.

**Listing 23.8 classReference.fsx:**  
Objects assignment can cause aliasing.

```

1 type aClass () =
2     let mutable v = 0
3     member this.value with get () = v and set (a) = v <- a
4
5 let a = aClass ()
6 let b = a
7 a.value <- 2
8 printfn "%d %d" a.value b.value

```

---

```

1 $ fsharp --nologo classReference.fsx && mono
   classReference.exe
2 2 2

```

**Listing 23.9 classCopy.fsx:**  
A copy method is often needed. Compare with Listing 23.8.

```

1 type aClass () =
2     let mutable v = 0
3     member this.value with get () = v and set (a) = v <- a
4     member this.copy () =
5         let o = aClass ()
6         o.value <- v
7         o
8 let a = aClass ()
9 let b = a.copy ()
10 a.value <- 2
11 printfn "%d %d" a.value b.value

```

---

```

1 $ fsharp --nologo classCopy.fsx && mono classCopy.exe
2 2 0

```

## 23.4 Static Classes

Classes can act as modules and hold data which is identical for all objects of its type. These are defined using the `static`-keyword. And since they do not belong to a single object, but are shared between all objects, they are defined without the self-identifier and accessed using the class name, and they cannot refer to the arguments of the constructor. For example, consider a class whose objects each hold a unique identification number (id): When an object is instantiated, the object must be given the next available identification number. The next available id could be given as an argument to the constructor, however, this delegates the task of maintaining the uniqueness of ids to the application program. It is better to use a static field and delegate the administration of ids completely to the constructors, as demonstrated in Listing 23.10. Notice in line 2 that a static field `nextAvailableID` is created for the

**Listing 23.10** `classStatic.fsx`:

Static fields and members are identical to all objects of the type.

```

1 type student (name : string) =
2     static let mutable nextAvailableID = 0 // A global id for
      all objects
3     let studentID = nextAvailableID // A per object id
4     do nextAvailableID <- nextAvailableID + 1
5     member this.id with get () = studentID
6     member this.name = name
7     static member nextID = nextAvailableID // A global member
8 let a = student ("Jon") // Students will get unique ids, when
      instantiated
9 let b = student ("Hans")
10 printfn "%s: %d, %s: %d" a.name a.id b.name b.id
11 printfn "Next id: %d" student.nextID // Accessing the class's
      member

```

---

```

1 $ fsharp --nologo classStatic.fsx && mono classStatic.exe
2 Jon: 0, Hans: 1
3 Next id: 2

```

value to be shared by all objects. The initialization of its value is only performed once, at the beginning of program execution. However, every time an object is instantiated, the value of `nextAvailableID` is copied to the object's field `studentID` in line 3, and `nextAvailableID` is updated. The static field can be accessed with a static accessor, as demonstrated in line 7. Notice how this definition does not include a self-identifier, and that the member is accessible from the application in line 11 using the class' name, in both cases since it is not a member of any particular object.

### 23.5 Recursive Members and Classes

The members of a class are inherently recursive: static and non-static methods may recurse using the self identifier and other members regardless of their lexicographical scope. This is demonstrated in Listing 23.11. For mutually recursive classes, the

**Listing 23.11** classRecursion.fsx:

Members can recurse without the `rec` keyword and refer to other members regardless of their lexicographical scope.

```
1 type twice (v : int) =
2     static member fac n = if n > 1 then n * (twice.fac (n-1))
3     else 1 // No rec
4     member this.copy = this.twice // No lexicographical scope
5     member this.twice = 2*v
6
7 let a = twice (2)
8 let b = twice.fac 3
9 printfn "%A %A %A" a.copy a.twice b
10
11 -----
12 $ fsharp --nologo classRecursion.fsx && mono
13     classRecursion.exe
14 2 4 4 6
```

keyword `and` must be used, as shown in Listing 23.12. Here `anInt` and `aFloat`

**Listing 23.12** classAssymetry.fsx:

Mutually recursive classes are defined using the `and` keyword.

```
1 type anInt (v : int) =
2     member this.value = v
3     member this.add (w : aFloat) : aFloat = aFloat ((float
4     this.value) + w.value)
5 and aFloat (w : float) =
6     member this.value = w
7     member this.add (v : anInt) : aFloat = aFloat ((float
8     v.value) + this.value)
9 let a = anInt (2)
10 let b = aFloat (3.2)
11 let c = a.add b
12 let d = b.add a
13 printfn "%A %A %A %A" a.value b.value c.value d.value
14
15 -----
16 $ fsharp --nologo classAssymetry.fsx && mono
17     classAssymetry.exe
18 2 2 3.2 5.2 5.2
```

hold an integer and a floating point value respectively, and they both implement



an addition of anInt an aFloat that returns and aFloat. Thus, they are mutually dependent and must be defined in the same `type` definition using `and`.

## 23.6 Function and Operator Overloading

It is often convenient to define different methods that have the same name, but with functionalities that depend on the number and type of arguments given. This is called *overloading*, and F# supports method overloading. An example is shown in Listing 23.13. In the example we define an object which can produce greetings

**Listing 23.13** classOverload.fsx:

Overloading methods `set : int -> ()` and `set : int * int -> ()` is permitted, since they differ in argument number or type.

```
1 type Greetings () =
2     let mutable greetings = "Hi"
3     let mutable name = "Programmer"
4     member this.str = greetings + " " + name
5     member this.setName (newName : string) : unit =
6         name <- newName
7     member this.setName (newName : string, newGreetings :
8         string) : unit =
9         greetings <- newGreetings
10        name <- newName
11 let a = Greetings ()
12 printfn "%s" a.str
13 a.setName ("F# programmer")
14 printfn "%s" a.str
15 a.setName ("Expert", "Hello")
16 printfn "%s" a.str
```

---

```
1 $ fsharp --nologo classOverload.fsx && mono classOverload.exe
2 Hi Programmer
3 Hi F# programmer
4 Hello Expert
```

strings of the form `<greeting> <name>`, using the `str` member. It has a default greeting “Hi” and name “Programmer”, but the name can be changed by calling the `setName` accessor with one argument, and both greeting and name can be changed by calling the overloaded `setName` with two arguments. Overloading in class definition is allowed as long as the arguments differ in number or type.

In Listing 23.12, the notation for addition is less than elegant. For such situations, F# supports *operator overloading*. All usual operators may be overloaded (see ??), and in contrast to regular operator overloading, the compiler uses type inference to

decide which function is to be called. All operators have a functional equivalence, and to overload the binary “+” and unary “-” operators, we overload their functional equivalence (+) and (~-) as static members. This is demonstrated in Listing 23.14. Thus, writing `v + w` is equivalent to writing `anInt.(+) (v, w)`. Presently, the

**Listing 23.14** `classOverloadOperator.fsx`:  
Operators can be overloaded using their functional equivalents.

```

1 type anInt (v : int) =
2     member this.value = v
3     static member (+) (v : anInt, w : anInt) = anInt (v.value +
4         w.value)
5     static member (~-) (v : anInt) = anInt (-v.value)
6 and aFloat (w : float) =
7     member this.value = w
8     static member (+) (v : aFloat, w : aFloat) = aFloat
9         (v.value + w.value)
10    static member (+) (v : anInt, w : aFloat) =
11        aFloat ((float v.value) + w.value)
12    static member (+) (w : aFloat, v : anInt) = v + w // reuse
13        def. above
14    static member (~-) (v : aFloat) = aFloat (-v.value)
15
16 let a = anInt (2)
17 let b = anInt (3)
18 let c = aFloat (3.2)
19 let d = a + b // anInt + anInt
20 let e = c + a // aFloat + anInt
21 let f = a + c // anInt + aFloat
22 let g = -a // unitary minus anInt
23 let h = a + -b // anInt + unitary minus anInt
24 printf "a=%A, b=%A, c=%A, d=%A" a.value b.value c.value
25     d.value
26 printf ", e=%A, f=%A, g=%A, h=%A" e.value f.value g.value
27     h.value

```

---

```

1 $ fsharp --nologo classOverloadOperator.fsx && mono
   classOverloadOperator.exe
2 a=2, b=3, c=3.2, d=5, e=5.2, f=5.2, g=-2, h=-1

```

former is to be preferred, but at times, e.g., when using functions as arguments, it is useful to be able to refer to an operator by its function-equivalent. Note that the functional equivalence of the multiplication operator (*) shares a prefix with the begin block comment lexeme “(“”, which is why the multiplication function is written as ( * ). Note also that unitary operators have a special notation using the “~”-lexeme, as illustrated in the above example for unitary minus. With the unitary minus, we are able to subtract objects of `anInt` by first negating the right-hand operand and then adding the result to the left-hand operand. In contrast, the binary minus would have been defined as `static member (-) (v : anInt, w : aFloat) = anInt ((float v.value) - w.value)`.

In Listing 23.14, notice how the second (+) operator overloads the first by calling the first with the proper order of arguments. This is a general principle: **avoid duplication of code, reuse of existing code is almost always preferred.** ★ Here it is to be preferred for two reasons. Firstly, if we discover a mistake in the multiplication code, then we need only correct it once, which implies that both multiplication methods are corrected once and reduces the chance of introducing new mistakes by attempting to correct old ones. Secondly, if we later decide to change the internal representation, then we only need to update one version of the multiplication function, hence we reduce programming time and risk of errors as well.

Beware that operator overloading outside class definitions overwrites *all* definitions of the operator. E.g., overloading (+) (v, w) outside a class will influence integer, real, string, etc. Thus, **operator overloading should only be done inside class definitions.** ★

## 23.7 Additional Constructors

Like methods, constructors can also be overloaded by using the `new` keyword. E.g., the example in Listing 23.13 may be modified, such that the name and possibly greeting is set at object instantiation rather than by using the accessor. This is illustrated in Listing 23.15. The top constructor that does not use the `new`-keyword is called the *pri-*

**Listing 23.15** classExtraConstructor.fsx:  
Extra constructors can be added, using `new`.

```
1 type classExtraConstructor (name : string, greetings :
   string) =
2     static let defaultGreetings = "Hello"
3     // Additional constructors are defined by new ()
4     new (name : string) =
5         classExtraConstructor (name, defaultGreetings)
6     member this.name = name
7     member this.str = greetings + " " + name
8
9 let s = classExtraConstructor ("F#") // Calling additional
   constructor
10 let t = classExtraConstructor ("F#", "Hi") // Calling primary
   constructor
11 printfn "%A, %A" s.str t.str
```

---

```
1 $ fsharp --nologo classExtraConstructor.fsx && mono
   classExtraConstructor.exe
2 "Hello F#", "Hi F#"
```

- mary constructor*. The body of the additional constructor must call the primary constructor, and the body cannot extend the primary constructor's fields and functions. It
- ★ is useful to **think of the primary constructor as a superset of arguments and the additional ones as subsets or specializations**. As regular scope rules dictate, the additional constructor has access to the primary constructor's bindings. However, in order to access the object's members, the self identifier has to be explicitly declared, using the `as`-keyword in the header. E.g., writing `new(x : float, y : float) as alsoThis = ...`. However beware. Even though the body of the additional constructor now may access the property `alsoThis.x`, this value has first been created once the primary constructor has been called. E.g., calling the primary constructor in the additional constructor as `new(x : float, y : float) as alsoThis = classExtraConstructor(fst alsoThis.x, y, defaultSeparator)` will result in an exception at runtime. Code may be executed in additional constructors: Before the call to the primary constructor, `let` and `do` statements are allowed. If code is to be executed after the primary constructor has been called, then it must be preceded by the `then` keyword, as shown in Listing 23.16. The `do`-keyword is often understood to be implied by F#, e.g., in front of all `printf`-statements, but in the above examples they are required where used. This may change in future releases of F#. F# allows for many additional constructors, but they must be distinguishable by type.

**Listing 23.16 classDoThen.fsx:**

The optional **do**- and **then**-keywords allow for computations before and after the primary constructor is called.

```
1 type classDoThen (aValue : float) =
2   // "do" is mandatory to execute code in the primary
   constructor
3   do printfn " Primary constructor called"
4   // Some calculations
5   do printfn " Primary done" (* *)
6   new () =
7     // "do" is optional in additional constructors
8     printfn " Additional constructor called"
9     classDoThen (0.0)
10    // Use "then" to execute code after construction
11    then
12      printfn " Additional done"
13    member this.value = aValue
14
15 printfn "Calling additional constructor"
16 let v = classDoThen ()
17 printfn "Calling primary constructor"
18 let w = classDoThen (1.0)
```

---

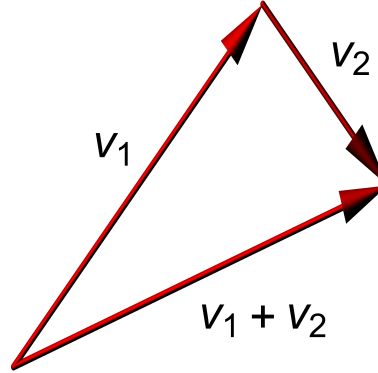
```
1 $ fsharp --nologo classDoThen.fsx && mono classDoThen.exe
2 Calling additional constructor
3   Additional constructor called
4   Primary constructor called
5   Primary done
6   Additional done
7 Calling primary constructor
8   Primary constructor called
9   Primary done
```

## 23.8 Programming Intermezzo: Two Dimensional Vectors

Consider the following problem.

### Problem 23.1

Euclidean vector is a geometric object that has a direction, a length, and two operations: vector addition and scalar multiplication, see Figure 23.3. Define a class for a vector in two dimensions.



**Fig. 23.3** Illustration of vector addition in two dimensions.

An essential part in designing a solution for the above problem is to decide which representation to use internally for vectors. The Cartesian representation of a vector is as a tuple of real values  $(x, y)$ , where  $x$  and  $y$  are real values, and where we can imagine that the tail of the vector is in the origin, and its tip is at the coordinate  $(x, y)$ . For vectors on Cartesian form,

$$\mathbf{v} = (x, y), \quad (23.1)$$

the basic operations are defined as

$$\mathbf{v}_1 + \mathbf{v}_2 = (x_1 + x_2, y_1 + y_2), \quad (23.2)$$

$$a\mathbf{v} = (ax, ay), \quad (23.3)$$

$$\text{dir}(\mathbf{v}) = \tan^{-1} \frac{y}{x}, \quad x \neq 0, \quad (23.4)$$

$$\text{len}(\mathbf{v}) = \sqrt{x^2 + y^2}, \quad (23.5)$$

where  $x_i$  and  $y_i$  are the elements of vector  $\mathbf{v}_i$ ,  $a$  is a scalar, and  $\text{dir}$  and  $\text{len}$  are the direction and length functions, respectively. The polar representation of vectors is also a tuple of real values  $(\theta, l)$ , where  $\theta$  is the vector's angle from the  $x$ -axis and  $l$  is the vector's length. This representation is closely tied to the definition of a vector, and has the constraint that  $0 \leq \theta < 2\pi$  and  $0 \leq l$ . This representation reminds us

that vectors do not have a position. For vectors on polar form,

$$\mathbf{v} = (\theta, l), \quad (23.6)$$

their basic operations are defined as

$$x(\theta, l) = l \cos(\theta), \quad (23.7)$$

$$y(\theta, l) = l \sin(\theta), \quad (23.8)$$

$$\mathbf{v}_1 + \mathbf{v}_2 = (x(\theta_1, l_1) + x(\theta_2, l_2), y(\theta_1, l_1) + y(\theta_2, l_2)) \quad (23.9)$$

$$a\mathbf{v} = (\theta, al), \quad (23.10)$$

where  $\theta_i$  and  $l_i$  are the elements of vector  $\mathbf{v}_i$ ,  $a$  is a scalar, and  $x$  and  $y$  are the Cartesian coordinate functions.

So far in our analysis, we have realized that:

- both the Cartesian and polar representations use a pair of reals to represent the vector,
- both require functions to calculate the elements of the other representation,
- the polar representation is invalid for negative lengths, and
- the addition operator under the polar representation is also more complicated and essentially requires access to the Cartesian representation.

The first step in shaping our solution is to decide on file structure: For conceptual separation, we choose to use a library and an application file. F# wants files to define namespaces or modules, so we choose the library to be a `Geometry` module, which implements the vector class to be called `vector`. Furthermore, when creating vector objects we would like to give the application program the ability to choose either Cartesian or polar form. This can be done using *discriminated unions*. Discriminated unions allow us to tag values of possibly identical form, but they also lead to longer programs. Thus, we will also provide an additional constructor on implicit Cartesian form, since this is the most common representation of vectors.

A key point when defining libraries is to consider their interface with the application program. Hence, our second step is to write an application using the yet to be written library in order to get a feel for how such an interface could be. This is demonstrated in the application program Listing 23.17. The application of the vector class seems natural, makes use of the optional discriminated unions, uses the infix operators “+” and “*” in a manner close to standard arithmetic, and interacts smoothly with the `printf` family. Thus, we have further sketched requirements to the library with the emphasis on application.

**Listing 23.17** `vectorApp.fsx`:  
An application using the library in Listing 23.18.

```
1 open Geometry
2 let v = vector(Cartesian (1.0,2.0))
3 let w = vector(Polar (3.2,1.8))
4 let p = vector()
5 let q = vector(1.2, -0.9)
6 let a = 1.5
7 printfn "%A * %A = %A" a v (a * v)
8 printfn "%A + %A = %A" v w (v + w)
9 printfn "vector() = %A" p
10 printfn "vector(1.2, -0.9) = %A" q
11 printfn "v.dir = %A" v.dir
12 printfn "v.len = %A" v.len
```

After a couple of trials, our library implementation has ended up as shown in Listing 23.18. Realizations achieved during writing this code are: Firstly, in order to implement a vector class using discriminated unions, we had to introduce a constructor with helper variables `_x`, `_y`, etc. The consequence is that the Cartesian and polar representation is evaluated once and only once every time an object is created. Unfortunately, discriminated unions do not implement guards on subsets, so we still have to cast an exception when the application attempts to create an object with a negative length. Secondly, for the `ToString` override we have implemented static members for typesetting vectors, since it seems more appropriate that all vectors should be typeset identically. Changing typesetting thus respects dynamic scope.

The output of our combined library and application is shown in Listing 23.19. The output is as expected, and for the vector class, our solution seems to be a good compromise between versatility and syntactical bloating.



**Listing 23.18** vector.fs:

A library serving the application in Listing 23.19.

```

1 module Geometry
2 type Coordinate =
3   Cartesian of float * float // (x, y)
4   | Polar of float * float // (dir, len)
5 type vector(c : Coordinate) =
6   let (_x, _y, _dir, _len) =
7     match c with
8     | Cartesian (x, y) ->
9       (x, y, atan2 y x, sqrt (x * x + y * y))
10    | Polar (dir, len) when len >= 0.0 ->
11      (len * cos dir, len * sin dir, dir, len)
12    | Polar (dir, _) ->
13      failwith "Negative length in polar representation."
14 new(x : float, y : float) =
15   vector(Cartesian (x, y))
16 new() =
17   vector(Cartesian (0.0, 0.0))
18 member this.x = _x
19 member this.y = _y
20 member this.len = _len
21 member this.dir = _dir
22 static member val left = "(" with get, set
23 static member val right = ")" with get, set
24 static member val sep = ", " with get, set
25 static member ( * ) (a : float, v : vector) : vector =
26   vector(Polar (v.dir, a * v.len))
27 static member ( * ) (v : vector, a : float) : vector =
28   a * v
29 static member (+) (v : vector, w : vector) : vector =
30   vector(Cartesian (v.x + w.x, v.y + w.y))
31 override this.ToString() =
32   sprintf "%s%A%s%A%s" vector.left this.x vector.sep this.y
   vector.right

```

**Listing 23.19:** Compiling and running the code from Listing 23.18 and 23.17.

```

1 $ fsharpc --nologo vector.fs vectorApp.fsx && mono
   vectorApp.exe
2 1.5 * (1.0, 2.0) = (1.5, 3.0)
3 (1.0, 2.0) + (-1.796930596, -0.1050734582) = (-0.796930596,
   1.894926542)
4 vector() = (0.0, 0.0)
5 vector(1.2, -0.9) = (1.2, -0.9)
6 v.dir = 1.107148718
7 v.len = 2.236067977

```

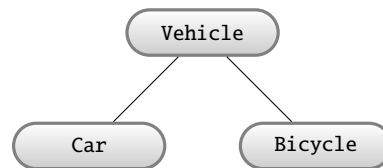


## Chapter 24

### Derived Classes

#### 24.1 Inheritance

Sometimes it is useful to derive new classes from old ones in order to reuse code or to emphasize a program structure. For example, consider the concepts of a *car* and *bicycle*. They are both *vehicles* that can move forward and turn, but a car can move in reverse, has 4 wheels, and uses gasoline or electricity, while a bicycle has 2 wheels and needs to be pedaled. Structurally, we can say that “a car is a vehicle” and “a bicycle is a vehicle”. Such a relation is sometimes drawn as a tree as shown in Figure 24.1 and is called an *is-a relation*. Is-a relations can be implemented using



**Fig. 24.1** Both a car and a bicycle is a (type of) vehicle.

class *inheritance*, where vehicle is called the *base class*, and car and bicycle are each a *derived class*. The advantage is that a derived class can inherit the members of the base class, *override*, and possibly add new members. Another advantage is that objects from derived classes can be made to look like as if they were objects of the base class while still containing all their data. Such masquerading is useful when, for example, listing cars and bicycles in the same list.

In F#, inheritance is indicated using the `inherit` keyword in the class definition. An extensions of the syntax in Listing 24.1 is:

**Listing 24.1:** A class definition with inheritance.

```

1 type <classIdent> ({<arg>}) [as <selfIdent>]
2   [inherit <baseClassIdent>({<arg>})]
3   {[let <binding>] | [do <statement>]}
4   {(member | abstract member | default | override)
    <memberDef>}

```

New syntactical elements are: the `inherit` keyword, which indicates that this is a derived class and where `<baseClassIdent>` is the name of the base class. Further, members may be regular members using the `member` keyword as discussed in the previous chapter, and members can also be other types, as indicated by the keywords: `abstract member`, `default`, and `override`.

An example of defining base and derived classes for vehicles is shown in Listing 24.2. In the example, a simple base class `vehicle` is defined to include `wheels` as its

**Listing 24.2** `vehicle.fsx`:  
New classes can be derived from old ones.

```

1  /// All vehicles have wheels
2  type vehicle (nWheels : int) =
3    member this.wheels = nWheels
4
5  /// A car is a vehicle with 4 wheels
6  type car (nPassengers : int) =
7    inherit vehicle (4)
8    member this.maxPassengers = nPassengers
9
10 /// A bicycle is a vehicle with 2 wheels
11 type bicycle () =
12   inherit vehicle (2)
13   member this.mustUseHelmet = true
14
15 let aVehicle = vehicle (1)
16 let aCar = car (4)
17 let aBike = bicycle ()
18 printfn "aVehicle has %d wheel(s)" aVehicle.wheels
19 printfn "aCar has %d wheel(s) with room for %d passenger(s)"
20   aCar.wheels aCar.maxPassengers
21 printfn "aBike has %d wheel(s). Is helmet required? %b"
22   aBike.wheels aBike.mustUseHelmet

```

---

```

1 $ fsharp --nologo vehicle.fsx && mono vehicle.exe
2 aVehicle has 1 wheel(s)
3 aCar has 4 wheel(s) with room for 4 passenger(s)
4 aBike has 2 wheel(s). Is helmet required? true

```

single member. The derived classes inherit all the members of the base class, but do not have access to any non-members of the base constructor. I.e., `car` and `bicycle`

automatically have the `wheels` property. Both derived classes additional members `maxPassengers` and `mustUseHelmet`, respectively.

Derived classes can replace base class members by defining new members *overshadow* the base members. The base members are still available through the `base`-keyword. Consider the example in the Listing 24.3. In this case, we have defined three

**Listing 24.3** `memberOvershadowingVar.fsx`:

Inherited members can be overshadowed, but we can still access the base member. Compare with Listing 24.7.

```

1  /// hi is a greeting
2  type greeting () =
3      member this.str = "hi"
4  /// hello is a greeting
5  type hello () =
6      inherit greeting ()
7      member this.str = "hello"
8  /// howdy is a greeting
9  type howdy () =
10     inherit greeting ()
11     member this.str = "howdy"
12
13  let a = greeting ()
14  let b = hello ()
15  let c = howdy ()
16  printfn "%s, %s, %s" a.str b.str c.str

```

---

```

1  $ fsharp --nologo memberOvershadowingVar.fsx && mono
   memberOvershadowingVar.exe
2  hi, hello, howdy

```

greetings: `greeting`, `hello`, and `howdy`. The two later inherit `member this.str = "hi"` from `greeting`, but since they both also define a member property `str`, these overshadow the one from `greeting`. In `hello` and `howdy` the base value of `str` is available as `base.str`.

Even though derived classes are different from their base, the derived class includes the base class, which can be recalled using *upcasting* by the upcast operator `:>`. At compile-time, this operator removes the additions and overshadowing of the derived class, as illustrated in Listing 24.4. Here `howdy` is derived from `hello`, overshadows `str`, and adds property `altStr`. By upcasting object `b`, we create object `c` as a copy of `b` with all its fields, functions, and members, as if it had been of type `hello`. I.e., `c` contains the base class version of `str` and does not have property `altStr`. Objects `a` and `c` are now of same type and can be put into, e.g., an array as `let arr = [|a, c|]`. Previously upcasted objects can also be downcasted again using the *downcast* operator `?:>`, but the validity of the operation is checked at runtime. Thus, **avoid downcasting when possible.** ★

**Listing 24.4 upCasting.fsx:**

Objects can be upcasted resulting in an object to appear to be of the base type. Implementations from the derived class are ignored.

```
1  /// hello holds property str
2  type hello () =
3      member this.str = "hello"
4  /// howdy is a hello class and has property altStr
5  type howdy () =
6      inherit hello ()
7      member this.str = "howdy"
8      member this.altStr = "hi"
9
10 let a = hello ()
11 let b = howdy ()
12 let c = b :> hello // a howdy object as if it were a hello
13     object
14     printfn "%s %s %s %s" a.str b.str b.altStr c.str
15
16 -----
17 1 $ fsharp --nologo upCasting.fsx && mono upCasting.exe
2 2 hello howdy hi hello
```

## 24.2 Interfacing with the `printf` Family

In previous examples, we accessed the property in order to print the contents of objects. Luckily, a more elegant solution is available. Objects can be printed directly, but the result is most often not very useful, as can be seen in Listing 24.5. All classes

### Listing 24.5 `classPrintf.fsx`:

Printing classes yields low-level information about the class.

```
1 type vectorDefaultToString (x : float, y : float) =
2     member this.x = (x,y)
3
4 let v = vectorDefaultToString (1.0, 2.0)
5 printfn "%A" v // Printing objects gives low-level
                  information
-----
1 $ fsharp --nologo classPrintf.fsx && mono classPrintf.exe
2 ClassPrintf+vectorDefaultToString
```

implicitly inherit from a class with the peculiar name, *System.Object*, and as a consequence, all classes have a number of already defined members. One example is the `ToString() : () -> string` function, which is useful in conjunction with, e.g., `printf`. When an object is given as argument to a `printf` function with the `%A` or `%O` placeholders in the formatting string, `printf` calls the object's `ToString()` function. The default implementation returns low-level information about the object, as can be seen above, but we may *override* this member using the *override*-keyword, as demonstrated in Listing 24.6. Note, despite that `ToString()` returns a string, the `%s` placeholder only accepts values of the basic string type. We see

### Listing 24.6 `classToString.fsx`:

Overriding `ToString()` function for better interaction with members of the `printf` family of procedures. Compare with Listing 24.5.

```
1 type vectorWToString (x : float, y : float) =
2     member this.x = (x,y)
3     // Custom printing of objects by overriding this.ToString()
4     override this.ToString() =
5         sprintf "(%A, %A)" (fst this.x) (snd this.x)
6
7 let v = vectorWToString(1.0, 2.0)
8 printfn "%A" v // No change in application but result is
                  better
-----
1 $ fsharp --nologo classToString.fsx && mono classToString.exe
2 (1.0, 2.0)
```

that as a consequence, the `printf` statement is much simpler. However beware, an

- application program may require other formatting choices than selected at the time of designing the class, e.g., in our example, the application program may prefer square brackets as delimiters for vector tuples. So in general **when designing an override to ToString(), choose simple, generic formatting for the widest possible use.**

The most generic formatting is not always obvious, and in the vector case some candidates for the formatting string of ToString() are “%A %A”, “%A, %A”, “(%A, %A)”, and “[%A, %A]”. Considering each carefully, it seems that arguments can be made against all them. A common choice is to let the formatting be controlled by static members that can be changed by the application program through accessors.

### 24.3 Abstract Classes

In the previous sections, we have discussed inheritance as a method to modify and extend any class. I.e., the definition of the base classes were independent of the definitions of inherited classes. In that sense, the base classes were oblivious to any future derivation of them. Sometimes it is useful to define base classes which are not independent of derived classes and which impose design constraints of derived classes. Two such dependencies in F# are abstract classes and interfaces.

An *abstract class* contains members defined using the *abstract member* and optionally the *default* keywords. An *abstract member* in the base class is a type definition, and derived classes must provide an implementation using the *override* keyword. Optionally, the base class may provide a default implementation using the *default* keyword, in which case overriding is not required in derived classes. Objects of classes containing abstract members without default implementations cannot be instantiated, but derived classes that provide the missing implementations can. Note that abstract classes must be given the [*AbstractClass*] attribute. Note also that in contrast to overshadowing, upcasting keeps the implementations of the derived classes. Examples of this are shown in Listing 24.7. In the example, we define a base class and two derived classes. Note how the abstract member is defined in the base class using the “:”-operator as a type declaration rather than a name binding. Note also that since the base class does not provide a default implementation, the derived classes supply an implementation using the *override*-keyword. In the example, objects of `baseClass` cannot be created, since such objects would have no implementation for `this.hello`. Finally, the two different derived and up-casted objects can be put in the same array, and when calling their implementation of `this.hello`, we still get the derived implementations, which is in contrast to overshadowing.

Abstract classes may also specify a default implementation, such that derived classes have the option of implementing an overriding member, but are not forced to. In spite



**Listing 24.7 abstractClass.fsx:**

In contrast to regular objects, upcasted derived objects use the derived implementation of abstract methods. Compare with Listing 24.3.

```

1  /// An abstract class for general greeting classes with
    property str
2  [<AbstractClass>]
3  type greeting () =
4      abstract member str : string
5  /// hello is a greeting
6  type hello () =
7      inherit greeting ()
8      override this.str = "hello"
9  /// howdy is a greeting
10 type howdy () =
11     inherit greeting ()
12     override this.str = "howdy"
13
14 let a = hello ()
15 let b = howdy ()
16 let c = [| a :> greeting; b :> greeting |] // arrays of
    greetings
17 Array.iter (fun (elm : greeting) -> printfn "%s" elm.str) c

```

---

```

1  $ fsharp --nologo abstractClass.fsx && mono abstractClass.exe
2  hello
3  howdy

```

of implementations being available in the abstract class, the abstract class still cannot be used to instantiate objects. The example in Listing 24.8 shows an extension of Listing 24.7 with a default implementation. In the example, the program in Listing 24.7 has been modified such that `greeting` is given a default implementation for `str`, in which case `hello` does not need to supply one. However, in order for `howdy` to provide a different greeting, it still needs to provide an override member.

Note that even if all abstract members in an abstract class have defaults, objects of its type can still not be created, but must be derived as, e.g., shown with `hello` above.

As a side note, every class implicitly derives from a base class *System.Object*, which is an abstract class defining among other members, the `ToString` method with default implementation.

**Listing 24.8** `abstractDefaultClass.fsx`:  
Default implementations in abstract classes make implementations in derived classes optional. Compare with Listing 24.7.

```

1  /// An abstract class for general greeting classes with
    property str
2  [<AbstractClass>]
3  type greeting () =
4      abstract member str : string
5      default this.str = "hello" // Provide default
        implementation
6  /// hello is a greeting
7  type hello () =
8      inherit greeting ()
9  /// howdy is a greeting
10 type howdy () =
11     inherit greeting ()
12     override this.str = "howdy"
13
14 let a = hello ()
15 let b = howdy ()
16 let c = [| a :> greeting; b :> greeting |] // arrays of
        greetings
17 Array.iter (fun (elm : greeting) -> printfn "%s" elm.str) c

```

---

```

1  $ fsharp --nologo abstractDefaultClass.fsx && mono
    abstractDefaultClass.exe
2  hello
3  howdy

```

## 24.4 Interfaces

Inheritance of an abstract base class allows an application to rely on the definition of the base, regardless of any future derived classes. This gives great flexibility, but at times even less knowledge is needed about objects in order to write useful applications. This is what *interfaces* offer. An interface specifies which members must exist, but nothing more. Interfaces are defined as an abstract class *without arguments* and *only with abstract members*. Classes implementing interfaces must specify implementations for the abstract members using the *interface with* keywords. Objects of classes implementing interfaces can be upcasted as if they had an abstract base class of the interface's name. Consider the example in Listing 24.9. Here, two distinctly different classes are defined: `house` and `person`. These are not related by inheritance, since no sensible common structure seems available. However, they share structures in the sense that they both have an integer property and a `float -> float` method. For each of the derived classes, these members have different meanings. Still, some treatment of these members by an application will only rely on their type and not their meaning. E.g., in Listing 24.9, the `printfn`

**Listing 24.9 classInterface.fsx:**

Interfaces specify which members classes contain, and with upcasting gives more flexibility than abstract classes.

```

1  /// An interface for classes that have method fct and member
   value
2  type IValue =
3      abstract member fct : float -> float
4      abstract member value : int
5  /// A house implements the IValue interface
6  type house (floors: int, baseArea: float) =
7      interface IValue with
8          // calculate total price based on per area average
9          member this.fct (pricePerArea : float) =
10             pricePerArea * (float floors) * baseArea
11             // return number of floors
12             member this.value = floors
13  /// A person implements the IValue interface
14  type person(name : string, height: float, age : int) =
15      interface IValue with
16          // calculate body mass index (kg/(m*m)) using hypothetic
           mass
17          member this.fct (mass : float) = mass / (height * height)
18          // return the length of name
19          member this.value = name.Length
20          member this.data = (name, height, age)
21
22  let a = house(2, 70.0) // a two storage house with 70 m*m
           base area
23  let b = person("Donald", 1.8, 50) // a 50 year old person 1.8
           m high
24  let lst = [a :> IValue; b :> IValue]
25  let printInterfacePart (o : IValue) =
26      printfn "value = %d, fct(80.0) = %g" o.value (o.fct 80.0)
27  List.iter printInterfacePart lst

```

---

```

1  $ fsharp --nologo classInterface.fsx && mono
   classInterface.exe
2  value = 2, fct(80.0) = 11200
3  value = 6, fct(80.0) = 24.6914

```

function only needs to know the member's type, not its meaning. As a consequence, the application can upcast them both to the implicit abstract base class `IValue`, put them in an array, and apply a function using the member definition of `IValue` with the higher-order `List.iter` function. Another example could be a higher-order function calculating average values: For average values of the number of floors and average value of the length of people's names, the higher-order function would only need to know that both of these classes implement the `IValue` interfaces in order to calculate the average of list of either objects' types.

As a final note, inheritance ties classes together in a class hierarchy. Abstract members enforce inheritance and impose constraints on the derived classes. Like abstract classes, interfaces impose constraints on derived classes, but without requiring a hierarchical structure.

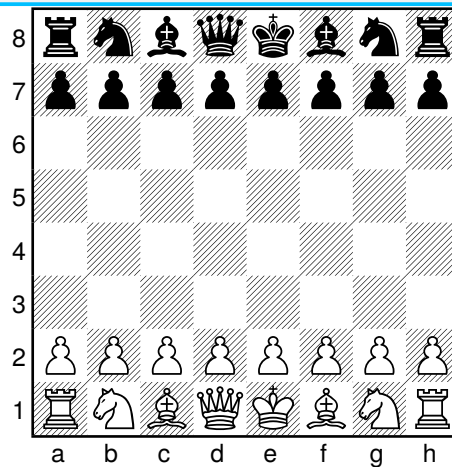
## 24.5 Programming Intermezzo: Chess

To demonstrate the use of hierarchies, consider the following problem.

### Problem 24.1

The game of chess is a turn-based game for two which consists of a board of  $8 \times 8$  squares, and a set of 16 black and 16 white pieces. A piece can be either a king, queen, rook, bishop, knight or pawn, and each piece has a specific movement pattern on the board. Pieces are added to, moved on, and removed from the board during the game, and there can be at most one piece per square. A piece strikes another piece of opposing color by moving to its square and the piece of opposing color is removed from the game. The game starts with the configuration shown in Figure 24.2.

Make a program that allows two humans to play simple chess using only kings and rooks. The king must be able to move to all neighboring squares not occupied by a piece of the same color and cannot move onto a square where it can be struck in the next turn. The rook must be able to move in horizontal and vertical lines until a piece of the same color or up to and including a piece of opposing color.



**Fig. 24.2** Starting position for the game of chess.

Since we expect that the solution to the above problem is going to be a relatively long program, we have decided to split the code into a library and an application program. Before writing a library, it is often useful to start thinking about how the library should be used. Thus we start by sketching the application program, and in the process consider options for the main methods and properties to be used.

We also foresee future extensions to include more pieces, but also that these pieces will obey the same game mechanics that we design for the present problem. Thus,

we will put the main part of the library in a file defining the module called `Chess` and the derived pieces in another file defining the module `Pieces`.

Every game needs a board, and we will define a class `Board`. A board is like an array, so it seems useful to be able to move pieces by index notation. Thus, the board must have a two-dimensional `Item` property. We also decide that each position will hold an option type, such that when a square is empty it holds `None`, and otherwise it holds piece `p` as `Some p`. Although chess notation would be neat, for ease of programming we will let index (0,0) correspond to position `a1` in chess notation, etc. The most common operation will probably be to move pieces around, so we will give the board a `move` method. We will most likely also like to print the board with pieces in their right locations. For simplicity, we choose to override the `ToString` method in `Board`, and that this method also prints information about each individual piece, such as where it is, where it can move to, and which pieces it can either protect or hit. The pieces that a piece can protect or hit we will call the piece's neighbor pieces.

A piece can be one of several types, so this gives a natural hierarchical structure which is well suited for inheritance. Each piece must be given a color, which may conveniently be given as argument at instantiation. Thus, we have decided to make a base class called `chessPiece` with argument `Color`, and derived classes `king` and `rook`. The color may conveniently be define as a discriminated union type of either `White` or `Black`. Each piece will also override the `ToString` method for ease of printing. The override will be used in conjunction with the board's override, so it should only give information about the piece's type and color. For compact printing, we will use a single letter for the type of piece, upper case if white, and lower case if black. We expect the pieces also to need to know something about the their relation to board, so we will make a `position` property which holds the coordinates of the piece, and we will make a `availableMoves` method that lists the possible moves a piece can make. Thus, we produce the application in Listing 24.10, and an illustration of what the program should do is shown in Figure 24.3. At this point, we are fairly happy with the way the application is written. The double bookkeeping of pieces in an array and on the board seems a bit excessive, but for testing it seems useful to be able to easily access all pieces, both those in play and struck. Although the `position` property of a `chessPiece` could be replaced by a function searching for a specific piece on the board, we have a hunch that we will need to retrieve a piece's position often, and that this double bookkeeping will most likely save execution time later.

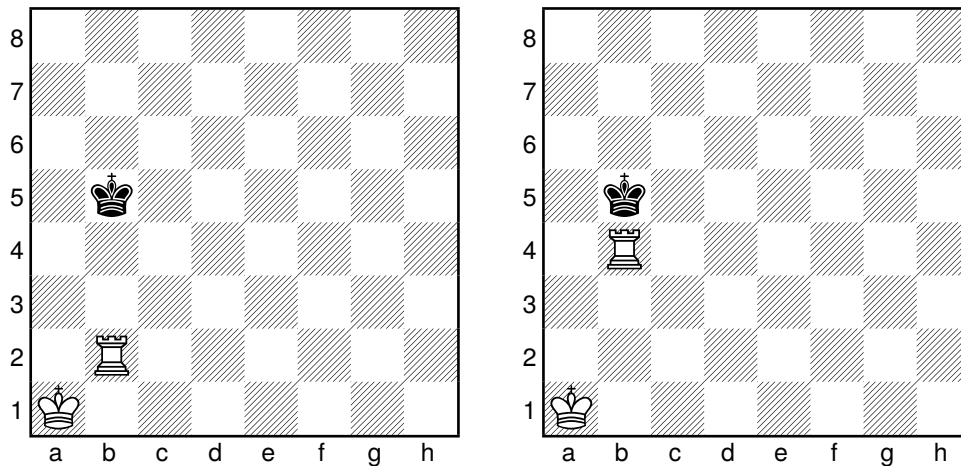
Continuing our outer to inner approach, as a second step, we consider the specific pieces: They will inherit a base piece and implement the details that are special for that piece. Each piece is signified by its color and its type, and each type has a specific motion pattern. Since we have already decided to use discriminated unions for the color, it seems natural to let the color be part of the constructor of the base class. As in the example application in Listing 24.10, pieces are upcasted to `chessPiece`, thus, the base class must know how to print the piece type. For this, we will define an

**Listing 24.10** chessApp.fsx:  
A chess application.

```

1 open Chess
2 open Pieces
3 /// Print various information about a piece
4 let printPiece (board : Board) (p : chessPiece) : unit =
5     printfn "%A: %A %A" p p.position (p.availableMoves board)
6
7 // Create a game
8 let board = Chess.Board () // Create a board
9 // Pieces are kept in an array for easy testing
10 let pieces = [|
11     king (White) :> chessPiece;
12     rook (White) :> chessPiece;
13     king (Black) :> chessPiece |]
14 // Place pieces on the board
15 board[0,0] <- Some pieces[0]
16 board[1,1] <- Some pieces[1]
17 board[4,1] <- Some pieces[2]
18 printfn "%A" board
19 Array.iter (printPiece board) pieces
20
21 // Make moves
22 board.move (1,1) (3,1) // Moves a piece from (1,1) to (3,1)
23 printfn "%A" board
24 Array.iter (printPiece board) pieces

```



**Fig. 24.3** Starting at the left and moving white rook to b4.

abstract property, such that everything needed for overriding `ToString` is available to the base class, but also such that the name of the type of the piece is set in the derived class.

For a piece on the board, its available moves depend on its type and the other pieces. The application program will need to make a decision on whether to move the piece depending on which vacant squares it can move to, and its relation to its neighbors, i.e., is the piece protecting one of its own color, or does it have the opportunity to hit an opponent's piece. Thus, given the board with all the pieces, it seems useful that `availableMoves` returns two lists: a list of vacant squares and a list of neighboring pieces of either color. Each piece has a certain movement pattern which we will specify regardless of the piece's position on the board and relation to other pieces. Thus, this will be an abstract member called `candidateRelativeMoves` implemented in the derived pieces. These candidate relative moves are then to be sifted for legal moves, and the process will be the same for all pieces. Thus, sifting can be implemented in the base class as the `availableMoves`.

Many pieces move in runs, e.g., the rook can move horizontally and vertically until there is another piece. Vacant squares behind the blocking piece are unavailable. For a rook, we must analyze four runs: northward, eastward, southward, and westward. For each run, we must consult the board to see how many vacant fields there are in that direction, and which is the piece blocking, if any. Thus, we decide that the board must have a function that can analyze a list of runs, and that the result is concatenated into a single list of vacant squares and a single list of neighboring pieces, if any. This function we call `getVacentNNeighbours`. And so we arrive at Listing 24.11.



**Listing 24.11** pieces.fs:  
An extension of chess base.

```

1 module Pieces
2 open Chess
3 /// A king moves 1 square in any direction
4 type king(col : Color) =
5   inherit chessPiece(col)
6   // A king has runs of length 1 in 8 directions:
7   // (N, NE, E, SE, S, SW, W, NW)
8   override this.candidateRelativeMoves =
9     [[(-1,0)];[(-1,1)];[(0,1)];[(1,1)];
10      [(1,0)];[(1,-1)];[(0,-1)];[(-1,-1)]]
11   override this.nameOfType = "king"
12 /// A rook moves horizontally and vertically
13 type rook(col : Color) =
14   inherit chessPiece(col)
15   // A rook can move horizontally and vertically
16   // Make a list of relative coordinate lists. We consider the
17   // current position and try all combinations of relative
18   // moves (1,0); (2,0) ... (7,0); (-1,0); (-2,0); ...;
19   // (0,-7).
20   // Some will be out of board, but will be assumed removed as
21   // illegal moves.
22   // A list of functions for relative moves
23   let indToRel = [
24     fun elm -> (elm,0); // South by elm
25     fun elm -> (-elm,0); // North by elm
26     fun elm -> (0,elm); // West by elm
27     fun elm -> (0,-elm) // East by elm
28   ]
29   // For each function f in indToRel, we calculate
30   // List.map f [1..7].

```

The king has the simplest relative movement candidates, being the hypothetical eight neighboring squares. Rooks have a considerably longer list of candidates of relative moves, since it potentially can move to all 7 squares northward, eastward, southward, and westward. This could be hardcoded as 4 potential runs, `[(1,0); (2,0); ... (7,0)]; [(-1,0); (-2,0); ... (0,-7)]`. Each run will be based on the list `[1..7]`, which gives us the idea to use `List.map` to convert a list of single indices `[1..7]` into lists of runs as required by `candidateRelativeMoves`. Each run may be generated from `[1..7]` as

```
South: List.map (fun elm -> (elm, 0)) [1..7]
North: List.map (fun elm -> (-elm, 0)) [1..7]
West: List.map (fun elm -> (0, elm)) [1..7]
East: List.map (fun elm -> (0, -elm)) [1..7]
```

and which can be combined as a list of 4 lists of runs. Further, since functions are values, we can combine the 4 different anonymous functions into a list of functions and use a for-loop to iterate over the list of functions. This is shown in Listing 24.12. However, this solution is imperative in nature and does not use the elegance of the

**Listing 24.12 imperativeRuns.fsx:**  
Calculating the runs of a rook using imperative programming.

```
30 let mutable listOfRuns : ((int * int) list) list = []
31 for f in indToRel do
32   let run = List.map f [1..7]
33   listOfRuns <- run :: listOfRuns
```

functional programming paradigm. A direct translation into functional programming is given in Listing 24.13. The functional version is slightly longer, but avoids the

**Listing 24.13 functionalRuns.fsx:**  
Calculating the runs of a rook using functional programming.

```
30 let rec makeRuns lst =
31   match lst with
32   | [] -> []
33   | f :: rest ->
34     let run = List.map f [1..7]
35     run :: makeRuns rest
36 makeRuns indToRel
```

mutable variable.

Generating lists of runs from the two lists `[1..7]` and `indToRel` can also be performed with two `List.maps`, as shown in Listing 24.14.

The anonymous function,

```
fun e -> List.map e [1..7],
```

**Listing 24.14 ListMapRuns.fsx:**  
**Calculating the runs of a rook using double List.maps.**

```
30 List.map (fun e -> List.map e [1..7]) indToRel
```

is used to wrap the inner `List.map` functional. An alternative, sometimes seen is to use currying with argument swapping: Consider the function, `let altMap lst e = List.map e lst`, which reverses the arguments of `List.map`. With this, the anonymous function can be written as `fun e -> altMap [1..7] e` or simply replaced by currying as `altMap [1..7]`. Reversing orders of arguments like this in combination with currying is what the `swap` function is for,

```
let swap f a b = f b a.
```

With `swap` we can write `let altMap = swap List.map`. Thus,

```
swap List.map [1..7]
```

is the same function as `fun e -> List.map e [1..7]`, and in which case we could rewrite the solution in Listing 24.14 as

```
List.map (swap List.map [1..7]) indToRel
```

if we wanted a very compact, but possible less readable solution.

The final step will be to design the `Board` and `chessPiece` classes. The `Chess` module implements discriminated unions for color and an integer tuple for a position. These are shown in Listing 24.15. The `chessPiece` will need to know what a board

**Listing 24.15 chess.fs:**  
**A chess base: Module header and discriminated union types.**

```
1 module Chess
2 type Color = White | Black
3 type Position = int * int
```

is, so we must define it as a mutually recursive class with `Board`. Furthermore, since all pieces must supply an implementation of `availableMoves`, we set it to be abstract by the abstract class attribute and with an abstract member. The board will need to be able to ask for a string describing each piece, and to keep the board on the screen we include an abbreviated description of the piece's properties color and piece type. The result is shown in Listing 24.16.

Our `Board` class is by far the largest and will be discussed in Listing 24.17–24.19. The constructor is shown in Listing 24.17. For memory efficiency, the board has been

**Listing 24.16 chess.fs:**  
**A chess base. Abstract type chessPiece.**

```

4  /// An abstract chess piece
5  [<AbstractClass>]
6  type chessPiece(color : Color) =
7      let mutable _position : Position option = None
8      abstract member nameOfType : string // "king", "rook", ...
9      member this.color = color // White, Black
10     member this.position // E.g., (0,0), (3,4), etc.
11         with get() = _position
12         and set(pos) = _position <- pos
13     override this.ToString () = // E.g. "K" for white king
14         match color with
15         | White -> (string this.nameOfType.[0]).ToUpper ()
16         | Black -> (string this.nameOfType.[0]).ToLower ()
17     /// A list of runs, which is a list of relative movements,
18     /// e.g.,
19     /// [(1,0); (2,0);...]; [(-1,0); (-2,0)]...]. Runs must be
20     /// ordered such that the first in a list is closest to the
21     /// piece
22     /// at hand.
23     abstract member candidateRelativeMoves : Position list list
24     /// Available moves and neighbours [(1,0); (2,0);...],
25     [p1; p2])
26     member this.availableMoves (board : Board) : (Position list
27     * chessPiece list) =
28         board.getVacantNNeighbours this

```

implemented using a `Array2D`, since pieces will move around often. For later use, in the members shown in Listing 24.19 we define two functions that convert relative coordinates into absolute coordinates on the board, and remove those that fall outside the board. These are called `validPositionWrap` and `relativeToAbsolute`.

For ease of use in an application, `Board` implements `Item`, such that the board can be read and written to using array notation. And `ToString` is overridden, such that an application may print the board anytime using a `printf` function. This is shown in Listing 24.18. Note that for efficiency, location is also stored in each piece, so `set` also needs to update the particular piece's position, as done in line 48. Note also that the board is printed with the first coordinate of the board being rows and second columns, and such that element (0,0) is at the bottom right complying with standard chess notation.

**Listing 24.17 chess.fs:  
A chess base: the constructor**

```
25 /// A board
26 and Board () =
27   let _board = Collections.Array2D.create<chessPiece option>
28     8 8 None
29   /// Wrap a position as option type
30   let validPositionWrap (pos : Position) : Position option =
31     let (rank, file) = pos // square coordinate
32     if rank < 0 || rank > 7 || file < 0 || file > 7 then
33       None
34     else
35       Some (rank, file)
36   /// Convert relative coordinates to absolute and remove
37   /// out-of-board coordinates.
38   let relativeToAbsolute (pos : Position) (lst : Position
39     list) : Position list =
40     let addPair (a : int, b : int) (c : int, d : int) :
41       Position =
42         (a+c,b+d)
43     // Add origin and delta positions
44     List.map (addPair pos) lst
45     // Choose absolute positions that are on the board
46     |> List.choose validPositionWrap
```

**Listing 24.18 chess.fs:****A chess base: Board header, constructor, and non-static members.**

```

44  /// Board is indexed using .[,] notation
45  member this.Item
46      with get(a : int, b : int) = _board.[a, b]
47      and set(a : int, b : int) (p : chessPiece option) =
48          if p.IsSome then p.Value.position <- Some (a,b)
49          _board.[a, b] <- p
50  /// Produce string of board for, e.g., the printfn function.
51  override this.ToString() =
52      let mutable str = ""
53      for i = Array2D.length1 _board - 1 downto 0 do
54          str <- str + string i
55          for j = 0 to Array2D.length2 _board - 1 do
56              let p = _board.[i,j]
57              let pieceStr =
58                  match p with
59                      None -> " ";
60                      | Some p -> p.ToString()
61              str <- str + " " + pieceStr
62          str <- str + "\n"
63      str + " 0 1 2 3 4 5 6 7"
64
65  /// Move piece by specifying source and target coordinates
66  member this.move (source : Position) (target : Position) :
67      unit =
68      this.[fst target, snd target] <- this.[fst source, snd
69      source]
70      this.[fst source, snd source] <- None
71  /// Find the tuple of empty squares and first neighbour if
72  any.
73  member this.getVacantNOccupied (run : Position list) :
74      (Position list * (chessPiece option)) =
75      try
76          // Find index of first non-vacant square of a run
77          let idx = List.findIndex (fun (i, j) ->
78              this.[i,j].IsSome) run

```

The main computations are done in the static methods of the board, as shown in Listing 24.19. A chess piece must implement `candidateRelativeMoves`, and we de-

**Listing 24.19** chess.fs:

A chess base: Board static members.

```

74     let (i,j) = run.[idx]
75     let piece = this.[i, j] // The first non-vacant
    neighbour
76     if idx = 0 then
77       ([], piece)
78     else
79       (run[..(idx-1)], piece)
80     with
81       _ -> (run, None) // outside the board
82     /// find the list of all empty squares and list of
    neighbours
83 member this.getVacantNNeighbours (piece : chessPiece) :
    (Position list * chessPiece list) =
84     match piece.position with
85     None ->
86       ([],[])
87     | Some p ->
88       let convertNWrap =
89         (relativeToAbsolute p) >> this.getVacantNOccupied
90       let vacantPieceLists = List.map convertNWrap
    piece.candidateRelativeMoves
91       // Extract and merge lists of vacant squares
92       let vacant = List.collect fst vacantPieceLists
93       // Extract and merge lists of first obstruction pieces
94       let neighbours = List.choose snd vacantPieceLists
95       (vacant, neighbours)

```

cided in Listing 24.16 that moves should be specified relative to the piece's position. Since the piece does not know which other pieces are on the board, it can only specify all potential positions. For convenience, we will allow pieces to also specify positions outside the board, such that, e.g., the rook can specify the 7 nearest neighboring squares up, down, left, and right, regardless that some may be outside the board. Thus `getVacantNNeighbours` must first convert the relative positions to absolute and clip any outside the board. This is done by `relativeToAbsolute`. Then for each run, the first occupied square must be identified. Since `availableMoves` must return two lists, vacant squares, and immediate neighbors, this structure is imposed on the output of `convertNWrap` as well. This is computed in `getVacantNOccupied` by use of the built-in `List.findIndex` function. This function returns the index of the first element in a list for which the supplied function is true and otherwise throws an exception. Exceptions are always somewhat inelegant, but in this case, it is harmless, since the exception signifies a valid situation where no pieces exist on the run. After having analyzed all runs independently, then all the vacant lists are merged, all the neighboring pieces are merged and both are returned to the caller.

Compiling the library files with the application and executing gives the result shown in Listing 24.20. We see that the program has correctly determined that initially, the

**Listing 24.20: Running the program. Compare with Figure 24.3.**

```
1 $ fsharpc --nologo chess.fs pieces.fs chessApp.fsx && mono
  chessApp.exe
2
3 chessApp.fsx(15,20): error FS0597: Successive arguments
  should be separated by spaces or tupled, and arguments
  involving function or method applications should be
  parenthesized
4
5 chessApp.fsx(16,20): error FS0597: Successive arguments
  should be separated by spaces or tupled, and arguments
  involving function or method applications should be
  parenthesized
6
7 chessApp.fsx(17,20): error FS0597: Successive arguments
  should be separated by spaces or tupled, and arguments
  involving function or method applications should be
  parenthesized
```

white king has the white rook as its neighbors and due to its location in the corner only has two free positions to move to. The white rook has many and the black king as its neighbor. The black king is free to move to all its eight neighboring fields. After moving the white rook to (3,1) or b4 in regular chess notation, then the white king has no neighbors, and the white rook and the black king are now neighbors with an appropriate restriction on their respective vacant squares. These simple use-tests are in no way a thorough test of the quality of the code, but they give us a good indication that our library offers a tolerable interface for the application, and that at least major parts of the code function as expected. Thus, we conclude this intermezzo.

## 24.6 Debugging Classes



## Chapter 25

# The Object-Oriented Programming Paradigm

*Object-oriented programming* is a paradigm for encapsulating data and methods into cohesive units. Key features of object-oriented programming are:

### Encapsulation

Data and methods are collected into a cohesive unit, and an application program need only focus on how to use the object, not on its implementation details.

### Inheritance

Objects are organized in a hierarchy of gradually increased specialty. This promotes a design of code that is of general use, and code reuse.

### Polymorphism

By overriding methods from a base class, derived classes define new data types while their methods still produce results compatible with the base class definitions.

Object-oriented programming has a well-developed methodology for analysis and design. The analysis serves as input to the design phase, where the analysis reveals *what* a program is supposed to do, and the design *how* it is supposed to be doing it. The analysis should be expressed in general terms irrespective of the technologic constraints, while the design should include technological constraints such as defined by the targeted language and hardware.

The primary steps for *object-oriented analysis and design* are:

1. identify objects,
2. describe object behavior,
3. describe object interactions,

4. describe some details of the object's inner workings,
5. write a precise description for classes, properties and methods using, e.g., F#'s XML documentation standard,
6. write mockup code,
7. write unit tests and test the basic framework using the mockup code,
8. replace the mockup with real code while testing to keep track of your progress. Extend the unit test as needed,
9. evaluate code in relation to the desired goal,
10. complete your documentation both in-code and outside.

Steps 1–4 are the analysis phase which gradually stops in step 4, while the design phase gradually starts at step 4 and gradually stops when actual code is written in step 7. Notice that the last steps are identical to imperative programming, Chapter 22. Programming is never a linear experience, and you will often need to go back to previous steps to update or change decisions. You should not refrain from improving your program design and implementation, but you should always be mindful of the goal. Often less than the perfect solution will suffice.

An object-oriented analysis can be a daunting process. A good starting point is a *use case*, *problem statement*, or a *user story*, which in human language describes a number of possibly hypothetical interactions between a user and a system with the purpose of solving some task. Two useful methodologies for performing an object-oriented analysis is the method of nouns-and-verbs and the unified modeling language, described in the following sections.

### **25.1 Identification of Objects, Behaviors, and Interactions by Nouns-and-Verbs**

A key point in object-oriented programming is that objects should to a large extent be independent and reusable. As an example, the type `int` models the concept of integer numbers. It can hold integer values from -2,147,483,648 to 2,147,483,647, and a number of standard operations and functions are defined for it. We may use integers in many different programs, and it is certain that the original designers did not foresee our use, but strived to make a general type applicable for many uses. Such a design is a useful goal when designing objects, that is, our objects should model the general concepts and be applicable in future uses.

Analyzing a specific use-case, good candidates for objects are persons, places, things, events, concept etc., which are almost always characterized by being *nouns* in the text. Interactions between objects are actions that bind objects together, and actions are often associated with *verbs*. When choosing methods, it is important to maintain an object-centered perspective, i.e., for a general-purpose object, we should limit the need for including information about other objects. E.g., a value of type `int` need not know anything about the program in which it is being used.

Said briefly, the *nouns-and-verbs method* is:

Nouns are object candidates, and verbs are candidate methods that describe interactions between objects.

## 25.2 Class Diagrams in the Unified Modelling Language

Having found an initial list of candidate objects and interactions, it is often useful to make a drawing of these relations with an increased focus on the object's inner workings. A *class diagram* is a schematic drawing of the program, highlighting its object-oriented structure, and we will use the *Unified Modelling Language 2 (UML)* [5] standard. The standard is very broad, and here we will discuss structure diagrams for use in describing objects.

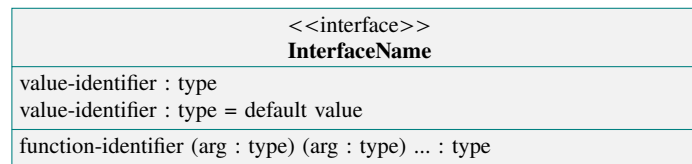
A class is drawn as shown in Figure 25.1. In UML, classes are represented as

ClassName
value-identifier : type value-identifier : type = default value
function-identifier (arg : type) (arg : type) ... : type <i>function-identifier (arg : type) (arg : type) ... : type</i>

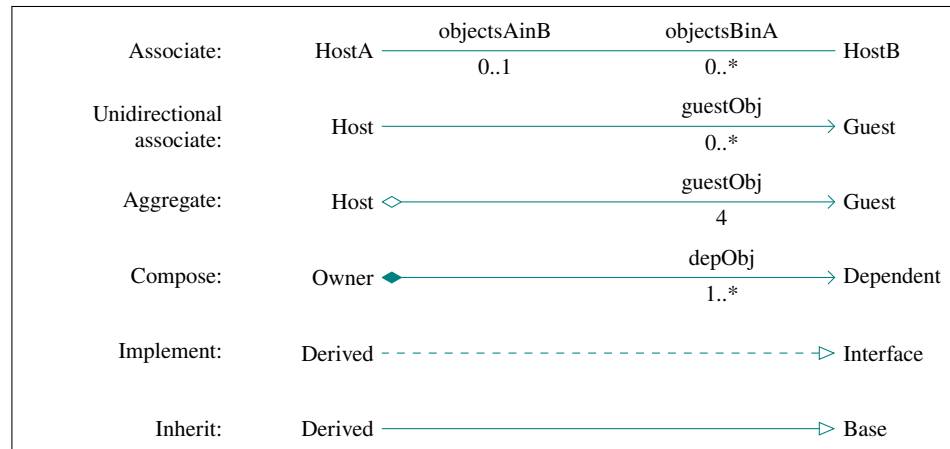
**Fig. 25.1** A UML diagram for a class consists of it's name, zero or more attributes, and zero or more methods.

boxes with their class name. Depending on the desired level of details, zero or more properties and methods are described. These describe the basic interface to the class and objects of its type. Abstract members that require an implementation are shown in cursive. Here we have used F# syntax to conform with this book theme, but typically C# syntax is used. Interfaces are a special type of class that require an implementation. To highlight this, UML uses the notation shown in Figure 25.2.

Relations between classes and objects are indicated by lines and arrows. The most common ones are summarized in Figure 25.3. Their meaning will be described in detail in the following.



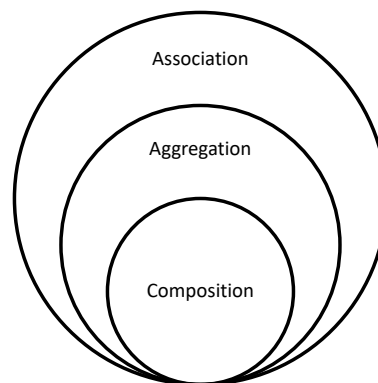
**Fig. 25.2** An interface is a class that requires an implementation.



**Fig. 25.3** Arrows used in class diagrams to show relations between objects.

### 25.2.1 Associations

A family of relations is association, aggregation, and composition, and these are distinguished by how they handle the objects they are in relation with. The relation between the three relations is shown in Figure 25.4. Aggregational and compositional



**Fig. 25.4** The relation between Association, Aggregation and Composition in UML.

are specialized types of associations that imply ownership and are often called *has-a* relations. A composition is a collection of parts that makes up a whole. In

object-oriented design, a compositional relation is a strong relation, where a guest object makes little sense without the host, as a room cannot exist without a house. An aggregation is a collection of assorted items, and in object-oriented design, an aggregational relation is a loose relation, like how a battery can meaningfully be separated from a torchlight. Some associations are neither aggregational nor compositional, and commonly just called an association. An association is a group of people or things linked for some common purpose a cooccurrence. In object-oriented design, associations between objects are the loosest possible relations, like how a student may be associated with the local coffee shop. Sometimes associational relations are called a *knows-about*.

### Association

The most general type of association, which is just called an association, is the possibility for objects to send messages to each other. This implies that one class knows about the other, e.g., uses it as arguments of a function or similar. A host is associated with a guest if the host has a reference to the guest. Objects are reference types, and therefore, any object which is not created by the host, but where a name is bound to a guest object but not explicitly copied, then this is an association relation.

Bidirectional association means that classes know about each other. The UML notation is shown in Figure 25.5. Association may be annotated by an identifier and



**Fig. 25.5** Bidirectional association is shown as a line with optional annotation.

a multiplicity. In the figure, HostA has 0 or more variables of type HostB named objectsBinA, while HostB has 0 or 1 variables of HostA named objectsAinB. The multiplicity notation is very similar to F#'s slicing notation. Typical values are shown in Table 25.1. If the association is unidirectional, then an arrow is added for emphasis.

n	exactly n instances
*	zero or more instances
n..m	n to m instances
n..*	from n to infinite instances

**Table 25.1** Notation for association multiplicities is similar to F#'s slicing notation.

sis, as shown in Figure 25.6. In this example, Host knows about Guest and has one



**Fig. 25.6** Unidirectional association shows a one-side *has-a* relation. instance of it, and Guest is oblivious about Host.

A programming example showing a unidirectional association is given in Listing 25.1. Here, the `student` is unidirectionally associated with a `teacher` since the

**Listing 25.1** `umlAssociation.fsx`:

The `student` is associated with a `teacher`.

```
1 type teacher () =
2   member this.answer (q : string) = "4"
3 type student (t : teacher) =
4   member this.ask () = t.answer("What is 2+2?")
5
6 let t = teacher ()
7 let s = student (t)
8 s.ask()
```

`student` can send and receive messages to and from the `teacher`. The `teacher`, on the other hand, does not know anything about the `student`. In UML this is depicted as shown in Figure 25.7.



**Fig. 25.7** The `teacher` and `student` objects can access each other's functions, and thus they have an association relation.

## Aggregation

Aggregated relationships are a specialization of associations. As an example, an author may have written a book, but once created, the book gets a life independent of the author and may, for example, be given to a reader, and the book continues to exist even when the author dies. That is, In aggregated relations, the host object has a reference to a guest object and may have created the guest, but the guest will be shared with other objects, and when the host is deleted, the guest is not.

Aggregation is illustrated using a diamond tail and an open arrow, as shown in Figure 25.8. Here the `Host` class has stored aliases to four different `Guest` objects.



**Fig. 25.8** Aggregation relations are a subset of associations where local aliases are stored for later use.

An programming example of an aggregation relation is given in Listing 25.2. In aggregated relations, there is a sense of ownership, and in the example, the `author` object creates a `book` object which is published and bought by a reader. Hence the `book` change ownership during the execution of the program. In UML this is to be depicted as shown in Figure 25.9.

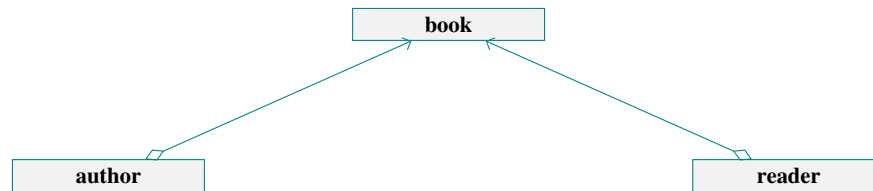
**Listing 25.2** `umlAggregation.fsx`:

The book has an aggregated relation to author and reader.

```

1 type book (name : string) =
2   let mutable _name = name
3 type author () =
4   let _book = book("Learning to program")
5   member this.publish() = _book
6 type reader () =
7   let mutable _book : book option = None
8   member this.buy (b : book) = _book <- Some b
9
10 let a = author ()
11 let r = reader ()
12 let b = a.publish ()
13 r.buy (b)

```

**Fig. 25.9** A book is an object that can be owned by both an author and a reader.**Composition**

A compositional relationship is a specialization of aggregations. As an example, a dog has legs, and dog legs can not very sensibly be given to other animals. That is, in compositional relations, the host creates the guest, and when the host is deleted, so is the guest. A composition is a stronger relation than aggregation and is illustrated using a filled diamond tail, as illustrated in Figure 25.10. In this example,

**Fig. 25.10** Composition relations are a subset of aggregation where the host controls the lifetime of the guest objects.

Owner has created 1 or more objects of type Dependent, and when Owner is deleted, so are these objects.

A programming example of a composition relation is given in Listing 25.3. In Listing 25.3, a dog object creates four leg objects, and it makes less sense to be able to turn over the ownership of each leg to other objects. Thus, a dog is a composition of leg objects. Using UML, this should be depicted as shown in Figure 25.11.

**Listing 25.3** umlComposition.fsx:  
The dog object is a composition of four leg objects.

```

1 type leg () =
2   member this.move = "moving"
3 type dog () =
4   let _leg = List.init 4 (fun e -> leg ())
5
6 let bestFriend = dog ()

```



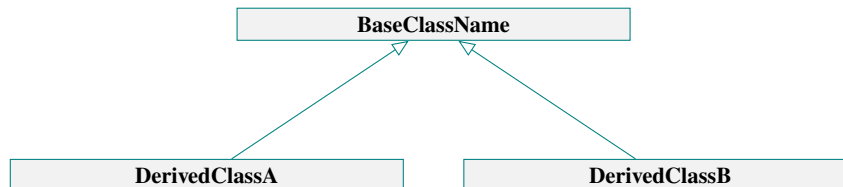
**Fig. 25.11** A dog is a composition of legs.

### 25.2.2 Inheritance-type relations

Classes may inherit other classes where the parent is called the base class and the children its derived classes. Such a relation is often called an *is-a* relation, since the derived class *is a* kind of base class.

#### Inheritance

Inheritance is a relation between properties of classes. As an example, a student and a teacher is a type of person. All persons have names, while a student also has a reading list, and a teacher also has a set of slides. Thus, both students and teacher may inherit from a person to gain the common property, name. In UML this is illustrated with an non-filled, closed arrow as shown in Figure 25.12. Here two



**Fig. 25.12** Inheritance is shown by a closed arrowhead pointing to the base.

classes inherit the base class.

A programming example of an inheritance is given in Listing 25.4. In Listing 25.4, the `student` and the `teacher` classes are derived from the same `person` class. Thus, they all three have the `name` property. Using UML, this should be depicted as shown in Figure 25.13.



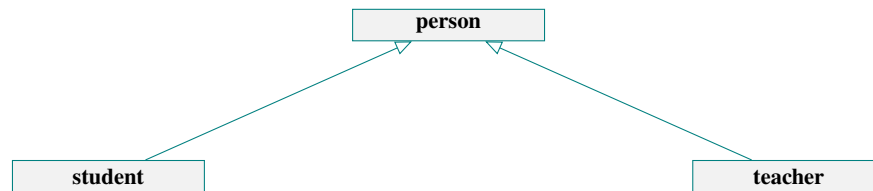
**Listing 25.4** umlInheritance.fsx:

The student and the teacher class inherits from the person class.

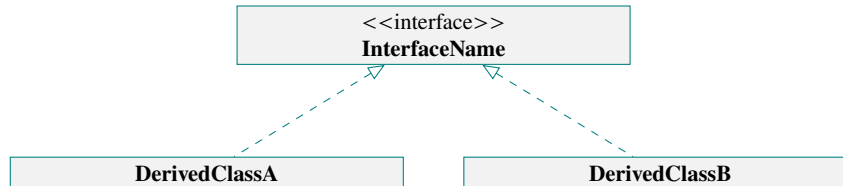
```

1 type person (name : string) =
2   member this.name = name
3 type student (name : string, book : string) =
4   inherit person(name)
5   member this.book = book
6 type teacher (name : string, slides : string) =
7   inherit person(name)
8   member this.slides = slides
9
10 let s = student("Hans", "Learning to Program")
11 let t = teacher("Jon", "Slides of the day")

```

**Fig. 25.13** A student and a teacher inherit from a person class.**Interface**

An interface is a relation between the properties of an abstract class and a regular class. As an example, a television and a car both have buttons, that you can press, although their effect will be quite different. Thus, a television and a car may both implement the same interface. In UML, interfaces are shown similarly to inheritance, but using a stippled line, as shown in Figure 25.14.

**Fig. 25.14** Implementations of interfaces is shown with stippled line and closed arrowhead pointing to the base.

A programming example of an interface is given in Listing 25.5. In Listing 25.5, the television and the car classes implement the `button` interface. Hence, although they are different classes, they both have the `press ()` method and, e.g., can be given as a function requiring only the existence of the `press ()` method. Using UML, this should be depicted as shown in Figure 25.15.

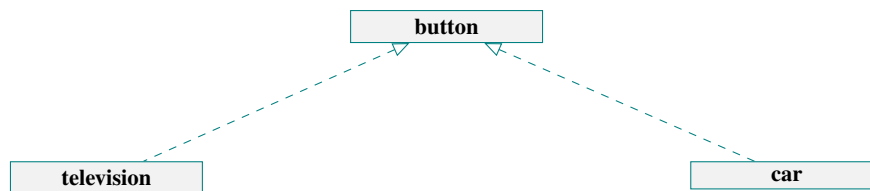
**Listing 25.5** umlInterface.fsx:

The television and the car class both implement the button interface.

```

1 type button =
2     abstract member press : unit -> string
3 type television () =
4     interface button with
5         member this.press () = "Changing channel"
6 type car () =
7     interface button with
8         member this.press () = "Activating wipers"
9 let pressIt (elm : #button) =
10     elm.press()
11
12 let t = television()
13 let c = car()
14 printfn "%s" (pressIt t)
15 printfn "%s" (pressIt c)

```

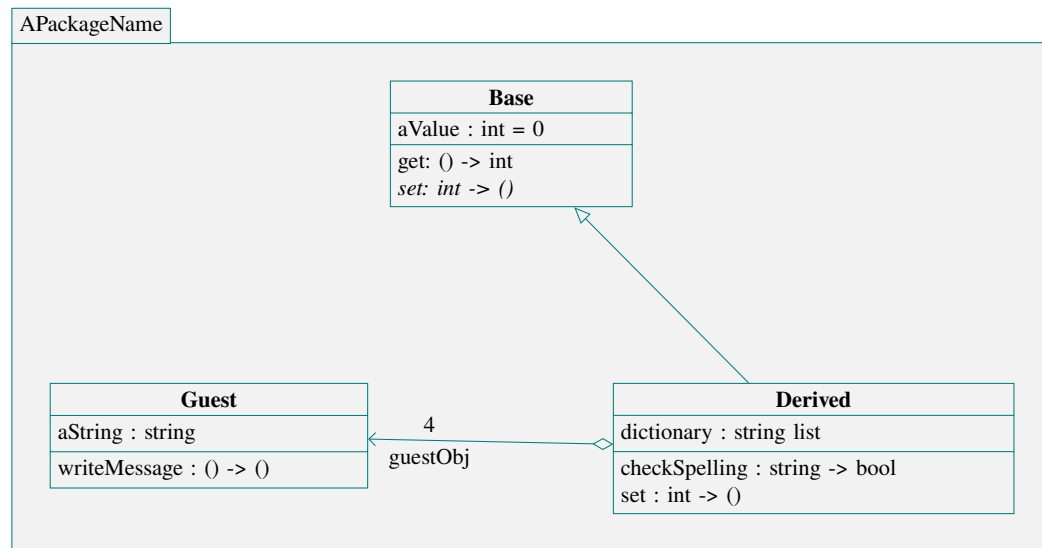
**Fig. 25.15** A student and a teacher inherit from a person class.**25.2.3 Packages**

Namespace and modules

For visual flair, modules and namespaces are often visualized as *packages*, as shown in Figure 25.16. A package is like a module in F#.

**25.3 Programming Intermezzo: Designing a Racing Game**

An example is the following *problem statement*:



**Fig. 25.16** Packages are a visualizations of modules and namespaces.

#### Problem 25.1

rite a racing game, where each player controls his or her vehicle on a track. Each vehicle must have individual features such as top acceleration, speed, and handling. The player must be able to turn the vehicle left and right, and to accelerate up and down. At the beginning of the game, each vehicle is placed behind the starting line. Once the start signal is given, then the players may start to operate their vehicles. The player who first completes 3 rounds wins.

To seek a solution, we will use the *nouns-and-verbs method*. Below, the problem statement is repeated with **nouns** and **verbs** highlighted.

Write a racing game, where each player controls his or her vehicle on a track. Each vehicle must have individual features such as top acceleration, speed, and handling. The player must be able to turn the vehicle left and right, and to accelerate up and down. At the beginning of the game, each vehicle is placed behind the starting line. Once the start signal is given, then the players may start to operate their vehicles. The player who first completes 3 rounds wins.

The above nouns and verbs are candidates for objects, their behaviour, and their interaction. A deeper analysis is:

Identification of objects by nouns (Step 1):

Identified unique nouns are: racing game (game), player, vehicle, track, feature, top acceleration, speed, handling, beginning, starting line, start signal, rounds. From this list we seek cohesive units that are independent and reusable. The nouns

game, player, vehicle, and track

seem to fulfill these requirements, while all the rest seems to be features of the former and thus not independent concepts. E.g., **top acceleration** is a feature of a **vehicle**, and **starting line** is a feature of a **track**.

Object behavior and interactions by verbs (Steps 2 and 3):

To continue our object-oriented analysis, we will consider the object candidates identified above, and verbalize how they would act as models of general concepts useful in our game.

**player** The **player** is associated with the following verbs:

- A **player** **controls/operates** a **vehicle**.
- A **player** **turns** and **accelerates** a **vehicle**.
- A **player** **completes** rounds.
- A **player** **wins**.

Verbalizing a **player**, we say that a **player** in general must be able to control the **vehicle**. In order to do this, the **player** must receive information about the **track** and all **vehicles**, or at least some information about the nearby **vehicles** and **track**. Furthermore, the **player** must receive information about the state of the **game**, i.e., when the race starts and stops.

**vehicle** A **vehicle** is controlled by a **player** and further associated with the following verbs:

- A **vehicle** **has** features **top acceleration**, **speed**, and **handling**.
- A **vehicle** **is placed** on the **track**.

To further describe a **vehicle**, we say that a **vehicle** is a model of a physical object which moves around on the **track** under the influence of a **player**. A **vehicle** must have a number of attributes such as top acceleration, speed, and handling, and must be able to receive information about when to turn and accelerate. A **vehicle** must be able to determine its location in particular if it is on or off **track** and, and it must be able to determine if it has crashed into an obstacle such as another **vehicle**.

**track** A **track** is the place where vehicles operate and is further associated with the following verbs:

- A **track** **has** a **starting line**.

- A **track** has rounds.

Thus, a **track** is a fixed entity on which the **vehicles** race. It has a size and a shape, a starting and a finishing line, which may be the same, and **vehicles** may be placed on the **track** and can move on and possibly off the **track**.

**game** Finally, a **game** is associated with the following verbs:

- A **game** has a beginning and a start signal.
- A **game** can be won.

A **game** is the total sum of all the **players**, the **vehicles**, the **tracks**, and their interactions. A **game** controls events, including inviting **players** to race, sending the **start signal**, and monitoring when a **game** is finished and who won.

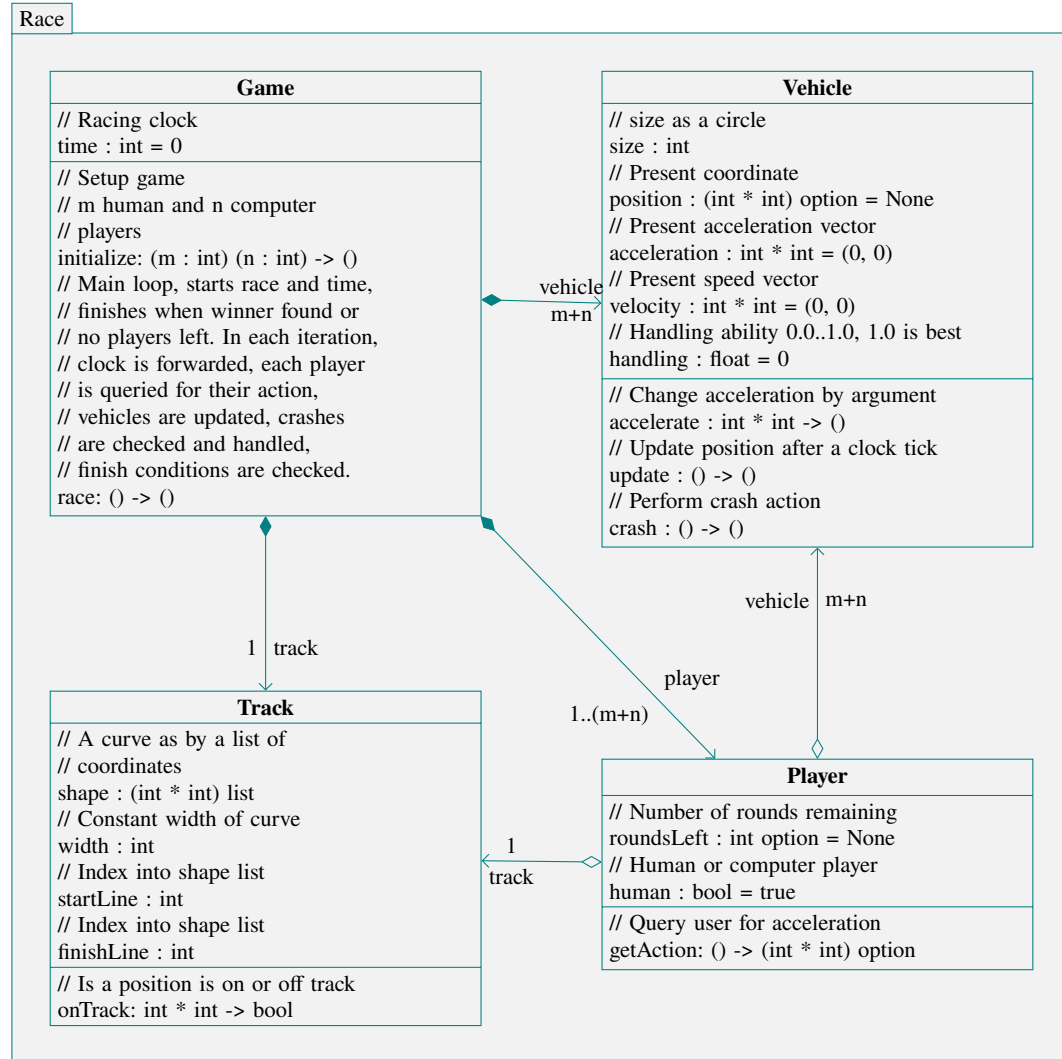
From the above we see that the object candidates **features** seems to be a natural part of the description of the **vehicle**'s attributes, and similarly, a **starting line** may be an intricate part of a **track**. Also, many of the *verbs* used in the problem statement and in our extended verbalization of the general concepts indicate methods that are used to interact with the object. The object-centered perspective tells us that for a general-purpose **vehicle** object, we need not include information about the **player**, analogous to how a value of type `int` need not know anything about the program, in which it is being used. In contrast, the candidate **game** is not as easily dismissed and could be used as a class which contains all the above.

With this description, we see that 'start signal' can be included as a natural part of the game object. Being confident in our working hypothesis of the essential objects for the solution, we continue our investigation into further details about the objects and their interactions.

Analysis details (Step 4):

A class diagram of our design for the proposed classes and their relations is shown in Figure 25.17.

In the present description, there will be a single **Game** object that initializes the other objects, executes a loop updating the clock, queries the players for actions, and informs the vehicles that they should move and under what circumstances. The track has been chosen to be dumb and does not participate much in the action. Player's method `getAction` will be an input from a user by keyboard, joystick or similar, but the complexity of the code for a computer player will be large, since it needs to take a sensible decision based on the track and the location of the other vehicles. What at present is less clear, is whether it is the responsibility of **Game** or **Vehicle** to detect an off track or a crash event. If a vehicle is to do this, then each vehicle must have aggregated association to all other vehicles and obstacles. So, on the one hand, it



**Fig. 25.17** A class diagram for a racing game.

would seem an elegant delegation of responsibilities that a vehicle knows whether it has crashed into an obstacle or not, but on the other hand, it seems wasteful of memory resources to have duplicated references of all obstacles in every vehicle. The final choice is thus one of elegance versus resource management, and in the above, we have favored resource management. Thus, the main loop in *Game* must check all vehicles for a crash event after the vehicle's positions have been updated, and in case of a crash, informs the relevant vehicles.

Having created a design for a racing game, we are now ready to start coding (Step 6–). It is not uncommon that transforming our design into code will reveal new structures

and problems that possibly require our design to be updated. Nevertheless, a good design phase is almost always a sure course to avoid many problems once coding, since the design phase allows the programmer to think about the problem from a helicopter perspective before tackling details of specific sub-problems.





## Chapter 26

### Where to Go from Here

You have now learned to program in a number of important paradigms and mastered the basics of F#, so where are good places to go now? I will highlight a number of options:

#### Program, program, program

You are at this stage no longer a novice programmer, so it is time for you to use your skills and create programs that solve problems. I have always found great inspiration in interacting with other domains and seeking solutions by programming. Experience is a must if you want to become a good programmer, since your newly acquired skills need to settle in your mind, and you need to be exposed to new problems that require you to adapt and develop your skills.

#### Learn to use an Integrated Development Environment effectively

An Integrated Development Environment (IDE) is a tool that may increase your coding efficiency. IDEs can help you get started in different environments, such as on a laptop or a phone, and it can quickly give you an overview of available options when you are programming. E.g., all IDEs will show you available members for identifiers as you type, reducing time to search members and reducing the risk of spelling errors. Many IDEs will also help you to quickly refactor your code, e.g., by highlighting all occurrences of a name in a scope and letting you change all of them in one action.

In this book, we have emphasized the console. Compiling and running from the console is the basis of which all IDEs build, and many of the problems with using IDEs efficiently are related to understanding how it can best help you compiling and running programs.

#### Learn other cool features of F#

F# is a large language with many features. Some have been presented in this book, but more advanced topics have been neglected. Examples are:

- **regular expressions:** Much computations concern processing of text. Regular expressions is a simple but powerful language for searching and replacing in strings. F# has built-in support for regular expressions as `System.Text.RegularExpressions`.
- **sequence seq:** All list type data structures in F# are built on sequences. Sequences are, however, more than lists and arrays. A key feature is that sequences can effectively contain large or even infinite ordered lists which you do not necessarily need or use, i.e., they are lazy and only compute its elements as needed. Sequences are programmed using computation expressions.
- **computation expressions:** Sequential expressions is an example of computation expressions, e.g., the sequence of squares  $i^2, i = 0..9$  can be written as `seq {for i in 0 .. 9 -> i * i}`
- **asynchronous computations async:** F# has a native implementation of asynchronous computation, which means that you can very easily set up computations that run independently of others, such that they do not block each other. This is extremely convenient if you, e.g., need to process a list of homepages, where each homepage may be slow to read, such that reading them in sequence will be slow. With asynchronous computations, they can easily be read in parallel with a huge speedup for the total task as a result. Asynchronous workflows rely on computation expressions.

#### Learn another programming language

F# is just one of a great number of programming languages, and you should not limit yourself. Languages are often designed to be used for particular tasks, and when looking to solve a problem, you would do well in selecting the language that best fits the task. C# is an example from the Mono family which emphasizes object-oriented programming, and many of the built-in libraries in F# are written in C#. C++ and C are ancestors of C# and are very popular since they allow for great control over the computer at the expense of programming convenience. Python is a popular prototyping language which emphasizes interactive programming like `fsharp`, and it is seeing a growing usage in web-backends and machine learning. And the list goes on. To get an idea of the wealth of languages, browse <http://www.99-bottles-of-beer.net> which has examples of solutions to the simple problem: Write a program that types the lyrics of song “99 bottles of beer on the wall” and stop. At the present time, many solutions in more than 1500 different languages have been submitted.

## Appendix A

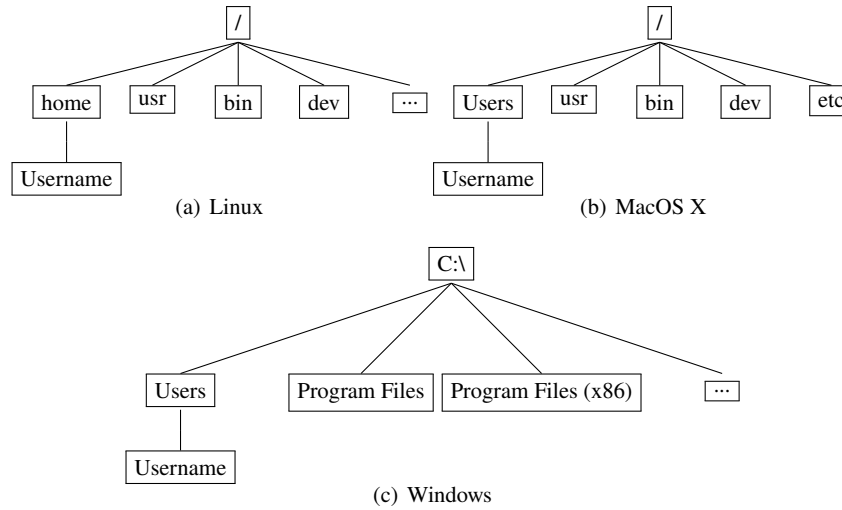
### The Console in Windows, MacOS X, and Linux

Almost all popular operating systems are accessed through a user-friendly *graphical user interface (GUI)* that is designed to make typical tasks easy to learn to solve. As a computer programmer, you often need to access some of the functionalities of the computer, which, unfortunately, are sometimes complicated by this particular graphical user interface. The *console*, also called the *terminal* and the *Windows command line*, is the right hand of a programmer. The console is a simple program that allows you to complete text commands. Almost all the tasks that can be done with the graphical user interface can be done in the console and vice versa. Using the console, you will benefit from its direct control of the programs we write, and in your education, you will benefit from the fast and raw information you get through the console.

#### A.1 The Basics

When you open a *directory* or *folder* in your preferred operating system, the directory will have a location in the file system, whether from the console or through the operating system's graphical user interface. The console will almost always be associated with a particular directory or folder in the file system, and it is said that it is the directory that the console is in. The exact structure of file systems varies between Linux, MacOS X, and Windows, but common is that it is a hierarchical structure. This is illustrated in Figure A.1.

There are many predefined console commands, available in the console, and you can also make your own. In the following sections, we will review the most important commands in the three different operating systems. These are summarized in Table A.1.



**Fig. A.1** The top file hierarchy levels of common operating systems.

Windows	MacOS X/Linux	Description
<code>dir</code>	<code>ls</code>	Show content of present directory.
<code>cd &lt;d&gt;</code>	<code>cd &lt;d&gt;</code>	Change present directory to <code>&lt;d&gt;</code> .
<code>mkdir &lt;d&gt;</code>	<code>mkdir &lt;d&gt;</code>	Create directory <code>&lt;d&gt;</code> .
<code>rmdir &lt;d&gt;</code>	<code>rmdir &lt;d&gt;</code>	Delete <code>&lt;d&gt;</code> (Warning: cannot be reverted).
<code>move &lt;f&gt; &lt;f   d&gt;</code>	<code>mv &lt;f&gt; &lt;f   d&gt;</code>	Move <code>&lt;fil&gt;</code> to <code>&lt;f   d&gt;</code> .
<code>copy &lt;f1&gt; &lt;f2&gt;</code>	<code>cp &lt;f1&gt; &lt;f2&gt;</code>	Create a new file called <code>&lt;f2&gt;</code> as a copy of <code>&lt;f1&gt;</code> .
<code>del &lt;f&gt;</code>	<code>rm &lt;f&gt;</code>	delete <code>&lt;f&gt;</code> (Warning: cannot be reverted).
<code>echo &lt;s   v&gt;</code>	<code>echo &lt;s   v&gt;</code>	Write a string or content of a variable to screen.

**Table A.1** The most important console commands for Windows, MacOS X, and Linux. Here `<f*>` is shorthand for any filename, `<d>` for any directory name, `<s>` for any string, and `<v>` for any shell-variable.

## A.2 Windows

In this section we will discuss the commands summarized in Table A.1. Windows 7 and earlier versions: To open the console, press **Start** -> **Run** in the lower left corner, and then type `cmd` in the box. In Windows 8 and 10, you right-click on the windows icon, choose **Run** or equivalent in your local language, and type `cmd`. Alternatively, you can type **Windows-key** + **R**. Now you should open a console window with a prompt showing something like Listing A.1.

**Listing A.1: The Windows console.**

```
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation. All rights
reserved.

C:\Users\sporrington>
```

To see which files are in the directory, use *dir*, as shown in Listing A.2.

**Listing A.2: Directory listing with dir.**

```
C:\Users\sporrington>dir
Volume in drive C has no label.
Volume Serial Number is 94F0-31BD

Directory of C:\Users\sporrington

30-07-2015  15:23    <DIR>          .
30-07-2015  15:23    <DIR>          ..
30-07-2015  14:27    <DIR>          Contacts
30-07-2015  14:27    <DIR>          Desktop
30-07-2015  17:40    <DIR>          Documents
30-07-2015  15:11    <DIR>          Downloads
30-07-2015  14:28    <DIR>          Favorites
30-07-2015  14:27    <DIR>          Links
30-07-2015  14:27    <DIR>          Music
30-07-2015  14:27    <DIR>          Pictures
30-07-2015  14:27    <DIR>          Saved Games
30-07-2015  17:27    <DIR>          Searches
30-07-2015  14:27    <DIR>          Videos
                0 File(s)                0 bytes
                13 Dir(s)  95.004.622.848 bytes free

C:\Users\sporrington>
```

We see that there are no files and thirteen directories (DIR). The columns tell from left to right: the date and time of their creation, the file size or if it is a folder, and the name file or directory name. The first two folders “.” and “..” are found in each folder and refer to this folder as well as the one above in the hierarchy. In this case, the folder “.” is an alias for C:\Users\sporrington and “..” for C:\Users.

Use *cd* to change directory, e.g., to Documents, as in Listing A.3.

**Listing A.3: Change directory with cd.**

```
C:\Users\sporrington>cd Documents

C:\Users\sporrington\Documents>
```

Note that some systems translate default filenames, so their names may be given different names in different languages in the graphical user interface as compared to the console.

You can use *mkdir* to create a new directory called, e.g., *myFolder*, as illustrated in Listing A.4.

**Listing A.4: Creating a directory with *mkdir*.**

```
C:\Users\sporrington\Documents>mkdir myFolder

C:\Users\sporrington\Documents>dir
Volume in drive C has no label.
Volume Serial Number is 94F0-31BD

Directory of C:\Users\sporrington\Documents

30-07-2015  19:17    <DIR>          .
30-07-2015  19:17    <DIR>          ..
30-07-2015  19:17    <DIR>          myFolder
               0 File(s)                0 bytes
               3 Dir(s)  94.656.638.976 bytes free

C:\Users\sporrington\Documents>
```

By using *dir* we inspect the result.

Files can be created by, e.g., *echo* and *redirection*, as demonstrated in Listing A.5.

**Listing A.5: Creating a file with *echo* and *redirection*.**

```
C:\Users\sporrington\Documents>echo "Hi" > hi.txt

C:\Users\sporrington\Documents>dir
Volume in drive C has no label.
Volume Serial Number is 94F0-31BD

Directory of C:\Users\sporrington\Documents

30-07-2015  19:18    <DIR>          .
30-07-2015  19:18    <DIR>          ..
30-07-2015  19:17    <DIR>          myFolder
30-07-2015  19:18                8 hi.txt
               1 File(s)                8 bytes
               3 Dir(s)  94.656.634.880 bytes free

C:\Users\sporrington\Documents>
```

To move the file *hi.txt* to the directory *myFolder*, use *move*, as shown in Listing A.6.

**Listing A.6: Move a file with move.**

```
C:\Users\sporrington\Documents>move hi.txt myFolder
1 file(s) moved.

C:\Users\sporrington\Documents>
```

Finally, use *del* to delete a file and *rmdir* to delete a directory, as shown in Listing A.7.

**Listing A.7: Delete files and directories with del and rmdir.**

```
C:\Users\sporrington\Documents>cd myFolder

C:\Users\sporrington\Documents\myFolder>del hi.txt

C:\Users\sporrington\Documents\myFolder>cd ..

C:\Users\sporrington\Documents>rmdir myFolder

C:\Users\sporrington\Documents>dir
Volume in drive C has no label.
Volume Serial Number is 94F0-31BD

Directory of C:\Users\sporrington\Documents

30-07-2015  19:20    <DIR>          .
30-07-2015  19:20    <DIR>          ..
               0 File(s)                0 bytes
               2 Dir(s)  94.651.142.144 bytes free

C:\Users\sporrington\Documents>
```

The commands available from the console must be in its *search path*. The search path can be seen using *echo*, as shown in Listing A.8.

**Listing A.8: Displaying the search path.**

```
C:\Users\sporrington\Documents>echo %Path%
C:\Windows\system32;C:\Windows;C:\Windows\System32\Wbem;
C:\Windows\System32\WindowsPowerShell\v1.0\;"\Program
Files\emacs-24.5\bin\"

C:\Users\sporrington\Documents>
```

The path can be changed using the Control panel in the graphical user interface. In Windows 7, choose the Control panel, choose System and Security → System → Advanced system settings → Environment Variables. In Windows 10, you can find this window by searching for “Environment” in the Control panel. In

the window's **System variables** box, double-click on **Path** and add or remove a path from the list. The search path is a list of paths separated by “;”. Beware, Windows uses the search path for many different tasks, so remove only paths that you are certain are not used for anything.

A useful feature of the console is that you can use the **tab**-key to cycle through filenames. E.g., if you write `cd` followed by a space and **tab** a couple of times, then the console will suggest to you the available directories.

### A.3 MacOS X and Linux

MacOS X (OSX) and Linux are very similar, and both have the option of using *bash* as console. It is in the standard console on MacOS X and on many Linux distributions. A summary of the most important *bash* commands is shown in Table A.1. In MacOS X, you find the console by opening **Finder** and navigating to **Applications** → **Utilities** → **Terminal**. In Linux, the console can be started by typing **Ctrl + Alt + T**. Some Linux distributions have other key-combinations such as **Super + T**.

Once opened, the console is shown in a window with content, as shown in Listing A.9.

#### Listing A.9: The MacOS console.

```
Last login: Thu Jul 30 11:52:07 on ttys000
FN11194:~ sporring$
```

“FN11194” is the name of the computer, the character `~` is used as an alias for the user’s home directory, and “sporring” is the username for the user presently logged onto the system. Use *ls* to see which files are present, as shown in Listing A.10.

#### Listing A.10: Display a directory content with *ls*.

```
FN11194:~ sporring$ ls
Applications  Documents    Library      Music
Public
Desktop       Downloads    Movies        Pictures
FN11194:~ sporring$
```

More details about the files are available by using flags to *ls* as demonstrated in Listing A.11.



**Listing A.11: Display extra information about files using flags to `ls`.**

```

FN11194:~ sporring$ ls -l
drwx----- 6 sporring  staff   204 Jul 30 14:07
    Applications
drwx-----+ 32 sporring  staff  1088 Jul 30 14:34 Desktop
drwx-----+ 76 sporring  staff  2584 Jul  2 15:53 Documents
drwx-----+  4 sporring  staff   136 Jul 30 14:35 Downloads
drwx-----@ 63 sporring  staff  2142 Jul 30 14:07 Library
drwx-----+  3 sporring  staff   102 Jun 29 21:48 Movies
drwx-----+  4 sporring  staff   136 Jul  4 17:40 Music
drwx-----+  3 sporring  staff   102 Jun 29 21:48 Pictures
drwxr-xr-x+  5 sporring  staff   170 Jun 29 21:48 Public
FN11194:~ sporring$

```

The flag `-l` means long, and many other flags can be found by querying the built-in manual with `man ls`. The output is divided into columns, where the left column shows a number of codes: “d” stands for directory, and the set of three of optional “rwx” denote whether respectively the owner, the associated group of users, and anyone can respectively “r” - read, “w” - write, and “x” - execute the file. In all directories but the Public directory, only the owner can do any of the three. For directories, “x” means permission to enter. The second column can often be ignored, but shows how many links there are to the file or directory. Then follows the username of the owner, which in this case is `sporring`. The files are also associated with a group of users, and in this case, they all are associated with the group called `staff`. Then follows the file or directory size, the date of last change, and the file or directory name. There are always two hidden directories: “.” and “..”, where “.” is an alias for the present directory, and “..” for the directory above. Hidden files will be shown with the `-a` flag.

Use `cd` to change to the directory, for example to `Documents` as shown in Listing A.12.

**Listing A.12: Change directory with `cd`.**

```

FN11194:~ sporring$ cd Documents/
FN11194:Documents sporring$

```

Note that some graphical user interfaces translate standard filenames and directories to the local language, such that navigating using the graphical user interface will reveal other files and directories, which, however, are aliases.

You can create a new directory using `mkdir`, as demonstrated in Listing A.13.

**Listing A.13: Creating a directory using `mkdir`.**

```
FN11194:Documents sporring$ mkdir myFolder
FN11194:Documents sporring$ ls
myFolder
FN11194:tmp sporring$
```

A file can be created using `echo` and with *redirection*, as shown in Listing A.14.

**Listing A.14: Creating a file with `echo` and redirection.**

```
FN11194:Documents sporring$ echo "hi" > hi.txt
FN11194:Documents sporring$ ls
hi.txt          myFolder
```

To move the file `hi.txt` into `myFolder`, use `mv`. This is demonstrated in Listing A.15.

**Listing A.15: Moving files with `mv`.**

```
FN11194:Documents sporring$ echo mv hi.txt myFolder/
FN11194:Documents sporring$
```

To delete the file and the directory, use `rm` and `rmdir`, as shown in Listing A.16.

**Listing A.16: Deleting files and directories.**

```
FN11194:Documents sporring$ cd myFolder/
FN11194:myFolder sporring$ rm hi.txt
FN11194:myFolder sporring$ cd ..
FN11194:Documents sporring$ rmdir myFolder/
FN11194:Documents sporring$ ls
FN11194:Documents sporring$
```

Only commands found on the *search path* are available in the console. The content of the search path is seen using the `echo` command, as demonstrated in Listing A.17.

**Listing A.17: The content of the search path.**

```
FN11194:Documents sporring$ echo $PATH
/Applications/Maple
17:/Applications/PackageManager.app/Contents/MacOS/:
/Applications/MATLAB_R2014b.app/bin:/opt/local/bin:
/opt/local/sbin:/usr/local/bin:/usr/bin:/bin:/usr/sbin:
/sbin:/opt/X11/bin:/Library/TeX/texbin
FN11194:Documents sporring$
```

The search path can be changed by editing the setup file for Bash. On MacOS X it is called `~/.profile`, and on Linux it is either `~/.bash_profile` or `~/.bashrc`.

Here new paths can be added by adding the following line: `export PATH=<new path>:<another new path>:$PATH`.

A useful feature of Bash is that the console can help you write commands. E.g., if you write `fs` followed by pressing the `tab`-key, and if `Mono` is in the search path, then Bash will typically respond by completing the line as `fsharp`, and by further pressing the `tab`-key some times, Bash will show the list of options, typically `fshpari` and `fsharpc`. Also, most commands have an extensive manual which can be accessed using the `man` command. E.g., the manual for `rm` is retrieved by `man rm`.



## Appendix B

# Number Systems on the Computer

### B.1 Binary Numbers

Humans like to use the *decimal number* system for representing numbers. Decimal numbers are *base 10* meaning that a decimal number consists of a sequence of digits separated by a *decimal point*, where each *digit* can have values  $d \in \{0, 1, 2, \dots, 9\}$  and the weight of each digit is proportional to its place in the sequence of digits with respect to the decimal point, i.e., the number  $357.6 = 3 \cdot 10^2 + 5 \cdot 10^1 + 7 \cdot 10^0 + 6 \cdot 10^{-1}$ , or in general, for a number consisting of digits  $d_i$  with  $n + 1$  and  $m$  digits to the left and right of the decimal point, the value  $v$  is calculated as:

$$v = \sum_{i=-m}^n d_i 10^i. \quad (\text{B.1})$$

The basic unit of information in almost all computers is the binary digit, or *bit* for short. A *binary number* consists of a sequence of binary digits separated by a decimal point, where each digit can have values  $b \in \{0, 1\}$ , and the base is 2. The general equation is,

$$v = \sum_{i=-m}^n b_i 2^i, \quad (\text{B.2})$$

and examples are  $1011.1_2 = 1 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 + 1 \cdot 2^{-1} = 11.5$ . Notice that we use subscript 2 to denote a binary number, while no subscript is used for decimal numbers. The left-most bit is called the *most significant bit*, and the right-most bit is called the *least significant bit*. Due to typical organisation of computer memory, 8 binary digits is called a *byte*, and the term *word* is not universally defined but typically related to the computer architecture, a program is running on, such as 32 or 64 bits.

Other number systems are often used, e.g., *octal numbers*, which are base 8 numbers and have digits  $o \in \{0, 1, \dots, 7\}$ . Octals are useful short-hand for binary, since 3 binary digits map to the set of octal digits. Likewise, *hexadecimal numbers* are base 16 with digits  $h \in \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, a, b, c, d, e, f\}$ , such that  $a_{16} = 10$ ,  $b_{16} = 11$  and so on. Hexadecimals are convenient, since 4 binary digits map directly to the set of hexadecimal digits. Thus  $367 = 101101111_2 = 557_8 = 16f_{16}$ . A list of the integers 0–63 in various bases is given in Table B.1.

Dec	Bin	Oct	Hex	Dec	Bin	Oct	Hex
0	0	0	0	32	100000	40	20
1	1	1	1	33	100001	41	21
2	10	2	2	34	100010	42	22
3	11	3	3	35	100011	43	23
4	100	4	4	36	100100	44	24
5	101	5	5	37	100101	45	25
6	110	6	6	38	100110	46	26
7	111	7	7	39	100111	47	27
8	1000	10	8	40	101000	50	28
9	1001	11	9	41	101001	51	29
10	1010	12	a	42	101010	52	2a
11	1011	13	b	43	101011	53	2b
12	1100	14	c	44	101100	54	2c
13	1101	15	d	45	101101	55	2d
14	1110	16	e	46	101110	56	2e
15	1111	17	f	47	101111	57	2f
16	10000	20	10	48	110000	60	30
17	10001	21	11	49	110001	61	31
18	10010	22	12	50	110010	62	32
19	10011	23	13	51	110011	63	33
20	10100	24	14	52	110100	64	34
21	10101	25	15	53	110101	65	35
22	10110	26	16	54	110110	66	36
23	10111	27	17	55	110111	67	37
24	11000	30	18	56	111000	70	38
25	11001	31	19	57	111001	71	39
26	11010	32	1a	58	111010	72	3a
27	11011	33	1b	59	111011	73	3b
28	11100	34	1c	60	111100	74	3c
29	11101	35	1d	61	111101	75	3d
30	11110	36	1e	62	111110	76	3e
31	11111	37	1f	63	111111	77	3f

**Table B.1** A list of the integers 0–63 in decimal, binary, octal, and hexadecimal.

## B.2 IEEE 754 Floating Point Standard

The set of real numbers, also called *reals*, includes all fractions and irrational numbers. It is infinite in size both in the sense that there is no largest nor smallest number,

and that between any 2 given numbers there are infinitely many numbers. Reals are widely used for calculation, but since any computer only has finite memory, there are infinitely many numbers which cannot be represent on a computer. Hence, any computation performed on a computer with reals must rely on approximations. *IEEE 754 double precision floating-point format (binary64)*, known as a *double*, is a standard for representing an approximation of reals using 64 bits. These bits are divided into 3 parts: sign, exponent and fraction,

$$s e_1 e_2 \dots e_{11} m_1 m_2 \dots m_{52},$$

where  $s$ ,  $e_i$ , and  $m_j$  are binary digits. The bits are converted to a number using the equation by first calculating the exponent  $e$  and the mantissa  $m$ ,

$$e = \sum_{i=1}^{11} e_i 2^{11-i}, \quad (\text{B.3})$$

$$m = \sum_{j=1}^{52} m_j 2^{-j}. \quad (\text{B.4})$$

I.e., the exponent is an integer, where  $0 \leq e < 2^{11}$ , and the mantissa is a rational, where  $0 \leq m < 1$ . For most combinations of  $e$  and  $m$ , the real number  $v$  is calculated as,

$$v = (-1)^s (1 + m) 2^{e-1023} \quad (\text{B.5})$$

with the exceptions that

	$m = 0$	$m \neq 0$
$e = 0$	$v = (-1)^s 0$ (signed zero)	$v = (-1)^s m 2^{1-1023}$ (subnormals)
$e = 2^{11} - 1$	$v = (-1)^s \infty$	$v = (-1)^s \text{NaN}$ (not-a-number)

where  $e = 2^{11} - 1 = 11111111111_2 = 2047$ . The largest and smallest number that is not infinity is thus

$$e = 2^{11} - 2 = 2046, \quad (\text{B.6})$$

$$m = \sum_{j=1}^{52} 2^{-j} = 1 - 2^{-52} \simeq 1, \quad (\text{B.7})$$

$$v_{\max} = \pm \left(2 - 2^{-52}\right) 2^{1023} \simeq \pm 2^{1024} \simeq \pm 10^{308}. \quad (\text{B.8})$$

The density of numbers varies in such a way that when  $e - 1023 = 52$ , then

$$v = (-1)^s \left( 1 + \sum_{j=1}^{52} m_j 2^{-j} \right) 2^{52} \quad (\text{B.9})$$

$$= \pm \left( 2^{52} + \sum_{j=1}^{52} m_j 2^{-j} 2^{52} \right) \quad (\text{B.10})$$

$$= \pm \left( 2^{52} + \sum_{j=1}^{52} m_j 2^{52-j} \right) \quad (\text{B.11})$$

$$\stackrel{k=52-j}{=} \pm \left( 2^{52} + \sum_{k=51}^0 m_{52-k} 2^k \right), \quad (\text{B.12})$$

which are all integers in the range  $2^{52} \leq |v| < 2^{53}$ . When  $e - 1023 = 53$ , then the same calculation gives

$$v \stackrel{k=53-j}{=} \pm \left( 2^{53} + \sum_{k=52}^1 m_{53-k} 2^k \right), \quad (\text{B.13})$$

which are every second integer in the range  $2^{53} \leq |v| < 2^{54}$ , and so on for larger values of  $e$ . When  $e - 1023 = 51$ , the same calculation gives,

$$v \stackrel{k=51-j}{=} \pm \left( 2^{51} + \sum_{k=50}^{-1} m_{51-k} 2^k \right), \quad (\text{B.14})$$

which is a distance between numbers of  $1/2$  in the range  $2^{51} \leq |v| < 2^{52}$ , and so on for smaller values of  $e$ . Thus we may conclude that the distance between numbers in the interval  $2^n \leq |v| < 2^{n+1}$  is  $2^{n-52}$ , for  $-1022 = 1 - 1023 \leq n < 2046 - 1023 = 1023$ . For subnormals, the distance between numbers is

$$v = (-1)^s \left( \sum_{j=1}^{52} m_j 2^{-j} \right) 2^{-1022} \quad (\text{B.15})$$

$$= \pm \left( \sum_{j=1}^{52} m_j 2^{-j} 2^{-1022} \right) \quad (\text{B.16})$$

$$= \pm \left( \sum_{j=1}^{52} m_j 2^{-j-1022} \right) \quad (\text{B.17})$$

$$\stackrel{k=-j-1022}{=} \pm \left( \sum_{j=-1023}^{-1074} m_{-k-1022} 2^k \right), \quad (\text{B.18})$$



which gives a distance between numbers of  $2^{-1074} \simeq 10^{-323}$  in the range  $0 < |v| < 2^{-1022} \simeq 10^{-308}$ .



## Appendix C

### Commonly Used Character Sets

Letters, digits, symbols, and space are the core of how we store data, write programs, and communicate with computers and each other. These symbols are in short called characters and represent a mapping between numbers, also known as codes, and a pictorial representation of the character. E.g., the ASCII code for the letter 'A' is 65. These mappings are for short called character sets, and due to differences in natural languages and symbols used across the globe, many different character sets are in use. E.g., the English alphabet contains the letters 'a' to 'z'. These letters are common to many other European languages which in addition use even more symbols and accents. For example, Danish has further the letters 'æ', 'ø', and 'å'. Many non-European languages have completely different symbols, where the Chinese character set is probably the most extreme, and some definitions contain 106,230 different characters, albeit only 2,600 are included in the official Chinese language test at the highest level.

Presently, the most common character set used is Unicode Transformation Format (UTF), whose most popular encoding schemes are 8-bit (UTF-8) and 16-bit (UTF-16). Many other character sets exist, and many of the later build on the American Standard Code for Information Interchange (ASCII). The ISO-8859 codes were an intermediate set of character sets that are still in use, but which is greatly inferior to UTF. Here we will briefly give an overview of ASCII, ISO-8859-1 (Latin1), and UTF.

#### C.1 ASCII

The *American Standard Code for Information Interchange (ASCII)* [8], is a 7 bit code tuned for the letters of the English language, numbers, punctuation symbols, control codes and space, see Tables C.1 and C.2. The first 32 codes are reserved for

x0+0x	00	10	20	30	40	50	60	70
00	NUL	DLE	SP	0	@	P	'	p
01	SOH	DC1	!	1	A	Q	a	q
02	STX	DC2	"	2	B	R	b	r
03	ETX	DC3	#	3	C	S	c	s
04	EOT	DC4	\$	4	D	T	d	t
05	ENQ	NAK	%	5	E	U	e	u
06	ACK	SYN	&	6	F	V	f	v
07	BEL	ETB	'	7	G	W	g	w
08	BS	CAN	(	8	H	X	h	x
09	HT	EM	)	9	I	Y	i	y
0A	LF	SUB	*	:	J	Z	j	z
0B	VT	ESC	+	;	K	[	k	{
0C	FF	FS	,	<	L	\	l	
0D	CR	GS	-	=	M	]	m	}
0E	SO	RS	.	>	N	^	n	~
0F	SI	US	/	?	O	_	o	DEL

**Table C.1** ASCII

non-printable control characters to control printers and similar devices or to provide meta-information. The meaning of each control character is not universally agreed upon.

The code order is known as *ASCIIbetical order*, and it is sometimes used to perform arithmetic on codes, e.g., an uppercase letter with code *c* may be converted to lower case by adding 32 to its code. The ASCIIbetical order also has a consequence for sorting, i.e., when sorting characters according to their ASCII code, 'A' comes before 'a', which comes before the symbol '{'.

## C.2 ISO/IEC 8859

The ISO/IEC 8859 report [http://www.iso.org/iso/catalogue_detail?csnumber=28245](http://www.iso.org/iso/catalogue_detail?csnumber=28245) defines 10 sets of codes specifying up to 191 codes and graphics characters using 8 bits. Set 1, also known as ISO/IEC 8859-1, Latin alphabet No. 1, or *Latin1*, covers many European languages and is designed to be compatible with ASCII, such that code for the printable characters in ASCII is the same in ISO 8859-1. Table C.3 shows the characters above 7e. Codes 00-1f and 7f-9f are undefined in ISO 8859-1.

Code	Description
NUL	Null
SOH	Start of heading
STX	Start of text
ETX	End of text
EOT	End of transmission
ENQ	Enquiry
ACK	Acknowledge
BEL	Bell
BS	Backspace
HT	Horizontal tabulation
LF	Line feed
VT	Vertical tabulation
FF	Form feed
CR	Carriage return
SO	Shift out
SI	Shift in
DLE	Data link escape
DC1	Device control one
DC2	Device control two
DC3	Device control three
DC4	Device control four
NAK	Negative acknowledge
SYN	Synchronous idle
ETB	End of transmission block
CAN	Cancel
EM	End of medium
SUB	Substitute
ESC	Escape
FS	File separator
GS	Group separator
RS	Record separator
US	Unit separator
SP	Space
DEL	Delete

Table C.2 ASCII symbols.

### C.3 Unicode

Unicode is a character standard defined by the Unicode Consortium, <http://unicode.org>, as the *Unicode Standard*. Unicode allows for 1,114,112 different codes. Each code is called a *code point* which represents an abstract character. Code points are divided into 17 planes, each with  $2^{16} = 65,536$  code points. Planes are further subdivided into named *blocks*. The first plane is called the *Basic Multilingual plane* and its block of the first 128 code points is called the *Basic Latin block* and is identical to ASCII, see Table C.1, and code points 128-255 are called the *Latin-1 Supplement block*, and are identical to the upper range of ISO 8859-1, see Table C.3. Each code-point has a number of attributes such as the *Unicode general category*. Presently more than 128,000 code points are defined as covering 135 modern and historical writing systems, and obtained

x0+0x	80	90	A0	B0	C0	D0	E0	F0
00			NBSP	°	À	Đ	à	đ
01			¡	±	Á	Ñ	á	ñ
02			¢	²	Â	Ò	â	ò
03			£	³	Ã	Ó	ã	ó
04			¤	´	Ä	Ö	ä	ö
05			¥	µ	Å	Õ	å	õ
06			¦	¶	Æ	Ö	æ	ö
07			§	·	Ç	×	ç	÷
08			¨	¸	È	Ø	è	ø
09			©	¹	É	Ú	é	ù
0a			ª	º	Ê	Û	ê	ú
0b			«	»	Ë	Ü	ë	û
0c			¬	$\frac{1}{4}$	Ì	Ü	ì	ü
0d			SHY	$\frac{1}{2}$	Í	Ý	í	ý
0e			®	$\frac{3}{4}$	Î	Þ	î	þ
0f			¯		Ï	ß	ï	ÿ

**Table C.3** ISO-8859-1 (latin1) non-ASCII part. Note that the codes 7f – 9f are undefined.

Code	Description
NBSP	Non-breakable space
SHY	Soft hyphen

**Table C.4** ISO-8859-1 special symbols.

at <http://www.unicode.org/Public/UNIDATA/UnicodeData.txt>, which includes the code point, name, and general category.

A Unicode code point is an abstraction from the encoding and the graphical representation of a character. A code point is written as “U+” followed by its hexadecimal number, and for the Basic Multilingual plane, 4 digits are used, e.g., the code point with the unique name LATIN CAPITAL LETTER A has the Unicode code point “U+0041”, and is in this text visualized as ‘A’. More digits are used for code points of the remaining planes.

The general category is used to specify valid characters that do not necessarily have a visual representation but possibly transform text. Some categories and their letters in the first 256 code points are shown in Table C.5.

To store and retrieve code points, they must be encoded and decoded. A common encoding is *UTF-8*, which encodes code points as 1 to 4 bytes, and which is backward-compatible with ASCII and ISO 8859-1. Hence, in all 3 coding systems, the character with code 65 represents the character ‘A’. Another popular encoding scheme is *UTF-16*, which encodes characters as 2 or 4 bytes, but which is not backward-compatible with ASCII or ISO 8859-1. UTF-16 is used internally in many compilers, interpreters, and operating systems.

General category	Code points	Name
Lu	U+0041–U+005A, U+00C0–U+00D6, U+00D8–U+00DE	Upper case letter
Ll	U+0061–U+007A, U+00B5, U+00DF–U+00F6, U+00F8–U+00FF	Lower case letter
Lt	None	Digraphic letter, with first part uppercase
Lm	None	Modifier letter
Lo	U+00AA, U+00BA	Gender ordinal indicator
Nl	None	Letterlike numeric character
Pc	U+005F	Low line
Mn	None	Nonspacing combining mark
Mc	None	Spacing combining mark
Cf	U+00AD	Soft Hyphen

**Table C.5** Some general categories for the first 256 code points.





## Appendix D

### Common Language Infrastructure

The *Common Language Infrastructure (CLI)*, not to be confused with *Command Line Interface* with the same acronym, is a technical standard developed by Microsoft [4, 3]. The standard specifies a language, its format, and a runtime environment that can execute the code. The main feature is that it provides a common interface between many languages and many platforms, such that programs can collaborate in a language-agnostic manner and can be executed on different platforms without having to be recompiled. Main features of the standard are:

Common Type System (CTS) which defines a common set of types that can be used across different languages as if it were their own.

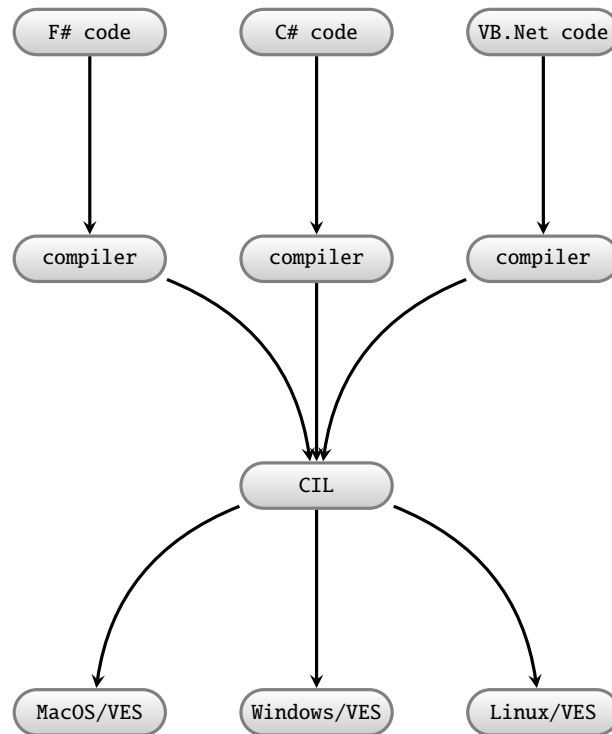
Metadata which defines a common method for referencing programming structures such as values and functions in a language-independent manner.

Common Intermediate Language (CIL) which is a platform-independent, stack-based, object-oriented assembly language that can be executed by the Virtual Execution System.

Virtual Execution System (VES) which is a platform dependent, virtual machine, which combines the above into code that can be executed at runtime. Microsoft's implementation of VES is called *Common Language Runtime (CLR)* and uses *just-in-time* compilation. In this book, we have been using the `mono` command.

The process of running an F# program is shown in Figure D.1. First the F# code is compiled or interpreted to CIL. This code possibly combined with other CIL code is then converted to a machine-readable code, and the result is then executed on the platform.

CLI defines a *module* as a single file containing executable code by VES. Hence, CLI's notion of a module is somewhat related to F#'s notion of module, but the



**Fig. D.1** The relation between some .NET/Mono languages with the Common intermediate language (CIL), and the Virtual execution systems (VES) on some operating system (mono).

two should not be confused. A collection of modules, a *manifest*, and possibly other resources, which jointly define a complete program is called an *assembly*. The manifest is the description of which files are included in the assembly together with its version, name, security information, and other bookkeeping information.

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