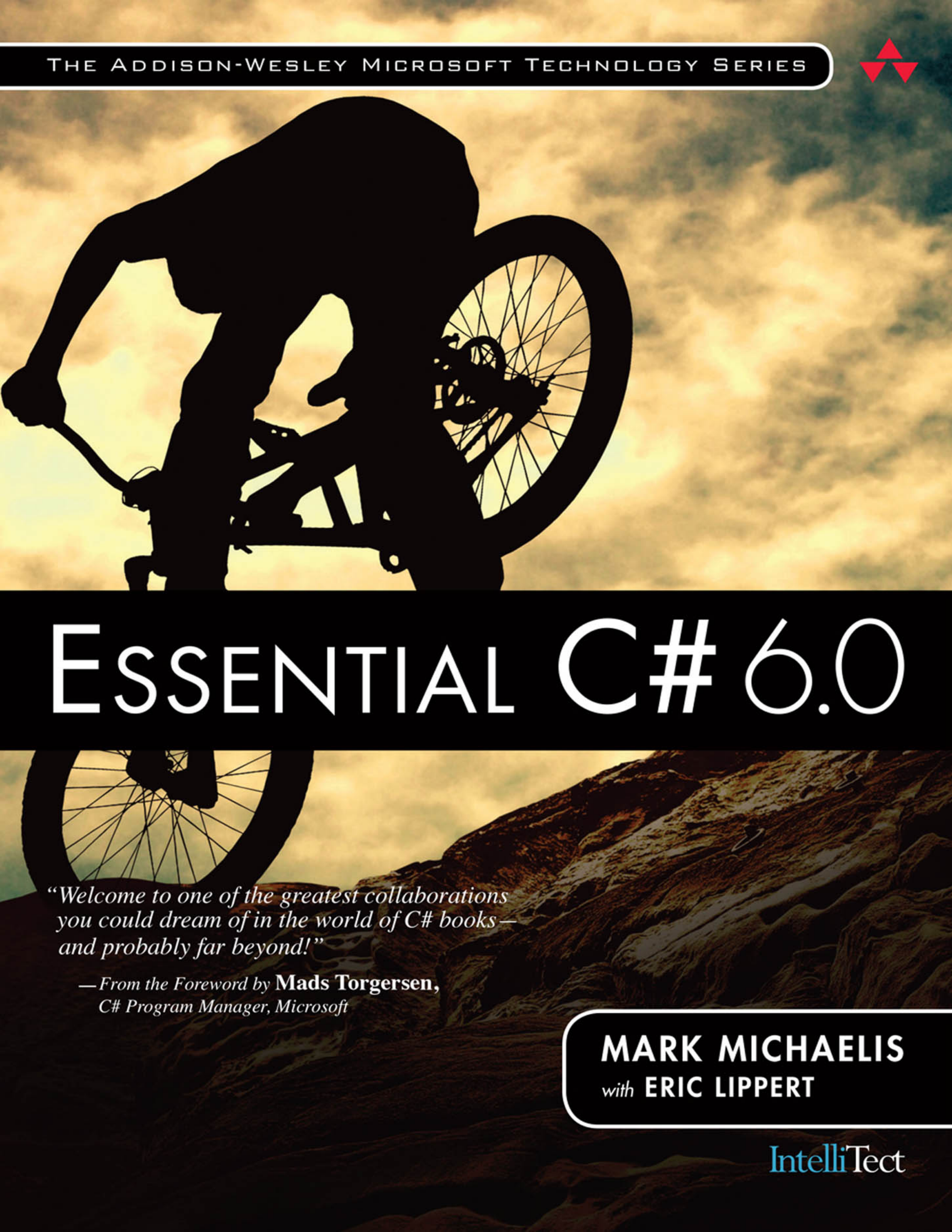

THE ADDISON-WESLEY MICROSOFT TECHNOLOGY SERIES

ESSENTIAL C# 6.0

"Welcome to one of the greatest collaborations you could dream of in the world of C# books—and probably far beyond!"

—*From the Foreword by* **Mads Torgersen,**
C# Program Manager, Microsoft

MARK MICHAELIS
with **ERIC LIPPERT**

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Essential C# 6.0

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Essential C# 6.0

Mark Michaelis
with Eric Lippert

Addison-Wesley

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To my family: Elisabeth, Benjamin, Hanna, and Abigail.

You have sacrificed a husband and daddy for countless hours of writing, frequently at times when he was needed most.

Thanks!

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Contents at a Glance

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Foreword

WELCOME TO ONE of the greatest collaborations you could dream of in the world of C# books—and probably far beyond! Mark Michaelis' *Essential C#* series was already a classic when, for the previous edition, he teamed up with famous C# blogger Eric Lippert—a masterstroke.

You may think of Eric as writing blogs and Mark as writing books, but that is not how I first got to know them.

In 2005 when LINQ (Language Integrated Query) was disclosed, I had only just joined Microsoft, and I got to tag along to the PDC conference for the big reveal. Despite my almost total lack of contribution to the technology, I thoroughly enjoyed the hype. The talks were overflowing, the printed leaflets were flying like hotcakes. It was a big day for C# and .NET, and I was having a great time.

It was pretty quiet in the hands-on labs area, though, where people could try out the technology preview themselves with nice, scripted walkthroughs. That's where I ran into Mark. Needless to say, he wasn't following the script. He was doing his own experiments, combing through the docs, talking to other folks, and busily pulling together his own picture.

As a newcomer to the C# community, I think I may have met a lot of people for the first time at that conference—people with whom I have since formed great relationships. But to be honest, I don't remember it—it's all a blur. The only one I remember is Mark. Here is why: When I asked him if he was liking the new stuff, he didn't just join the rave. He was totally level-headed: "*I don't know yet. I haven't made up my mind about it.*" He wanted to absorb and understand the full package, and until then he wasn't going to let anyone tell him what to think.

So instead of the quick sugar-rush of affirmation I might have expected, I got to have a frank and wholesome conversation—the first of many over the years—about details, consequences, and concerns with this new technology. And so it remains: Mark is an incredibly valuable community member for us language designers to have, because he is super smart, insists on understanding everything to the core, and has phenomenal insight into how things affect real developers. But perhaps most of all because he is forthright and never afraid to speak his mind. If something passes the "Mark Test," then we know we can start feeling pretty good about it!

These are the same qualities that make Mark such a great writer. He goes right to the essence and communicates with great integrity, no sugarcoating, and a keen eye for practical value and real-world problems.

Eric is, of course, my former colleague of seven years on the C# team. He'd been there much longer than I had, and the first I recall of him, he was explaining to the team how to untangle a bowl of spaghetti. More precisely, our C# compiler code base at the time was in need of some serious architectural TLC and was exceedingly hard to add new features to—something we desperately needed to be able to do with LINQ. Eric had been investigating what kind of architecture we ought to have (Phases! We didn't even really have those!), and more importantly, how to get from here to there, step by step. The remarkable thing was that as complex as this was, and as new as I was to the team and the code base, I immediately understood what he was saying!

You may recognize from his blogs the super-clear and well-structured untangling of the problem, the convincing clarity of enumerated solutions, and the occasional unmitigated hilarity. Well, you don't know the half of it! Every time Eric was grappling with a complex issue and was sharing his thoughts about it with the team, his emails about it were just as meticulous and every bit as hilarious. You fundamentally couldn't ignore an issue raised by Eric because you couldn't wait to read his prose about it. They were even purple, too! So I essentially got to enjoy a continuous supply of what amounts to unpublished installments of his blog, as well as, of course, his pleasant and insightful presence as a member of the C# compiler team and language design team. In his post-Microsoft days, Eric has continued to be a wonderful, insightful voice with a lot more influence on our decisions than he probably knows.

In summary, I am truly grateful to get to work with these two amazing people on a regular basis: Eric to help keep my thinking straight and Mark to help keep me honest. They share a great gift of providing clarity and elucidation, and by combining their "inside" and "outside" perspective on C#, their book reaches a new level of completeness. No one will help you get C# 6 like these two gentlemen do.

Enjoy!

—Mads Torgersen
C# Program Manager
Microsoft

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Preface

THROUGHOUT THE HISTORY of software engineering, the methodology used to write computer programs has undergone several paradigm shifts, each building on the foundation of the former by increasing code organization and decreasing complexity. This book is organized in such a way as to take you through similar paradigm shifts.

The beginning chapters of *Essential C# 6.0* take you through **sequential programming structure,** in which statements are written in the order in which they are executed. The problem with this model is that complexity increases exponentially as the requirements increase. To reduce this complexity, code blocks may be moved into methods, creating a **structured programming model.** This allows you to call the same code block from multiple locations within a program, without duplicating code. Even with this construct, however, growing programs may quickly become unwieldy and require further abstraction. Object-oriented programming, discussed in Chapter 5, was a response intended to rectify this situation. In subsequent chapters of this book, you will learn about additional methodologies, such as interface-based programming, LINQ (and the transformation it makes to the collection API), and eventually rudimentary forms of declarative programming (in Chapter 17) via attributes.

This book has three main functions:

- It provides comprehensive coverage of the C# language, going beyond a tutorial and offering a foundation upon which you can begin effective software development projects.

- For readers already familiar with C#, it provides insight into some of the more complex programming paradigms and provides in-depth coverage of the features introduced in the latest version of the language, C# 6.0 and .NET Framework 4.6.
- It serves as a timeless reference, even after you gain proficiency with the language.

The key to successfully learning C# is to start coding as soon as possible. Don't wait until you are an "expert" in theory—start writing software immediately. As a believer in iterative development, I hope this book enables even a novice programmer to begin writing basic C# code by the end of Chapter 2.

A number of topics are not covered in this book. You won't find coverage of topics such as ASP.NET, Entity Framework, smart client development such as WPF, distributed programming, and so on. Although these topics are relevant to the .NET Framework, to do them justice requires books of their own. Fortunately, Addison-Wesley's *.NET Development Series* provides a wealth of writing on these topics. *Essential C# 6.0* focuses on C# and the types within the Base Class Library. Reading this book will prepare you to focus on and develop expertise in any of the areas covered by the rest of the series.

Target Audience for This Book

My challenge with this book was to keep advanced developers awake while not abandoning beginners by using terms such as *assembly*, *link*, *chain*, *thread*, and *fusion*, as though the topic was more appropriate for blacksmiths than for programmers. This book's primary audience is experienced developers looking to add another language to their arsenal—another arrow in their quiver, as it were. However, I have carefully assembled this book to provide significant value to developers at all levels.

- *Beginners:* If you are new to programming, this book serves as a resource to help transition you from an entry-level programmer to a C# developer—one who is comfortable with any C# programming task that's thrown your way. This book not only teaches you syntax, but also trains you in good programming practices that will serve you well throughout your programming career.

- *Structured programmers:* Just as it's best to learn a foreign language through immersion, so learning a computer language is most effective when you begin using that language before you know all of its intricacies. In this vein, this book begins with a tutorial that will be comfortable for those familiar with structured programming, and by the end of Chapter 4, developers in this category should feel at home writing basic control flow programs. However, the key to excellence for C# developers is not just memorizing syntax. Rather, to transition from simple programs to enterprise development, the C# developer must think natively in terms of objects and their relationships. To this end, Chapter 5's Beginner Topics introduce classes and object-oriented development. The role filled by historically structured programming languages such as C, COBOL, and FORTRAN is still significant but shrinking, so it behooves software engineers to become familiar with object-oriented development. C# is an ideal language for making this transition because it was designed with object-oriented development as one of its core tenets.
- *Object-based and object-oriented developers:* C++ and Java programmers, and many experienced Visual Basic programmers, fall into this category. Many of you are already completely comfortable with semicolons and curly braces. A brief glance at the code in Chapter 1 reveals that at its core, C# is similar to the C and C++ styles of languages that you already know.
- *C# professionals:* For those already versed in C#, this book provides a convenient reference for less frequently encountered syntax. Furthermore, it provides answers to language details and subtleties that are seldom addressed. Most importantly, it presents the guidelines and patterns for programming robust and maintainable code. This book also aids in the task of teaching C# to others. With the emergence of C# 3.0, 4.0, 5.0, and now 6.0, some of the most prominent enhancements are as follows:
  - Implicitly typed variables (see Chapter 2)
  - Extension methods (see Chapter 5)
  - Partial methods (see Chapter 5)
  - Anonymous types (see Chapter 11)
  - Generics (see Chapter 11)
  - Lambda statements and expressions (see Chapter 12)

– Expression trees (see Chapter 12)
– Standard query operators (see Chapter 14)
– Query expressions (see Chapter 15)
– Dynamic programming (Chapter 17)
– Multithreaded programming with the Task Programming Library and `async` (Chapter 18)
– Parallel query processing with PLINQ (Chapter 18)
– Concurrent collections (Chapter 19)

These topics are covered in detail for those not already familiar with them. Also pertinent to advanced C# development is the subject of pointers, in Chapter 21. Often, even experienced C# developers do not understand this topic well.

Features of This Book

Essential C# 6.0 is a language book that adheres to the core C# Language 6.0 Specification. To help you understand the various C# constructs, it provides numerous examples demonstrating each feature. Accompanying each concept are guidelines and best practices, ensuring that code compiles, avoids likely pitfalls, and achieves maximum maintainability.

To improve readability, code is specially formatted and chapters are outlined using mind maps.

C# Coding Guidelines

One of the more significant features in *Essential C# 6.0* is the inclusion of C# coding guidelines, as shown in the following example taken from Chapter 16:

Guidelines

DO ensure that equal objects have equal hash codes.

DO ensure that the hash code of an object never changes while it is in a hash table.

DO ensure that the hashing algorithm quickly produces a well-distributed hash.

DO ensure that the hashing algorithm is robust in any possible object state.

These guidelines are the key to differentiating a programmer who knows the syntax from an expert who is able to discern the most effective code to write based on the circumstances. Such an expert not only gets the code to compile, but does so while following best practices that minimize bugs and facilitate maintenance well into the future. The coding guidelines highlight some of the key principles that readers will want to be sure to incorporate into their development.

Code Samples

The code snippets in most of this text can run on any implementation of the Common Language Infrastructure (CLI), including the Mono, DNX Core, and Microsoft .NET platforms. Platform- or vendor-specific libraries are seldom used, except when communicating important concepts relevant only to those platforms (appropriately handling the single-threaded user interface of Windows, for example). Any code that specifically requires C# 3.0, 4.0, or 5.0 compliance is called out in the C# version, and separate indexes at the end of the book.

Here is a sample code listing.

LISTING 1.17: Swapping the Indexed Placeholders and Corresponding Variables

```
System.Console.WriteLine("Your full name is {1}, {0}",
  firstName, lastName);
```

The formatting is as follows.

- Comments are shown in italics.

```
/* Display a greeting to the console
   using composite formatting. */
```

- Keywords are shown in bold.

```
static void Main()
```

- Highlighted code calls out specific code snippets that may have changed from an earlier listing, or demonstrates the concept described in the text.

```
   System.Console.Write /* No new line */ (
```

Highlighting can appear on an entire line or on just a few characters within a line.

```
System.Console.WriteLine(
     "Your full name is {0} {1}.",
```

- Incomplete listings contain an ellipsis to denote irrelevant code that has been omitted.

```
// ...
```

- Console output is the output from a particular listing that appears following the listing.

OUTPUT 1.4

```
>HeyYou.exe
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
```

User input for the program appears in **boldface.**

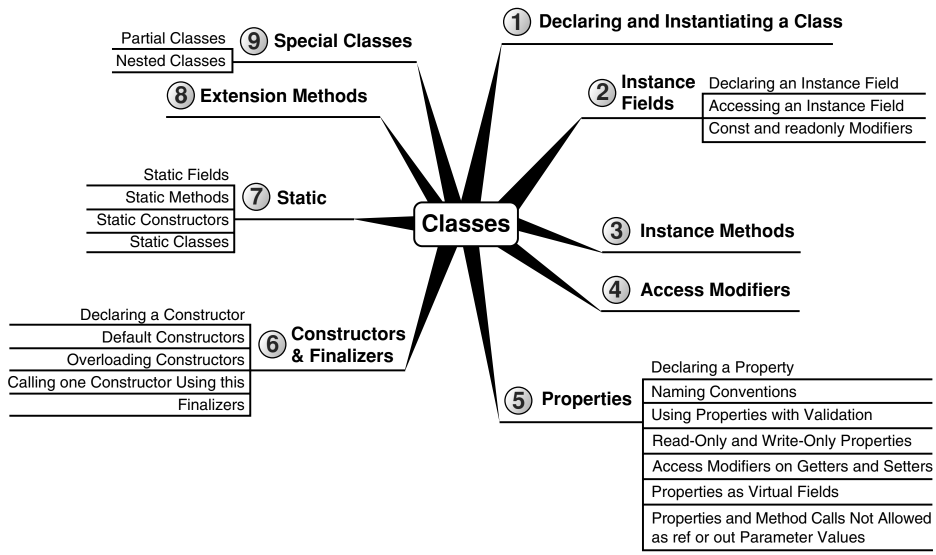
Although it might have been convenient to provide full code samples that you could copy into your own programs, doing so would detract from your learning a particular topic. Therefore, you need to modify the code samples before you can incorporate them into your programs. The core omission is error checking, such as exception handling. Also, code samples do not explicitly include using System statements. You need to assume the statement throughout all samples.

You can find sample code at Intellitect.com/essentialcsharp and at informit.com/mstechseries. In addition, the code is available on Github—see http://itl.tc/EssentialCSharpSCC. Instructions for downloading the tools to compile the source code as well as the compilation instructions themselves are found in Appendix A.

You can also access the errata at http://Intellitect.com/essentialcsharp.

Mind Maps

Each chapter's introduction includes a **mind map,** which serves as an outline that provides an at-a-glance reference to each chapter's content. Here is an example (taken from Chapter 5).



The theme of each chapter appears in the mind map's center. High-level topics spread out from the core. Mind maps allow you to absorb the flow from high-level to more detailed concepts easily, with less chance of encountering very specific knowledge that you might not be looking for.

Helpful Notes

Depending on your level of experience, special code blocks and tabs will help you navigate through the text.

- Beginner Topics provide definitions or explanations specifically targeted to entry-level programmers.
- Advanced Topics enable experienced developers to focus on the material that is most relevant to them.
- Callout notes highlight key principles so that readers easily recognize their significance.
- Language Contrast sidebars identify key differences between C# and its predecessors to aid those familiar with other languages.
- Page-edge **begin** and **end tabs** denote material specific to C# versions; where that material continues over multiple pages, just the version number appears in the tab.

How This Book Is Organized

At a high level, software engineering is about managing complexity, and it is toward this end that I have organized *Essential C# 6.0*. Chapters 1–4 introduce structured programming, which enable you to start writing simple functioning code immediately. Chapters 5–9 present the object-oriented constructs of C#. Novice readers should focus on fully understanding this section before they proceed to the more advanced topics found in the remainder of this book. Chapters 11–13 introduce additional complexity-reducing constructs, handling common patterns needed by virtually all modern programs. This leads to dynamic programming with reflection and attributes, which is used extensively for threading and interoperability in the chapters that follow.

The book ends with a chapter on the Common Language Infrastructure, which describes C# within the context of the development platform in which it operates. This chapter appears at the end because it is not C# specific and it departs from the syntax and programming style in the rest of the book. However, this chapter is suitable for reading at any time, perhaps most appropriately immediately following Chapter 1.

Here is a description of each chapter (in this list, chapter numbers shown in ***bold italics*** indicate the presence of C# 3.0–5.0 material).

- ***Chapter 1***—*Introducing C#:* After presenting the C# HelloWorld program, this chapter proceeds to dissect it. This should familiarize readers with the look and feel of a C# program and provide details on how to compile and debug their own programs. Chapter 1 also touches on the context of a C# program's execution and its intermediate language.
- ***Chapter 2***—*Data Types:* Functioning programs manipulate data, and this chapter introduces the primitive data types of C#. This includes coverage of two type categories, value types and reference types, along with conversion between types and support for arrays.
- ***Chapter 3***—*Operators and Control Flow:* To take advantage of the iterative capabilities in a computer, you need to know how to include loops and conditional logic within your program. This chapter also covers the C# operators, data conversion, and preprocessor directives.
- ***Chapter 4***—*Methods and Parameters:* This chapter investigates the details of methods and their parameters. It includes passing by value,

passing by reference, and returning data via a parameter. Default parameter support was added in C# 4.0, and this chapter explains how to use this support.

- ***Chapter 5***—*Classes:* Given the basic building blocks of a class, this chapter combines these constructs to form fully functional types. Classes form the core of object-oriented technology by defining the template for an object.
- ***Chapter 6***—*Inheritance:* Although inheritance is a programming fundamental to many developers, C# provides some unique constructs, such as the `new` modifier. This chapter discusses the details of the inheritance syntax, including overriding.
- ***Chapter 7***—*Interfaces:* This chapter demonstrates how interfaces are used to define the "versionable" interaction contract between classes. C# includes both explicit and implicit interface member implementation, enabling an additional encapsulation level not supported by most other languages.
- ***Chapter 8***—*Value Types:* Although it is more common to define reference types, it is sometimes necessary to define value types that behave in a fashion similar to the primitive types built into C#. This chapter describes how to define structures, while exposing the idiosyncrasies they may introduce.
- *Chapter 9—Well-Formed Types:* This chapter discusses more advanced type definition. It explains how to implement operators, such as + and casts, and describes how to encapsulate multiple classes into a single library. In addition, the chapter demonstrates the process of defining namespaces and the use of XML comments, and discusses how to design classes for garbage collection.
- ***Chapter 10***—*Exception Handling:* This chapter expands on the exception-handling introduction from Chapter 4 and describes how exceptions follow a hierarchy that supports the creation of custom exceptions. It also includes some best practices on exception handling.
- ***Chapter 11***—*Generics:* Generics is perhaps the core feature missing from C# 1.0. This chapter fully covers this 2.0 feature. In addition, C# 4.0 added support for covariance and contravariance—something covered in the context of generics in this chapter.

- ***Chapter 12****—Delegates and Lambda Expressions:* Delegates begin clearly distinguishing C# from its predecessors by defining patterns for handling events within code. This practice virtually eliminates the need for writing routines that poll. Lambda expressions are the key concept that make C# 3.0's LINQ possible. Chapter 12 explains how lambda expressions build on the delegate construct by providing a more elegant and succinct syntax. This chapter forms the foundation for the new collection API discussed next.
- ***Chapter 13****—Events:* Encapsulated delegates, known as events, are a core construct of the Common Language Runtime. Anonymous methods, another C# 2.0 feature, are also presented here.
- ***Chapter 14****—Collection Interfaces with Standard Query Operators:* The simple, yet elegantly powerful changes introduced in C# 3.0 begin to shine in this chapter, as we take a look at the extension methods of the new `Enumerable` class. This class makes available an entirely new collection API known as the standard query operators, which is discussed in detail here.
- ***Chapter 15****—LINQ with Query Expressions:* Using standard query operators alone results in some long statements that can be challenging to decipher. However, query expressions provide an alternative syntax that matches closely with SQL, as described in this chapter.
- ***Chapter 16****—Building Custom Collections:* In building custom APIs that work against business objects, it is sometimes necessary to create custom collections. This chapter details how to do this, and in the process introduces contextual keywords that make custom collection building easier.
- ***Chapter 17****—Reflection, Attributes, and Dynamic Programming:* Object-oriented programming formed the basis for a paradigm shift in program structure in the late 1980s. In a similar way, attributes facilitate declarative programming and embedded metadata, ushering in a new paradigm. This chapter looks at attributes and discusses how to retrieve them via reflection. It also covers file input and output via the serialization framework within the Base Class Library. In C# 4.0, a new keyword, `dynamic`, was added to the language. It removed all type checking until runtime, a significant expansion of what can be done with C#.

- ***Chapter 18****—Multithreading:* Most modern programs require the use of threads to execute long-running tasks while ensuring they provide an active response to simultaneous events. As programs become more sophisticated, they must take additional precautions to protect data in these dynamic environments. Programming multithreaded applications is complex. This chapter discusses how to work with threads and provides best practices to avoid the problems that plague multithreaded applications.
- ***Chapter 19****—Thread Synchronization:* Building on the preceding chapter, Chapter 19 demonstrates some of the built-in threading pattern support that can simplify the explicit control of multithreaded code.
- ***Chapter 20****—Platform Interoperability and Unsafe Code:* Given that C# is a relatively young language, far more code is written in other languages than in C#. To take advantage of this preexisting code, C# supports interoperability—the calling of unmanaged code—through P/Invoke. In addition, C# provides for the use of pointers and direct memory manipulation. Although code with pointers requires special privileges to run, it provides the power to interoperate fully with traditional C-based application programming interfaces.
- ***Chapter 21****—The Common Language Infrastructure:* Fundamentally, C# is the syntax that was designed as the most effective programming language on top of the underlying Common Language Infrastructure. This chapter delves into how C# programs relate to the underlying runtime and its specifications.
- ***Appendix A****—Downloading and Installing the C# Compiler and the CLI Platform:* This appendix provides instructions for setting up a C# compiler and the platform on which to run the code, Microsoft .NET or Mono.
- ***Appendix B****—Tic-Tac-Toe Source Code Listing:* This appendix provides a full listing of the Tic-Tac-Toe program referred to in Chapters 3 and 4.
- ***C# 3.0, 4.0, 5.0, and 6.0 Indexes***—These indexes provide a quick reference for the features added in C# 3.0 through 6.0. They are specifically designed to help programmers quickly update their language skills to a more recent version.

Appendix C, Interfacing with Multithreading Patterns Prior to the TPL and C# 6.0, and Appendix D, Timers Prior to the Async/Await Pattern of C# 6.0, can be found on the book's website, http://www.informit.com/title/9780134141046. Teaching resources that accompany this book will be made available to qualified instructors through Pearson's Instructor Resource Center.

I hope that you find this book to be a great resource in establishing your C# expertise, and that you continue to reference it for the more obscure areas of C# and its inner workings.

—Mark Michaelis
Blog: http://IntelliTect.com/mark
Twitter: @Intellitect, @MarkMichaelis

Acknowledgments

NO BOOK CAN be published by the author alone, and I am extremely grateful for the multitude of people who helped me with this one. The order in which I thank people is not significant, except for those who come first. By far, my family has made the biggest sacrifice to allow me to complete this project. Benjamin, Hanna, and Abigail often had a daddy distracted by this book, but Elisabeth suffered even more so. She was often left to take care of things, holding the family's world together on her own. I would like to say it got easier with each edition but, alas, no: As the kids got older, life became more hectic, and without me Elisabeth was stretched to the breaking point almost all the time. A huge "Sorry" and ginormous "Thank You!"

Many technical editors reviewed each chapter in minute detail to ensure technical accuracy. I was often amazed by the subtle errors these folks managed to catch: Paul Bramsman, Kody Brown, Ian Davis, Doug Dechow, Gerard Frantz, Thomas Heavey, Anson Horton, Brian Jones, Shane Kercheval, Angelika Langer, Eric Lippert, John Michaelis, Jason Morse, Nicholas Paldino, Jon Skeet, Michael Stokesbary, Robert Stokesbary, John Timney, and Stephen Toub.

Eric is no less than amazing. His grasp of the C# vocabulary is truly astounding, and I am very appreciative of his edits, especially when he pushed for perfection in terminology. His improvements to the C# 3.0 chapters were incredibly significant, and in the second edition my only regret was that I didn't have him review all the chapters. However, that regret no longer continues to fester. Eric has painstakingly reviewed every *Essential C#* chapter with amazing detail and precision. I am extremely grateful for his contribution to making this book even better than the first two editions. Thanks, Eric! I can't imagine anyone better for the job. You deserve all the credit for raising the bar from good to great.

Similar to the case with Eric and C#, there are only a handful of people who know .NET multithreading as well as Stephen Toub. Accordingly, Stephen focused on the two (rewritten for a third time) multithreading chapters and their new focus on async support in C# 5.0. Thanks, Stephen!

Thanks to everyone at Addison-Wesley for their patience in working with me in spite of my occasional tendency to focus on everything else except the manuscript. Thanks to Vicki Rowland, Ellie Bru, Curt Johnson, and Joan Murray. Joan deserves a special medal for her patience given the number of times I delayed not only providing deliverables but even responding to emails. Vicki is no less than amazing in her ability to work with technical authors. I was so appreciative of the updated, fully stylized manuscripts she provided following the *Essential C# 5.0* publication. It made writing *Essential C# 6.0* so much easier than my updates of the prior editions.

Thanks also to Mads Torgersen, for his willingness to write the Foreword. Even if only half of what he says is true, I am greatly honored.

About the Authors

Mark Michaelis is the founder of IntelliTect and serves as the Chief Technical Architect and Trainer. Since 1996, he has been a Microsoft MVP for C#, Visual Studio Team System, and the Windows SDK; in 2007, he was recognized as a Microsoft Regional Director. He also serves on several Microsoft software design review teams, including C#, the Connected Systems, Office/SharePoint, and Visual Studio. Mark speaks at developer conferences and has written numerous articles and other books. He holds a bachelor of arts in philosophy from the University of Illinois and a master's degree in computer science from the Illinois Institute of Technology. When not bonding with his computer, Mark stays busy with his family or training for another Ironman (having completed his first in 2008). Mark lives in Spokane, Washington, with his wife, Elisabeth, and three children, Benjamin, Hanna, and Abigail.

Eric Lippert works on tools for static analysis of C# at Coverity, now a part of Synopsys. Before joining Coverity, he was a principal developer on the C# compiler team at Microsoft. When not blogging or editing books about C#, Eric does his best to keep his tiny sailboat upright. He lives in Seattle, Washington, with his wife, Leah.

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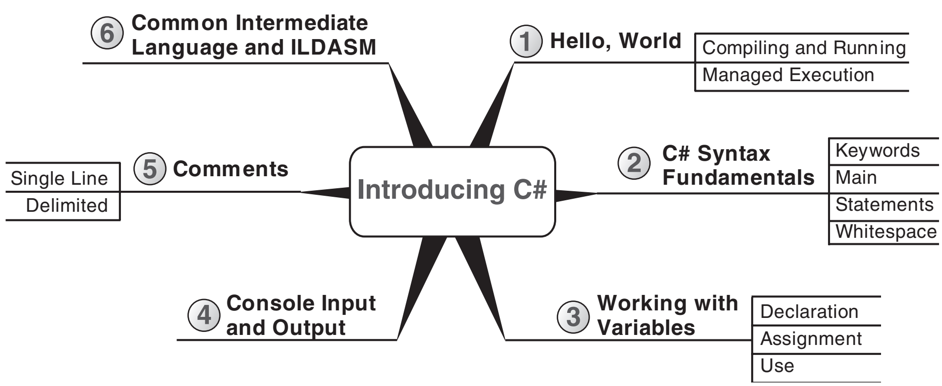
1

Introducing C#

C# IS NOW A WELL-ESTABLISHED language that builds on features found in its predecessor C-style languages (C, C++, and Java), making it immediately familiar to many experienced programmers.[1] Part of a larger, more complex open source execution platform called the Common Language Infrastructure (CLI), C# is a programming language for building software components and applications.



This chapter introduces C# using the traditional `HelloWorld` program. The chapter focuses on C# syntax fundamentals, including defining an entry point into the C# program. This will familiarize you with the C# syntax

1. The first C# design meeting took place in 1998.

style and structure, and it will enable you to produce the simplest of C# programs. Prior to the discussion of C# syntax fundamentals is a summary of managed execution context, which explains how a C# program executes at runtime. This chapter ends with a discussion of variable declaration, writing and retrieving data from the console, and the basics of commenting code in C#.

Hello, World

The best way to learn a new programming language is to write code. The first example is the classic `HelloWorld` program. In this program, you will display some text to the screen.

Listing 1.1 shows the complete `HelloWorld` program; in the following sections, you will compile the code.

LISTING 1.1: `HelloWorld` in C#[2]

```
class HelloWorld
{
 static void Main()
 {
   System.Console.WriteLine("Hello. My name is Inigo Montoya.");
 }
}
```

> **NOTE**
>
> C# is a case-sensitive language: Incorrect case prevents the code from compiling successfully.

Those experienced in programming with Java, C, or C++ will immediately see similarities. Like Java, C# inherits its basic syntax from C and C++.[3] Syntactic punctuation (such as semicolons and curly braces), features (such as case sensitivity), and keywords (such as `class`, `public`, and `void`) are familiar to programmers experienced in these languages. Beginners

2. Refer to the movie *The Princess Bride* if you're confused about the Inigo Montoya references.
3. When creating C#, the language creators reviewed the specifications for C/C++, literally crossing out the features they didn't like and creating a list of the ones they did like. The group also included designers with strong backgrounds in other languages.

and programmers from other languages will quickly find these constructs intuitive.

Compiling and Running the Application

The C# compiler allows any file extension for files containing C# source code, but `.cs` is typically used. After saving the source code to a file, developers must compile it. (Appendix A provides instructions for installing the compiler.) Because the mechanics of the command are not part of the C# standard, the compilation command varies depending on the C# compiler implementation.

If you place Listing 1.1 into a file called `HelloWorld.cs`, the compilation command in Output 1.1 will work with the Microsoft .NET compiler (assuming appropriate paths to the compiler are set up).[4]

OUTPUT 1.1

```
>csc.exe HelloWorld.cs
Microsoft (R) Visual C# Compiler version 1.0.0.50618
Copyright (C) Microsoft Corporation. All rights reserved.
```

The exact output will vary depending on which version of the compiler you use.

Running the resultant program, `HelloWorld.exe`, displays the message shown in Output 1.2.

OUTPUT 1.2

```
>HelloWorld.exe
Hello. My name is Inigo Montoya.
```

The program created by the C# compiler, `HelloWorld.exe`, is an **assembly.** Instead of creating an entire program that can be executed independently, developers can create a library of code that can be referenced by another, larger program. Libraries (or class libraries) use the filename

4. Compilation is also possible using .NET Core—a cross platform implementation of .NET available from http://dotnet.github.io/core. Although I would very much have liked to place instructions for other platforms here, doing so detracts from the topic of introducing C#. Instead, see Appendix A for details on .NET Core or from http://itl.tc/GettingStartedWithDNX.

extension `.dll`, which stands for Dynamic Link Library (DLL). A library is also an assembly. In other words, the output from a successful C# compile is an assembly regardless of whether it is a program or a library.

Begin 2.0

Language Contrast: Java—Filename Must Match Class Name

In Java, the filename must follow the name of the class. In C#, this convention is frequently followed but is not required. In C#, it is possible to have two classes in one file, and starting with C# 2.0, it's possible to have a single class span multiple files with a feature called a partial class.

End 2.0

C# Syntax Fundamentals

Once you successfully compile and run the `HelloWorld` program, you are ready to start dissecting the code to learn its individual parts. First, consider the C# keywords along with the identifiers that the developer chooses.

BEGINNER TOPIC

Keywords

To enable the compiler to interpret the code, certain words within C# have special status and meaning. Known as **keywords,** they provide the concrete syntax that the compiler uses to interpret the expressions the programmer writes. In the `HelloWorld` program, `class`, `static`, and `void` are examples of keywords.

The compiler uses the keywords to identify the structure and organization of the code. Because the compiler interprets these words with elevated significance, C# requires that developers place keywords only in certain locations. When programmers violate these rules, the compiler will issue errors.

C# Keywords

Table 1.1 shows the C# keywords.

Table 1.1: C# Keywords

abstract	enum	long	static
add* (1)	equals* (3)	nameof* (6)	string
alias* (2)	event	namespace	struct
as	explicit	new	switch
ascending* (3)	extern	null	this
async* (5)	false	object	throw
await* (5)	finally	on* (3)	true
base	fixed	operator	try
bool	float	orderby* (3)	typeof
break	for	out	uint
by* (3)	foreach	override	ulong
byte	from* (3)	params	unchecked
case	get* (1)	partial* (2)	unsafe
catch	global* (2)	private	ushort
char	goto	protected	using
checked	group* (3)	public	value* (1)
class	if	readonly	var* (3)
const	implicit	ref	virtual
continue	in	remove* (1)	void
decimal	int	return	volatile
default	interface	sbyte	where* (2)
delegate	internal	sealed	when* (6)
descending* (3)	into* (3)	select* (3)	while
do	is	set* (1)	yield* (2)
double	join* (3)	short	
dynamic* (4)	let* (3)	sizeof	
else	lock	stackalloc	

* Contextual keyword

Numbers in parentheses (n) identify in which version the contextual keyword was added.

Begin 2.0

After C# 1.0, no new **reserved keywords** were introduced to C#. However, some constructs in later versions use **contextual keywords,** which are significant only in specific locations. Outside these designated locations, contextual keywords have no special significance.[5] By this method, most C# 1.0 code is compatible with the later standards.[6]

End 2.0

Identifiers

Like other languages, C# includes **identifiers** to identify constructs that the programmer codes. In Listing 1.1, `HelloWorld` and `Main` are examples of identifiers. The identifiers assigned to a construct are used to refer back to the construct later, so it is important that the names the developer assigns are meaningful rather than arbitrary.

A keen ability to select succinct and indicative names is an important characteristic of a strong programmer because it means the resultant code will be easier to understand and reuse. Clarity coupled with consistency is important enough that the .NET Framework Guidelines (http://bit.ly/dotnetguidelines) advise against the use of abbreviations or contractions in identifier names and even recommend avoiding acronyms that are not widely accepted. If an acronym is sufficiently well established (HTML, for example), you should use it consistently: Avoid spelling out the accepted acronym sometimes but not others. Generally, adding the constraint that all acronyms be included in a glossary of terms places enough overhead on the use of acronyms such that they are not used flippantly. Ultimately, select clear, possibly even verbose names—especially when working on a team or when developing a library against which others will program.

There are two basic casing formats for an identifier. **Pascal case** (henceforth PascalCase), as the CLI creators refer to it because of its popularity in

---

5. For example, early in the design of C# 2.0, the language designers designated `yield` as a keyword, and Microsoft released alpha versions of the C# 2.0 compiler, with `yield` as a designated keyword, to thousands of developers. However, the language designers eventually determined that by using `yield return` rather than `yield`, they could ultimately avoid adding `yield` as a keyword because it would have no special significance outside its proximity to `return`.
6. There are some rare and unfortunate incompatibilities, such as the following:
   - C# 2.0 requiring implementation of `IDisposable` with the `using` statement, rather than simply a `Dispose()` method
   - Some rare generic expressions such as `F(G<A,B>(7))` means `F( (G<A), (B>7) )` in C# 1.0 will, in C# 2.0, instead mean to call generic method `G<A,B>` with argument `7` and pass the result to `F`

the Pascal programming language, capitalizes the first letter of each word in an identifier name; examples include `ComponentModel`, `Configuration`, and `HttpFileCollection`. As `HttpFileCollection` demonstrates with HTTP, when using acronyms that are more than two letters long only the first letter is capitalized. The second format, camel case (henceforth camelCase), follows the same convention, except that the first letter is lowercase; examples include `quotient`, `firstName`, `httpFileCollection`, `ioStream`, and `theDreadPirateRoberts`.

Guidelines

DO favor clarity over brevity when naming identifiers.

DO NOT use abbreviations or contractions within identifier names.

DO NOT use any acronyms unless they are widely accepted, and even then, only when necessary.

Notice that although underscores are legal, generally there are no underscores, hyphens, or other nonalphanumeric characters in identifier names. Furthermore, C# doesn't follow its predecessors in that Hungarian notation (prefixing a name with a data type abbreviation) is not used. This avoids the variable rename that is necessary when data types change or the inconsistency introduced due to failure to adjust the data type prefix when using Hungarian notation.

In some rare cases, some identifiers, such as `Main`, can have a special meaning in the C# language.

Guidelines

DO capitalize both characters in two-character acronyms, except for the first word of a camelCased identifier.

DO capitalize only the first character in acronyms with three or more characters, except for the first word of a camelCased identifier.

DO NOT capitalize any of the characters in acronyms at the beginning of a camelCased identifier.

DO NOT use Hungarian notation (that is, do not encode the type of a variable in its name).

ADVANCED TOPIC

Keywords

Although it is rare, keywords may be used as identifiers if they include "@" as a prefix. For example, you could name a local variable `@return`. Similarly (although it doesn't conform to the casing standards of C# coding standards), it is possible to name a method `@throw()`.

There are also four undocumented reserved keywords in the Microsoft implementation: `__arglist`, `__makeref`, `__reftype`, and `__refvalue`. These are required only in rare interop scenarios and you can ignore them for all practical purposes. Note that these four special keywords begin with two underscores. The designers of C# reserve the right to make any identifier that begins with two underscores into a keyword in a future version; for safety, avoid ever creating such an identifier yourself.

Type Definition

All executable code in C# appears within a type definition, and the most common type definition begins with the keyword `class`. A **class definition** is the section of code that generally begins with `class identifier { ... }`, as shown in Listing 1.2.

LISTING 1.2: Basic Class Declaration

```
class HelloWorld
{
  //...
}
```

The name used for the type (in this case, `HelloWorld`) can vary, but by convention, it must be PascalCased. For this particular example, therefore, other possible names are `Greetings`, `HelloInigoMontoya`, `Hello`, or simply `Program`. (`Program` is a good convention to follow when the class contains the `Main()` method, described next.)

Guidelines

DO name classes with nouns or noun phrases.

DO use PascalCasing for all class names.

Generally, programs contain multiple types, each containing multiple methods.

Main

BEGINNER TOPIC

What Is a Method?

Syntactically, a **method** in C# is a named block of code introduced by a method declaration (for example, `static void Main()`) and (usually) followed by zero or more statements within curly braces. Methods perform computations and/or actions. Similar to paragraphs in written languages, methods provide a means of structuring and organizing code so that it is more readable. More importantly, methods can be reused and called from multiple places, and so avoid the need to duplicate code. The method declaration introduces the method and defines the method name along with the data passed to and from the method. In Listing 1.3, `Main()` followed by `{ ... }` is an example of a C# method.

The location where C# programs begin execution is the **Main method,** which begins with `static void Main()`. When you execute the program by typing `HelloWorld.exe` at the command console, the program starts up, resolves the location of `Main`, and begins executing the first statement within Listing 1.3.

LISTING 1.3: Breaking Apart `HelloWorld`

```
class HelloWorld
{
  static void Main()        } Method Declaration                    Main      Class
  {                                                                           Definition
    System.Console.WriteLine("Hello, My name is Inigo Montoya");
  }                               Statement
}
```

Although the Main method declaration can vary to some degree, `static` and the method name, `Main`, are always required for a program.

ADVANCED TOPIC

Declaration of the Main Method

C# requires that the Main method return either `void` or `int`, and that it take either no parameters or a single array of strings. Listing 1.4 shows the full declaration of the Main method.

LISTING 1.4: The Main Method, with Parameters and a Return

```
static int Main(string[] args)
{
    //...
}
```

The `args` parameter is an array of strings corresponding to the command-line arguments. However, the first element of the array is not the program name but the first command-line parameter to appear after the executable name, unlike in C and C++. To retrieve the full command used to execute the program use `System.Environment.CommandLine`.

The `int` returned from `Main` is the status code and it indicates the success of the program's execution. A return of a nonzero value generally indicates an error.

Language Contrast: C++/Java—main() Is All Lowercase

Unlike its C-style predecessors, C# uses an uppercase *M* for the Main method to be consistent with the PascalCased naming conventions of C#.

The designation of the `Main` method as `static` indicates that other methods may call it directly off the class definition. Without the `static` designation, the command console that started the program would need to perform additional work (known as **instantiation**) before calling the method. (Chapter 5 contains an entire section devoted to the topic of static members.)

Placing `void` prior to `Main()` indicates that this method does not return any data. (This is explained further in Chapter 2.)

One distinctive C/C++ style characteristic followed by C# is the use of curly braces for the body of a construct, such as the class or the method. For example, the `Main` method contains curly braces that surround its implementation; in this case, only one statement appears in the method.

Statements and Statement Delimiters

The `Main` method includes a single statement, `System.Console.WriteLine()`, which is used to write a line of text to the console. C# generally uses a semicolon to indicate the end of a **statement,** where a statement comprises one or more actions that the code will perform. Declaring a variable, controlling the program flow, and calling a method are typical uses of statements.

Language Contrast: Visual Basic—Line-Based Statements

Some languages are line based, meaning that without a special annotation, statements cannot span a line. Until Visual Basic 2010, Visual Basic was an example of a line-based language. It required an underscore at the end of a line to indicate that a statement spans multiple lines. Starting with Visual Basic 2010, many cases were introduced where the line continuation character was optional.

ADVANCED TOPIC

Statements without Semicolons

Many programming elements in C# end with a semicolon. One example that does not include the semicolon is a `switch` statement. Because curly braces are always included in a `switch` statement, C# does not require a semicolon following the statement. In fact, code blocks themselves are considered statements (they are also composed of statements) and they don't require closure using a semicolon. Similarly, there are cases, such as the `using` declarative, in which a semicolon occurs at the end but it is not a statement.

Since creation of a new line does not separate statements, you can place multiple statements on the same line and the C# compiler will interpret the line as having multiple instructions. For example, Listing 1.5 contains two statements on a single line that, in combination, display `Up` and `Down` on two separate lines.

Listing 1.5: Multiple Statements on One Line

```
System.Console.WriteLine("Up");System.Console.WriteLine("Down");
```

C# also allows the splitting of a statement across multiple lines. Again, the C# compiler looks for a semicolon to indicate the end of a statement (see Listing 1.6).

Listing 1.6: Splitting a Single Statement across Multiple Lines

```
System.Console.WriteLine(
  "Hello. My name is Inigo Montoya.");
```

In Listing 1.6, the original `WriteLine()` statement from the `HelloWorld` program is split across multiple lines.

BEGINNER TOPIC

What Is Whitespace?

Whitespace is the combination of one or more consecutive formatting characters such as tab, space, and newline characters. Eliminating all whitespace between words is obviously significant, as is including whitespace within a quoted string.

Whitespace

The semicolon makes it possible for the C# compiler to ignore whitespace in code. Apart from a few exceptions, C# allows developers to insert whitespace throughout the code without altering its semantic meaning. In Listing 1.5 and Listing 1.6, it didn't matter whether a newline was inserted within a statement or between statements, and doing so had no effect on the resultant executable created by the compiler.

Frequently, programmers use whitespace to indent code for greater readability. Consider the two variations on `HelloWorld` shown in Listing 1.7 and Listing 1.8.

Listing 1.7: No Indentation Formatting

```
class HelloWorld
{
static void Main()
{
System.Console.WriteLine("Hello Inigo Montoya");
}
}
```

Listing 1.8: Removing Whitespace

```
class HelloWorld{static void Main()
{System.Console.WriteLine("Hello Inigo Montoya");}}
```

Although these two examples look significantly different from the original program, the C# compiler sees them as identical.

BEGINNER TOPIC

Formatting Code with Whitespace

Indenting the code using whitespace is important for greater readability. As you begin writing code, you need to follow established coding standards and conventions to enhance code readability.

The convention used in this book is to place curly braces on their own line and to indent the code contained between the curly brace pair. If another curly brace pair appears within the first pair, all the code within the second set of braces is also indented.

This is not a uniform C# standard, but a stylistic preference.

Working with Variables

Now that you've been introduced to the most basic C# program, it's time to declare a local variable. Once a variable is declared, you can assign it a value, replace that value with a new value, and use it in calculations, output, and so on. However, you cannot change the data type of the variable. In Listing 1.9, `string max` is a variable declaration.

LISTING 1.9: Declaring and Assigning a Variable

```
class miracleMax
{
  static void Main()
  {
            data type
            string max;
                  variable
      max = "Have fun storming the castle!";

      System.Console.WriteLine(max);
  }
}
```

BEGINNER TOPIC

Local Variables

A **variable** is a name that refers to a value that can change over time. *Local* indicates that the programmer **declared** the variable within a method.

To declare a variable is to define it, which you do by

1. Specifying the type of data which the variable will contain
2. Assigning it an identifier (name)

Data Types

Listing 1.9 declares a variable with the data type `string`. Other common data types used in this chapter are `int` and `char`.

- `int` is the C# designation of an integer type that is 32 bits in size.
- `char` is used for a character type. It is 16 bits, large enough for (nonsurrogate) Unicode characters.

The next chapter looks at these and other common data types in more detail.

BEGINNER TOPIC

What Is a Data Type?

The type of data that a variable declaration specifies is called a **data type** (or object type). A data type, or simply **type,** is a classification of things that share similar characteristics and behavior. For example, *animal* is a type. It classifies all things (monkeys, warthogs, and platypuses) that have animal characteristics (multicellular, capacity for locomotion, and so on). Similarly, in programming languages, a type is a definition for several items endowed with similar qualities.

Declaring a Variable

In Listing 1.9, `string max` is a variable declaration of a string type whose name is `max`. It is possible to declare multiple variables within the same statement by specifying the data type once and separating each identifier with a comma. Listing 1.10 demonstrates such a declaration.

LISTING 1.10: Declaring Two Variables within One Statement

```
string message1, message2;
```

Because a multivariable declaration statement allows developers to provide the data type only once within a declaration, all variables will be of the same type.

In C#, the name of the variable may begin with any letter or an underscore (_), followed by any number of letters, numbers, and/or underscores. By convention, however, local variable names are camelCased (the first letter in each word is capitalized, except for the first word) and do not include underscores.

Guidelines

DO use camelCasing for local variable names.

Assigning a Variable

After declaring a local variable, you must assign it a value before reading from it. One way to do this is to use the = **operator,** also known as the **simple assignment operator.** Operators are symbols used to identify the function the code is to perform. Listing 1.11 demonstrates how to use the assignment operator to designate the string values to which the variables `miracleMax` and `valerie` will point.

Listing 1.11: Changing the Value of a Variable

```
class StormingTheCastle
{
  static void Main()
  {
      string valerie;
      string miracleMax = "Have fun storming the castle!";

      valerie = "Think it will work?";

      System.Console.WriteLine(miracleMax);
      System.Console.WriteLine(valerie);

      max = "It would take a miracle.";
      System.Console.WriteLine(miracleMax);
  }
}
```

From this listing, observe that it is possible to assign a variable as part of the variable declaration (as it was for `miracleMax`), or afterward in a separate statement (as with the variable `valerie`). The value assigned must always be on the right side.

Running the compiled `StormingTheCastle.exe` program produces the code shown in Output 1.3.

Output 1.3

```
>StormingTheCastle.exe
Have fun storming the castle!
Think it will work?
It would take a miracle.
```

C# requires that local variables be determined by the compiler to be "definitely assigned" before they are read. Additionally, an assignment returns a value. Therefore, C# allows two assignments within the same statement, as demonstrated in Listing 1.12.

LISTING 1.12: Assignment Returning a Value That Can Be Assigned Again

```
class StormingTheCastle
{
  static void Main()
  {
    // ...
    string requirements, miracleMax;
    requirements = miracleMax = "It would take a miracle.";
    // ...
  }
}
```

Using a Variable

The result of the assignment, of course, is that you can then refer to the value using the variable identifier. Therefore, when you use the variable `miracleMax` within the `System.Console.WriteLine(miracleMax)` statement, the program displays `Have fun storming the castle!`, the value of `miracleMax`, on the console. Changing the value of `miracleMax` and executing the same `System.Console.WriteLine(miracleMax)` statement causes the new `miracleMax` value, "`It would take a miracle.`" to be displayed.

ADVANCED TOPIC

Strings Are Immutable

All data of type `string`, whether string literals or otherwise, is immutable (or unmodifiable). For example, it is not possible to change the string "`Come As You Are`" to "`Come As You Age`." A change such as this requires that you reassign the variable to refer to a new location in memory, instead of modifying the data to which the variable originally referred.

Console Input and Output

This chapter already used `System.Console.WriteLine` repeatedly for writing out text to the command console. In addition to being able to write out data, a program needs to be able to accept data that a user may enter.

Getting Input from the Console

One way to retrieve text that is entered at the console is to use `System.Console.ReadLine()`. This method stops the program execution so that the user can enter characters. When the user presses the Enter key, creating a newline, the program continues. The output, also known as the **return,** from the `System.Console.ReadLine()` method is the string of text that was entered. Consider Listing 1.13 and the corresponding output shown in Output 1.4.

Listing 1.13: Using `System.Console.ReadLine()`

```
class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      System.Console.WriteLine("Hey you!");

      System.Console.Write("Enter your first name: ");
      firstName = System.Console.ReadLine();

      System.Console.Write("Enter your last name: ");
      lastName = System.Console.ReadLine();
  }
}
```

Output 1.4

```
>HeyYou.exe
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
```

After each prompt, this program uses the `System.Console.ReadLine()` method to retrieve the text the user entered and assign it to an appropriate variable. By the time the second `System.Console.ReadLine()` assignment completes, `firstName` refers to the value `Inigo` and `lastName` refers to the value `Montoya`.

ADVANCED TOPIC

System.Console.Read()

In addition to the `System.Console.ReadLine()` method, there is a `System.Console.Read()` method. However, the data type returned by the `System.Console.Read()` method is an integer corresponding to the character value read, or `-1` if no more characters are available. To retrieve the actual character, it is necessary to first cast the integer to a character, as shown in Listing 1.14.

LISTING 1.14: Using System.Console.Read()

```
int readValue;
char character;
readValue = System.Console.Read();
character = (char) readValue;
System.Console.Write(character);
```

The `System.Console.Read()` method does not return the input until the user presses the Enter key; no processing of characters will begin, even if the user types multiple characters before pressing the Enter key.

Begin 2.0

In C# 2.0 and above, you can use `System.Console.ReadKey()`, which, in contrast to `System.Console.Read()`, returns the input after a single keystroke. It allows the developer to intercept the keystroke and perform actions such as key validation, restricting the characters to numerics.

End 2.0

Writing Output to the Console

In Listing 1.13, you prompt the user for his first and last names using the method `System.Console.Write()` rather than `System.Console.WriteLine()`. Instead of placing a newline character after displaying the text, the `System.Console.Write()` method leaves the current position on the same line. In this way, any text the user enters will be on the same line as the prompt for input. The output from Listing 1.13 demonstrates the effect of `System.Console.Write()`.

Begin 6.0

The next step is to write the values retrieved using `System.Console.ReadLine()` back to the console. In the case of Listing 1.15, the program writes out the user's full name. However, instead of using `System.Console.WriteLine()` as before, this code will use a slight variation. Output 1.5 shows the corresponding output.

Listing 1.15: Formatting Using String Interpolation

```
class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      System.Console.WriteLine("Hey you!");

      System.Console.Write("Enter your first name: ");
      firstName = System.Console.ReadLine();

      System.Console.Write("Enter your last name: ");
      lastName = System.Console.ReadLine();

      System.Console.WriteLine(
        $"Your full name is { firstName } { lastName }.");
  }
}
```

Output 1.5

```
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
Your full name is Inigo Montoya.
```

Instead of writing out "`Your full name is`" followed by another `Write` statement for `firstName`, a third `Write` statement for the space, and finally a `WriteLine` statement for `lastName`, Listing 1.15 writes out the entire output using C# 6.0's string interpolation. With string interpolation, the compiler interprets the interior of the curly brackets within the string as regions in which you can embed code (expressions) that the compiler will evaluate and convert to strings. Rather than executing lots of code snippets individually and combining the results as a string at the end, string interpolation allows you to do this in a single step. This makes the code easier to understand.

End 6.0

Prior to C# 6.0, C# used a different approach, that of **composite formatting.** With composite formatting, the code first supplies a **format string** to define the output format—see Listing 1.16.

LISTING 1.16: Formatting Using `System.Console.WriteLine()`'s Composite Formatting

```
class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      System.Console.WriteLine("Hey you!");

      System.Console.Write("Enter your first name: ");
      firstName = System.Console.ReadLine();

      System.Console.Write("Enter your last name: ");
      lastName = System.Console.ReadLine();

      System.Console.WriteLine(
        "Your full name is {0} {1}.", firstName, lastName);
  }
}
```

In this example, the format string is `"Your full name is {0} {1}."`. It identifies two indexed placeholders for data insertion in the string. Each placeholder corresponds the order of the arguments that appears after the format string.

Note that the index value begins at zero. Each inserted argument (known as a **format item**) appears after the format string in the order corresponding to the index value. In this example, since `firstName` is the first argument to follow immediately after the format string, it corresponds to index value `0`. Similarly, `lastName` corresponds to index value `1`.

Note that the placeholders within the format string need not appear in order. For example, Listing 1.17 switches the order of the indexed placeholders and adds a comma, which changes the way the name is displayed (see Output 1.6).

LISTING 1.17: Swapping the Indexed Placeholders and Corresponding Variables

```
System.Console.WriteLine("Your full name is {1}, {0}",
  firstName, lastName);
```

OUTPUT 1.6

```
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
Your full name is Montoya, Inigo
```

In addition to not having the placeholders appear consecutively within the format string, it is possible to use the same placeholder multiple times within a format string. Furthermore, it is possible to omit a placeholder. It is not possible, however, to have placeholders that do not have a corresponding argument.

Since C# 6.0-style string interpolation is almost always easier to understand than the alternative composite string approach, throughout the remainder of the book we will use string interpolation by default.

Comments

In this section, we modify the program in Listing 1.15 by adding comments. In no way does this change the execution of the program; rather, providing comments within the code can simply make the code more understandable in areas where it isn't inherently. Listing 1.18 shows the new code, and Output 1.7 shows the corresponding output.

LISTING 1.18: Commenting Your Code

```
class CommentSamples
{
  static void Main()
  {
                                   single-line comment
      string firstName; // Variable for storing the first name
      string lastName;  // Variable for storing the last name

      System.Console.WriteLine("Hey you!");

                        delimited comment inside statement
      System.Console.Write /* No new line */ (
          "Enter your first name: ");
      firstName = System.Console.ReadLine();

      System.Console.Write /* No new line */ (
          "Enter your last name: ");
      lastName = System.Console.ReadLine();

      /* Display a greeting to the console
         using composite formatting. */          delimited comment
```

```
        System.Console.WriteLine("Your full name is {0} {1}.",
            firstName, lastName);
        // This is the end
        // of the program listing
    }
  }
```

OUTPUT 1.7

```
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
Your full name is Inigo Montoya.
```

In spite of the inserted comments, compiling and executing the new program produces the same output as before.

Programmers use comments to describe and explain the code they are writing, especially where the syntax itself is difficult to understand, or perhaps a particular algorithm implementation is surprising. Since comments are pertinent only to the programmer reviewing the code, the compiler ignores comments and generates an assembly that is devoid of any trace that comments were part of the original source code.

Table 1.2 shows four different C# comment types. The program in Listing 1.18 includes two of these.

A more comprehensive discussion of the XML comments appears in Chapter 9, where we further discuss the various XML tags.

There was a period in programming history when a prolific set of comments implied a disciplined and experienced programmer. This is no longer the case. Instead, code that is readable without comments is more valuable than that which requires comments to clarify what it does. If developers find it necessary to enter comments to clarify what a particular code block is doing, they should favor rewriting the code more clearly over commenting it. Writing comments that simply repeat what the code clearly shows serves only to clutter the code, decrease its readability, and increase the likelihood of the comments going out of date because the code changes without the comments getting updated.

Begin 2.0

TABLE 1.2: C# Comment Types

Comment Type	Description	Example
Delimited comments	A forward slash followed by an asterisk, `/*`, identifies the beginning of a delimited comment. To end the comment use an asterisk followed by a forward slash: `*/`. Comments of this form may span multiple lines in the code file or appear embedded within a line of code. The asterisks that appear at the beginning of the lines but within the delimiters are simply for formatting.	`/*comment*/`
Single-line comments	Comments may be declared with a delimiter comprising two consecutive forward slash characters: `//`. The compiler treats all text from the delimiter to the end of the line as a comment. Comments of this form are considered a single line. It is possible, however, to place sequential single-line comments one after another, as is the case with the last comment in Listing 1.18.	`//comment`
XML delimited comments	Comments that begin with `/**` and end with `**/` are called XML delimited comments. They have the same characteristics as regular delimited comments, except that instead of ignoring XML comments entirely, the compiler can place them into a separate text file.†	`/**comment**/`
XML single-line comments	XML single-line comments begin with `///` and continue to the end of the line. In addition, the compiler can save single-line comments into a separate file with the XML delimited comments.	`///comment`

End 2.0

† XML delimited comments were explicitly added only in C# 2.0, but the syntax is compatible with C# 1.0.

Guidelines

DO NOT use comments unless they describe something that is not obvious to someone other than the developer who wrote the code.

DO favor writing clearer code over entering comments to clarify a complicated algorithm.

BEGINNER TOPIC

Extensible Markup Language

The Extensible Markup Language (XML) is a simple and flexible text format frequently used within Web applications and for exchanging data between applications. XML is extensible because included within an XML document is information that describes the data, known as **metadata.** Here is a sample XML file.

```
<?xml version="1.0" encoding="utf-8" ?>
<body>
  <book title="Essential C# 6.0">
      <chapters>
          <chapter title="Introducing C#"/>
          <chapter title="Operators and Control Flow"/>
          ...
      </chapters>
  </book>
</body>
```

The file starts with a header indicating the version and character encoding of the XML file. After that appears one main "book" element. Elements begin with a word in angle brackets, such as `<body>`. To end an element, place the same word in angle brackets and add a forward slash to prefix the word, as in `</body>`. In addition to elements, XML supports attributes. `title="Essential C# 6.0"` is an example of an XML attribute. Note that the metadata (book title, chapter, and so on) describing the data ("Essential C# 6.0", "Operators and Control Flow") is included in the XML file. This can result in rather bloated files, but it offers the advantage that the data includes a description to aid in interpreting it.

Application Programming Interface

All the methods (or more generically, the members) found on a data type like `System.Console` are what define the `System.Console`'s **application programming interface (API)**. The API defines how a software program interacts with a component. As such, it is found not just with a single data type, but more generically the combination of all the APIs for a set of data types are said to create an API for the collective set of components. In .NET, for example, all the types (and the members within those types) in an assembly are said to form the assembly's API. Likewise, given a combination of assemblies, like those found in the .NET Framework, the collective group of assemblies form a larger API. Often, this larger group of APIs are referred to as the **framework**—hence the term .NET Framework in reference to the APIs exposed by all the assemblies included with .NET. Generically, the API comprises the set of interfaces and protocols (or instructions) for programming against a set of components. In fact, with .NET, the protocols themselves are the rules for how .NET assemblies execute.

Managed Execution and the Common Language Infrastructure

The processor cannot directly interpret an assembly. Assemblies consist mainly of a second language known as **Common Intermediate Language (CIL),** or **IL** for short.[7] The C# compiler transforms the C# source file into this intermediate language. An additional step, usually performed at execution time, is required to change the CIL code into **machine code** that the processor can understand. This involves an important element in the execution of a C# program: the **Virtual Execution System (VES).** The VES, also casually referred to as the **runtime,** compiles CIL code as needed (a process known as **just-in-time** compilation or **jitting**). The code that executes under the context of an agent such as the runtime is termed **managed code,** and the process of executing under control of the runtime is called **managed execution.** The code is "managed" because the runtime controls significant portions of the program's behavior by managing aspects such as memory allocation, security, and just-in-time compilation. Code that does not require the runtime to execute is called **native code** (or **unmanaged code**).

The specification for a VES is included in a broader specification known as the **Common Language Infrastructure (CLI)** specification.[8] An international standard, the CLI includes specifications for the following:

---

7. A third term for CIL is Microsoft IL (MSIL). This book uses the term *CIL* because it is the term adopted by the CLI standard. IL is prevalent in conversation among people writing C# code because they assume that IL refers to CIL rather than other types of intermediate languages.
8. Miller, J., and S. Ragsdale. 2004. *The Common Language Infrastructure Annotated Standard.* Boston: Addison-Wesley.

- The VES or runtime
- The CIL
- A type system that supports language interoperability, known as the **Common Type System** (**CTS**)
- Guidance on how to write libraries that are accessible from CLI-compatible languages (available in the **Common Language Specification** [**CLS**])
- Metadata that enables many of the services identified by the CLI (including specifications for the layout or file format of assemblies)
- A common programming framework, the Base Class Library (BCL), which developers in all languages can utilize

NOTE

The term *runtime* can refer to either execution time or the Virtual Execution System. To help clarify the intended meaning, this book uses the term *execution time* to indicate when the program is executing, and it uses the term *runtime* when discussing the agent responsible for managing the execution of a C# program while it executes.

Running within the context of a CLI implementation enables support for a number of services and features that programmers do not need to code for directly, including the following:

- *Language interoperability:* interoperability between different source languages. This is possible because the language compilers translate each source language to the same intermediate language (CIL).
- *Type safety:* checks for conversion between types, ensuring that only conversions between compatible types will occur. This helps prevent the occurrence of buffer overruns, a leading cause of security vulnerabilities.
- *Code access security:* certification that the assembly developer's code has permission to execute on the computer.

- *Garbage collection:* memory management that automatically de-allocates memory previously allocated by the runtime.
- *Platform portability:* support for potentially running the same assembly on a variety of operating systems. One obvious restriction is that no platform-dependent libraries are used; therefore, as with Java, there are potentially some platform-dependent idiosyncrasies that need to be worked out.
- *BCL:* provides a large foundation of code that developers can depend on (in all CLI implementations) so that they do not have to develop the code themselves.

NOTE

This section gives a brief synopsis of the CLI to familiarize you with the context in which a C# program executes. It also provides a summary of some of the terms that appear throughout this book. Chapter 21 is devoted to the topic of the CLI and its relevance to C# developers. Although the chapter appears last in the book, it does not depend on any earlier chapters, so if you want to become more familiar with the CLI, you can jump to it at any time.

Begin 3.0

C# and .NET Versioning

Microsoft assigns inconsistent version numbers to the .NET Framework and the corresponding version of the C# language, simply because different teams had different versioning mechanisms. This means that if you compile with the C# 5.0 compiler, it will, by default compile against the ".NET Framework version 4.6," for example. Table 1.3 is a brief overview of the C# and .NET releases.

Most of the code within this text will work with platforms other than Microsoft's, as long as the compiler version corresponds to the version of code required. Although providing full details on each C# platform would be helpful for some readers, it can also detract from the focus of learning C#, so the main body of this text is restricted to information on Microsoft's platform, .NET. This choice was made simply because Microsoft has the predominant (by far) implementation. Furthermore, translation to another platform is fairly trivial.

Table 1.3: C# and .NET Versions

Comment Type	Description
C# 1.0 with .NET Framework 1.0/1.1 (Visual Studio 2002 and 2003)	The initial release of C#. A language built from the ground up to support .NET programming.
C# 2.0 with .NET Framework 2.0 (Visual Studio 2005)	Added generics to the C# language and libraries that supported generics to the .NET Framework 2.0.
.NET Framework 3.0	An additional set of APIs for distributed communications (Windows Communication Foundation [WCF]), rich client presentation (Windows Presentation Foundation [WPF]), workflow (Windows Workflow [WF]), and Web authentication (Cardspaces).
C# 3.0 with .NET Framework 3.5 (Visual Studio 2008)	Added support for LINQ, a significant improvement to the APIs used for programming collections. The .NET Framework 3.5 provided libraries that extended existing APIs to make LINQ possible.
C# 4.0 with .NET Framework 4 (Visual Studio 2010)	Added support for dynamic typing along with significant improvements in the API for writing multithreaded programs that capitalized on multiple processors and cores within those processors.
C# 5.0 with .NET Framework 4.5 (Visual Studio 2012) and WinRT integration	Added support for asynchronous method invocation without the explicit registration of a delegate callback. An additional change in the framework was support for interoperability with the Windows Runtime (WinRT).
C# 6.0 with .NET Framework 4.6 (Visual Studio 2015)	Added string interpolation, null propagating member access, exception filters, dictionary initializers, and numerous other features.

End 3.0

Perhaps the most important framework feature added alongside C# 6.0 was support for cross platform compilation. In other words, not only would the .NET Framework run on Windows, but Microsoft also provided an implementation (called "CoreFX") for .NET Core that would run on Linux and OS X. Although the .NET Core is not an equivalent feature set to the full .NET Framework, it includes enough functionality that entire (ASP. NET) websites can be hosted on operating systems other than Windows and its Internet Information Server (IIS). This means that with the same code base it is possible to compile and execute applications that run on cross platforms. .NET Core includes everything from the .NET Compiler Platform ("Roslyn"), which itself executes on Linux and OS X, to the .NET Core runtime, along with tools like the .NET Version Manager (DNVM) and the .NET Execution Environment (DNX).

Common Intermediate Language and `ILDASM`

As mentioned in the preceding section, the C# compiler converts C# code to CIL code and not to machine code. The processor can directly understand machine code, but CIL code needs to be converted before the processor can execute it. Given an assembly (either a DLL or an executable), it is possible to view the CIL code using a CIL disassembler utility to deconstruct the assembly into its CIL representation. (The CIL disassembler is commonly referred to by its Microsoft-specific filename, `ILDASM`, which stands for IL Disassembler.) This program will disassemble a program or its class libraries, displaying the CIL generated by the C# compiler.

The exact command used for the CIL disassembler depends on which implementation of the CLI is used. You can execute the .NET CIL disassembler from the command line as shown in Output 1.8.

Output 1.8

```
>ildasm /text HelloWorld.exe
```

The `/text` portion is used so that the output appears on the command console rather than in a new window. The stream of output that results from executing these commands is a dump of CIL code included in the `HelloWorld.exe` program. Note that CIL code is significantly easier to understand than machine code. For many developers, this may raise a concern because it is easier for programs to be decompiled and algorithms understood without explicitly redistributing the source code.

As with any program, CLI based or not, the only foolproof way of preventing disassembly is to disallow access to the compiled program altogether (for example, only hosting a program on a website instead of distributing it out to a user's machine). However, if decreased accessibility to the source code is all that is required, there are several obfuscators available. These obfuscators open up the IL code and transform it so that it does the same thing but in a way that is much more difficult to understand. This prevents the casual developer from accessing the code and creates assemblies that are much more difficult and tedious to decompile into comprehensible code. Unless a program requires a high degree of algorithm security, these obfuscators are generally sufficient.

ADVANCED TOPIC

CIL Output for `HelloWorld.exe`

Listing 1.19 shows the CIL code created by `ILDASM`.

LISTING 1.19: Sample CIL Output

```
//  Microsoft (R) .NET Framework IL Disassembler.  Version 4.6.81.0
//  Copyright (c) Microsoft Corporation.  All rights reserved.



// Metadata version: v4.0.30319
.assembly extern mscorlib
{
  .publickeytoken = (B7 7A 5C 56 19 34 E0 89 )                         //
.z\V.4..
  .ver 4:0:0:0
}
.assembly HelloWorld
{
  .custom instance void [mscorlib]System.Runtime.CompilerServices.
CompilationRelaxationsAttribute::.ctor(int32) = ( 01 00 08 00 00 00 00 00 )
  .custom instance void [mscorlib]System.Runtime.CompilerServices.
RuntimeCompatibilityAttribute::.ctor() = ( 01 00 01 00 54 02 16 57 72 61 70
4E 6F 6E 45 78   // ....T..WrapNonEx

63 65 70 74 69 6F 6E 54 68 72 6F 77 73 01 )       // ceptionThrows.

  // --- The following custom attribute is added automatically, do not
uncomment -------
  //  .custom instance void [mscorlib]System.Diagnostics.
DebuggableAttribute::.ctor(valuetype [mscorlib]System.Diagnostics.
DebuggableAttribute/DebuggingModes) = ( 01 00 07 01 00 00 00 00 )

  .hash algorithm 0x00008004
  .ver 0:0:0:0
}
.module HelloWorld.exe
// MVID: {1FB5153C-639E-401D-8C94-22A66C18DC7A}
```

```
.imagebase 0x00400000
.file alignment 0x00000200
.stackreserve 0x00100000
.subsystem 0x0003       // WINDOWS_CUI
.corflags 0x00000001    //  ILONLY
// Image base: 0x01190000


// =============== CLASS MEMBERS DECLARATION ===================

.class public auto ansi beforefieldinit AddisonWesley.Michaelis.
EssentialCSharp.Chapter01.Listing01_01.HelloWorld
       extends [mscorlib]System.Object
{
  .method public hidebysig static void  Main() cil managed
  {
    .entrypoint
    // Code size       13 (0xd)
    .maxstack  8
    IL_0000:  nop
    IL_0001:  ldstr      "Hello. My name is Inigo Montoya."
    IL_0006:  call       void [mscorlib]System.Console::WriteLine(string)
    IL_000b:  nop
    IL_000c:  ret
  } // end of method HelloWorld::Main

  .method public hidebysig specialname rtspecialname
          instance void  .ctor() cil managed
  {
    // Code size       8 (0x8)
    .maxstack  8
    IL_0000:  ldarg.0
    IL_0001:  call       instance void [mscorlib]System.Object::.ctor()
    IL_0006:  nop
    IL_0007:  ret
  } // end of method HelloWorld::.ctor

} // end of class AddisonWesley.Michaelis.EssentialCSharp.Chapter01.
Listing01_01.HelloWorld


// =============================================================

// *********** DISASSEMBLY COMPLETE ***********************
```

The beginning of the listing is the manifest information. It includes not only the full name of the disassembled module (`HelloWorld.exe`), but also all the modules and assemblies it depends on, along with their version information.

Perhaps the most interesting thing that you can glean from such a listing is how relatively easy it is to follow what the program is doing compared to trying to read and understand machine code (assembler). In the listing, an explicit reference to `System.Console.WriteLine()` appears. There is a lot of peripheral information to the CIL code listing, but if a developer wanted to understand the inner workings of a C# module (or any CLI-based program) without having access to the original source code, it would be relatively easy unless an obfuscator is used. In fact, several free tools are available (such as Red Gate's Reflector, ILSpy, JustDecompile, dotPeek, and CodeReflect) that can decompile from CIL to C# automatically.

SUMMARY

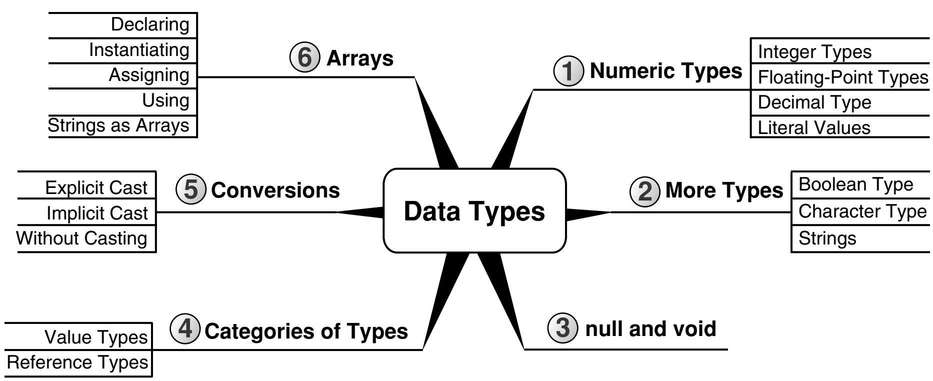
This chapter served as a rudimentary introduction to C#. It provided a means of familiarizing you with basic C# syntax. Because of C#'s similarity to C++-style languages, much of this might not have been new material to you. However, C# and managed code do have some distinct characteristics, such as compilation down to CIL. Although it is not unique, another key characteristic of C# is its full support for object-oriented programming. Even tasks such as reading and writing data to the console are object oriented. Object orientation is foundational to C#, as you will see throughout this book.

The next chapter examines the fundamental data types that are part of the C# language, and discusses how you can use these data types with operands to form expressions.

2

Data Types

FROM CHAPTER 1'S `HelloWorld` program, you got a feel for the C# language, its structure, basic syntax characteristics, and how to write the simplest of programs. This chapter continues to discuss the C# basics by investigating the fundamental C# types.



Until now, you have worked with only a few built-in data types, with little explanation. In C# thousands of types exist, and you can combine types to create new types. A few types in C#, however, are relatively simple and are considered the building blocks of all other types. These types are the **predefined types**. The C# language's predefined types include eight integer types, two binary floating-point types for scientific calculations and one decimal float for financial calculations, one Boolean type, and a character type. This chapter investigates these types, looks more closely at the `string` type, and introduces arrays.

Fundamental Numeric Types

The basic numeric types in C# have keywords associated with them. These types include integer types, floating-point types, and a special floating-point type called `decimal` to store large numbers with no representation error.

Integer Types

There are eight C# integer types. This variety allows you to select a data type large enough to hold its intended range of values without wasting resources. Table 2.1 lists each integer type.

TABLE 2.1: Integer Types

Type	Size	Range (Inclusive)	BCL Name	Signed	Literal Suffix
`sbyte`	8 bits	–128 to 127	`System.SByte`	Yes	
`byte`	8 bits	0 to 255	`System.Byte`	No	
`short`	16 bits	–32,768 to 32,767	`System.Int16`	Yes	
`ushort`	16 bits	0 to 65,535	`System.UInt16`	No	
`int`	32 bits	–2,147,483,648 to 2,147,483,647	`System.Int32`	Yes	
`uint`	32 bits	0 to 4,294,967,295	`System.UInt32`	No	U or u
`long`	64 bits	–9,223,372,036,854,775,808 to 9,223,372,036,854,775,807	`System.Int64`	Yes	L or l
`ulong`	64 bits	0 to 18,446,744,073,709,551,615	`System.UInt64`	No	UL or ul

Included in Table 2.1 (and in Tables 2.2 and 2.3) is a column for the full name of each type; we discuss the literal suffix later in the chapter. All the fundamental types in C# have both a short name and a full name. The full name corresponds to the type as it is named in the Base Class Library (BCL). This name, which is the same across all languages, uniquely identifies the type within an assembly. Because of the fundamental nature of these types, C# also supplies keywords as short names or abbreviations to the full names of fundamental types. From the compiler's perspective, both names refer to the same type, producing exactly the same code. In fact, an examination of the resultant CIL code would provide no indication of which name was used.

Although C# supports using both the full BCL name and the keyword, as developers we are left with the choice of which to use when. Rather than switching back and forth, it is better to use one or the other consistently. For this reason, C# developers generally go with using the C# keyword form—choosing, for example, `int` rather than `System.Int32` and `string` rather than `System.String` (or a possible shortcut of `String`).

Guidelines

DO use the C# keyword rather than the BCL name when specifying a data type (for example, `string` rather than `String`).

DO favor consistency rather than variety within your code.

The choice for consistency frequently may be at odds with other guidelines. For example, given the guideline to use the C# keyword in place of the BCL name, there may be occasions when you find yourself maintaining a file (or library of files) with the opposite style. In these cases it would better to stay consistent with the previous style than to inject a new style and inconsistencies in the conventions. Even so, if the "style" was actually a bad coding practice that was likely to introduce bugs and obstruct successful maintenance, by all means correct the issue throughout.

Language Contrast: C++—short Data Type

In C/C++, the `short` data type is an abbreviation for `short int`. In C#, `short` on its own is the actual data type.

Floating-Point Types (float, double)

Floating-point numbers have varying degrees of precision, and binary floating-point types can represent numbers exactly only if they are a fraction with a power of 2 as the denominator. If you were to set the value of a floating-point variable to be 0.1, it could very easily be represented as

0.0999999999999999 or 0.1000000000000000001 or some other number very close to 0.1. Similarly, setting a variable to a large number such as Avogadro's number, 6.02×10^{23}, could lead to a representation error of approximately 10^8, which after all is a tiny fraction of that number. The accuracy of a floating-point number is in proportion to the magnitude of the number it represents. A floating-point number is precise to a certain number of significant digits, not by a fixed value such as ±0.01.

C# supports the two binary floating-point number types listed in Table 2.2.

TABLE 2.2: Floating-Point Types

Type	Size	Range (Inclusive)	BCL Name	Significant Digits	Literal Suffix
`float`	32 bits	$\pm 1.5 \times 10^{-45}$ to $\pm 3.4 \times 10^{38}$	`System.Single`	7	F or f
`double`	64 bits	$\pm 5.0 \times 10^{-324}$ to $\pm 1.7 \times 10^{308}$	`System.Double`	15–16	ㄎ

Binary numbers appear as base 10 (denary) numbers for human readability. The number of bits (binary digits) converts to 15 decimal digits, with a remainder that contributes to a sixteenth decimal digit as expressed in Table 2.2. Specifically, numbers between 1.7×10^{307} and less than 1×10^{308} have only 15 significant digits. However, numbers ranging from 1×10^{308} to 1.7×10^{308} will have 16 significant digits. A similar range of significant digits occurs with the `decimal` type as well.

Decimal Type

C# also provides a decimal floating-point type with 128-bit precision (see Table 2.3). This type is suitable for financial calculations.

TABLE 2.3: `decimal` Type

Type	Size	Range (Inclusive)	BCL Name	Significant Digits	Literal Suffix
`decimal`	128 bits	1.0×10^{-28} to approximately 7.9×10^{28}	`System.Decimal`	28–29	M or m

Unlike binary floating-point numbers, the `decimal` type maintains exact accuracy for all denary numbers within its range. With the `decimal` type, therefore, a value of 0.1 is exactly 0.1. However, while the `decimal` type has greater precision than the floating-point types, it has a smaller range. Thus, conversions from floating-point types to the `decimal` type may result in overflow errors. Also, calculations with `decimal` are slightly (generally imperceptibly) slower.

ADVANCED TOPIC

Floating-Point Types Dissected

Denary numbers within the range and precision limits of the `decimal` type are represented exactly. In contrast, the binary floating-point representation of many denary numbers introduces a rounding error. Just as ⅓ cannot be represented exactly in any finite number of decimal digits, so $^{11}/_{10}$ cannot be represented exactly in any finite number of binary digits. In both cases, we end up with a rounding error of some kind.

A `decimal` is represented by `±N * 10`^{k} where the following is true:

- `N`, the mantissa, is a positive 96-bit integer.
- `k`, the exponent, is given by `-28 <= k <= 0`.

In contrast, a binary float is any number `±N * 2`^{k} where the following is true:

- `N` is a positive 24-bit (for `float`) or 53-bit (for `double`) integer.
- `k` is an integer ranging from `-149` to `+104` for `float` and from `-1074` to `+970` for `double`.

Literal Values

A **literal value** is a representation of a constant value within source code. For example, if you want to have `System.Console.WriteLine()` print out the integer value `42` and the `double` value `1.618034`, you could use the code shown in Listing 2.1.

Listing 2.1: Specifying Literal Values

```
System.Console.WriteLine(42);
System.Console.WriteLine(1.618034);
```

Output 2.1 shows the results of Listing 2.1.

Output 2.1

```
42
1.618034
```

BEGINNER TOPIC

Use Caution When Hardcoding Values

The practice of placing a value directly into source code is called **hardcoding,** because changing the values requires recompiling the code. Developers must carefully consider the choice between hardcoding values within their code and retrieving them from an external source, such as a configuration file, so that the values are modifiable without recompiling.

By default, when you specify a literal number with a decimal point, the compiler interprets it as a `double` type. Conversely, a literal value with no decimal point generally defaults to an `int`, assuming the value is not too large to be stored in an integer. If the value is too large, the compiler will interpret it as a `long`. Furthermore, the C# compiler allows assignment to a numeric type other than an `int`, assuming the literal value is appropriate for the target data type. `short s = 42` and `byte b = 77` are allowed, for example. However, this is appropriate only for constant values; `b = s` is not allowed without additional syntax, as discussed in the section Conversions between Data Types later in this chapter.

As previously discussed in the section Fundamental Numeric Types, there are many different numeric types in C#. In Listing 2.2, a literal value is placed within C# code. Since numbers with a decimal point will default to the `double` data type, the output, shown in Output 2.2, is `1.61803398874989` (the last digit, 5, is missing), corresponding to the expected accuracy of a `double`.

Listing 2.2: Specifying a Literal double

```
System.Console.WriteLine(1.618033988749895);
```

Output 2.2

```
1.61803398874989
```

To view the intended number with its full accuracy, you must declare explicitly the literal value as a `decimal` type by appending an `M` (or `m`) (see Listing 2.3 and Output 2.3).

Listing 2.3: Specifying a Literal decimal

```
System.Console.WriteLine(1.618033988749895M);
```

Output 2.3

```
1.618033988749895
```

Now the output of Listing 2.3 is as expected: `1.618033988749895`. Note that `d` is for `double`. To remember that `m` should be used to identify a `decimal`, remember that "m is for monetary calculations."

You can also add a suffix to a value to explicitly declare a literal as `float` or `double` by using the `F` and `D` suffixes, respectively. For integer data types, the suffixes are `U`, `L`, `LU`, and `UL`. The type of an integer literal can be determined as follows:

- Numeric literals with no suffix resolve to the first data type that can store the value in this order: `int`, `uint`, `long`, and `ulong`.
- Numeric literals with the suffix `U` resolve to the first data type that can store the value in the order `uint` and then `ulong`.
- Numeric literals with the suffix `L` resolve to the first data type that can store the value in the order `long` and then `ulong`.
- If the numeric literal has the suffix `UL` or `LU`, it is of type `ulong`.

Note that suffixes for literals are case insensitive. However, uppercase is generally preferred to avoid any ambiguity between the lowercase letter *l* and the digit 1.

In some situations, you may wish to use exponential notation instead of writing out several zeroes before or after the decimal point. To use exponential notation, supply the `e` or `E` infix, follow the infix character with a positive or negative integer number, and complete the literal with the appropriate data type suffix. For example, you could print out Avogadro's number as a `float`, as shown in Listing 2.4 and Output 2.4.

Listing 2.4: Exponential Notation

```
System.Console.WriteLine(6.023E23F);
```

Output 2.4

```
6.023E+23
```

Guidelines

DO use uppercase literal suffixes (for example, 1.618033988749895M).

BEGINNER TOPIC

Hexadecimal Notation

Usually you work with numbers that are represented with a base of 10, meaning there are 10 symbols (0–9) for each digit in the number. If a number is displayed with hexadecimal notation, it is displayed with a base of 16 numbers, meaning 16 symbols are used: 0–9, A–F (lowercase can also be used). Therefore, 0x000A corresponds to the decimal value 10 and 0x002A corresponds to the decimal value 42, being 2 × 16 + 10. The actual number is the same. Switching from hexadecimal to decimal, or vice versa, does not change the number itself, just the representation of the number.

Each hex digit is four bits, so a byte can represent two hex digits.

In all discussions of literal numeric values so far, we have covered only base 10 type values. C# also supports the ability to specify hexadecimal values. To specify a hexadecimal value, prefix the value with `0x` and then use any hexadecimal digit, as shown in Listing 2.5.

Listing 2.5: Hexadecimal Literal Value

```
// Display the value 42 using a hexadecimal literal.
System.Console.WriteLine(0x002A);
```

Output 2.5 shows the results of Listing 2.5.

Output 2.5

```
42
```

Note that this code still displays `42`, not `0x002A`.

ADVANCED TOPIC

Formatting Numbers As Hexadecimal

To display a numeric value in its hexadecimal format, it is necessary to use the `x` or `X` numeric formatting specifier. The casing determines whether the hexadecimal letters appear in lowercase or uppercase. Listing 2.6 shows an example of how to do this.

Listing 2.6: Example of a Hexadecimal Format Specifier

```
// Displays "0x2A"
System.Console.WriteLine($"0x{42:X}");
```

Output 2.6 shows the results.

Output 2.6

```
0x2A
```

Note that the numeric literal (`42`) can be in decimal or hexadecimal form. The result will be the same. Also, to achieve the hexadecimal formatting, we rely on the formatting specifier—separated from the string interpolation expression with a colon.

ADVANCED TOPIC

Round-Trip Formatting

By default, `System.Console.WriteLine(1.618033988749895);` displays `1.61803398874989`, with the last digit missing. To more accurately identify the string representation of the double value it is possible to convert it using a format string and the round-trip format specifier, `R` (or `r`). `string.Format("{0:R}", 1.618033988749895)`, for example, will return the result `1.6180339887498949`.

The round-trip format specifier returns a string that, if converted back into a numeric value, will always result in the original value. Listing 2.7 shows the numbers are not equal without use of the round-trip format.

LISTING 2.7: Formatting Using the R Format Specifier

```
// ...
const double number = 1.618033988749895;
double result;
string text;

text = $"{number}";
result = double.Parse(text);
System.Console.WriteLine($"{result == number}: result == number");

text = string.Format("{0:R}", number);
result = double.Parse(text);
System.Console.WriteLine($"{result == number}: result == number");

// ...
```

Output 2.7 shows the resultant output.

OUTPUT 2.7

```
False: result == number
True: result == number
```

When assigning `text` the first time, there is no round-trip format specifier; as a result, the value returned by `double.Parse(text)` is not the same as the original `number` value. In contrast, when the round-trip format specifier is used, `double.Parse(text)` returns the original value.

For those readers who are unfamiliar with the == syntax from C-based languages, `result == number` returns `true` if `result` is equal to `number`, while `result != number` does the opposite. Both assignment and equality operators are discussed in the next chapter.

More Fundamental Types

The fundamental types discussed so far are numeric types. C# includes some additional types as well: `bool`, `char`, and `string`.

Boolean Type (bool)

Another C# primitive is a Boolean or conditional type, `bool`, which represents true or false in conditional statements and expressions. Allowable values are the keywords `true` and `false`. The BCL name for `bool` is `System.Boolean`. For example, in order to compare two strings in a case-insensitive manner, you call the `string.Compare()` method and pass a `bool` literal `true` (see Listing 2.8).

LISTING 2.8: A Case-Insensitive Comparison of Two Strings

```
string option;
...
int comparison = string.Compare(option, "/Help", true);
```

In this case, you make a case-insensitive comparison of the contents of the variable option with the literal text /Help and assign the result to comparison.

Although theoretically a single bit could hold the value of a Boolean, the size of `bool` is 1 byte.

Character Type (char)

A `char` type represents 16-bit characters whose set of possible values are drawn from the Unicode character set's UTF-16 encoding. A `char` is the same size as a 16-bit unsigned integer (`ushort`), which represents values between 0 and 65,535. However, `char` is a unique type in C# and code should treat it as such.

The BCL name for `char` is `System.Char`.

BEGINNER TOPIC

The Unicode Standard

Unicode is an international standard for representing characters found in the majority of human languages. It provides computer systems with functionality for building **localized** applications, applications that display the appropriate language and culture characteristics for different cultures.

ADVANCED TOPIC

16 Bits Is Too Small for All Unicode Characters

Unfortunately, not all Unicode characters can be represented by just one 16-bit `char`. The original Unicode designers believed that 16 bits would be enough, but as more languages were supported, it was realized that this assumption was incorrect. As a result, some (rarely used) Unicode characters are composed of "surrogate pairs" of two `char` values.

To construct a literal `char`, place the character within single quotes, as in `'A'`. Allowable characters comprise the full range of keyboard characters, including letters, numbers, and special symbols.

Some characters cannot be placed directly into the source code and instead require special handling. These characters are prefixed with a backslash (\) followed by a special character code. In combination, the backslash and special character code constitute an **escape sequence.** For example, `\n` represents a newline, and `\t` represents a tab. Since a backslash indicates the beginning of an escape sequence, it can no longer identify a simple backslash; instead, you need to use `\\` to represent a single backslash character.

Listing 2.9 writes out one single quote because the character represented by `\'` corresponds to a single quote.

LISTING 2.9: Displaying a Single Quote Using an Escape Sequence

```
class SingleQuote
{
  static void Main()
  {
      System.Console.WriteLine('\'');
  }
}
```

In addition to showing the escape sequences, Table 2.4 includes the Unicode representation of characters.

TABLE 2.4: Escape Characters

Escape Sequence	Character Name	Unicode Encoding
`\'`	Single quote	`\u0027`
`\"`	Double quote	`\u0022`
`\\`	Backslash	`\u005C`
`\0`	Null	`\u0000`
`\a`	Alert (system beep)	`\u0007`
`\b`	Backspace	`\u0008`
`\f`	Form feed	`\u000C`
`\n`	Line feed (sometimes referred to as a newline)	`\u000A`
`\r`	Carriage return	`\u000D`
`\t`	Horizontal tab	`\u0009`
`\v`	Vertical tab	`\u000B`
`\uxxxx`	Unicode character in hex	`\u0029`
`\x[n][n][n]n`	Unicode character in hex (first three placeholders are options); variable-length version of `\uxxxx`	`\u3A`
`\Uxxxxxxxx`	Unicode escape sequence for creating surrogate pairs	`\uD840DC01` (𠀁)

You can represent any character using Unicode encoding. To do so, prefix the Unicode value with `\u`. You represent Unicode characters in hexadecimal notation. The letter *A*, for example, is the hexadecimal value `0x41`. Listing 2.10 uses Unicode characters to display a smiley face (`:)`), and Output 2.8 shows the results.

LISTING 2.10: Using Unicode Encoding to Display a Smiley Face

```
System.Console.Write('\u003A');
System.Console.WriteLine('\u0029');
```

OUTPUT 2.8

```
:)
```

Strings

A finite sequence of zero or more characters is called a **string.** The string type in C# is `string`, whose BCL name is `System.String`. The string type includes some special characteristics that may be unexpected to developers familiar with other programming languages. In addition to the string literal format discussed in Chapter 1, strings include a "verbatim string" prefix character of `@`, string interpolation with the $ prefix character, and the fact that strings are immutable.

Literals

You can enter a literal string into code by placing the text in double quotes ("), as you saw in the `HelloWorld` program. Strings are composed of characters, and because of this, character escape sequences can be embedded within a string.

In Listing 2.11, for example, two lines of text are displayed. However, instead of using `System.Console.WriteLine()`, the code listing shows `System.Console.Write()` with the newline character, `\n`. Output 2.9 shows the results.

LISTING 2.11: Using the \n Character to Insert a Newline

```
class DuelOfWits
{
  static void Main()
  {
      System.Console.Write(
          "\"Truly, you have a dizzying intellect.\"");
      System.Console.Write("\n\"Wait 'til I get going!\"\n");
  }
}
```

OUTPUT 2.9

```
"Truly, you have a dizzying intellect."
"Wait 'til I get going!"
```

The escape sequence for double quotes differentiates the printed double quotes from the double quotes that define the beginning and end of the string.

In C#, you can use the @ symbol in front of a string to signify that a backslash should not be interpreted as the beginning of an escape sequence. The resultant **verbatim string literal** does not reinterpret just the backslash character. Whitespace is also taken verbatim when using the @ string syntax. The triangle in Listing 2.12, for example, appears in the console exactly as typed, including the backslashes, newlines, and indentation. Output 2.10 shows the results.

LISTING 2.12: Displaying a Triangle Using a Verbatim String Literal

```
class Triangle
{
  static void Main()
  {
      System.Console.Write(@"begin
             /\
            /  \
           /    \
          /      \
         /________\
end");
  }
}
```

OUTPUT 2.10

```
begin
             /\
            /  \
           /    \
          /      \
         /________\
end
```

Without the @ character, this code would not even compile. In fact, even if you changed the shape to a square, eliminating the backslashes, the code still would not compile because a newline cannot be placed directly within a string that is not prefaced with the @ symbol.

The only escape sequence the verbatim string does support is `""`, which signifies double quotes and does not terminate the string.

Language Contrast: C++—String Concatenation at Compile Time

Unlike C++, C# does not automatically concatenate literal strings. You cannot, for example, specify a string literal as follows:

```
"Major Strasser has been shot."
"Round up the usual suspects."
```

Rather, concatenation requires the use of the addition operator. (If the compiler can calculate the result at compile time, however, the resultant CIL code will be a single string.)

If the same literal string appears within an assembly multiple times, the compiler will define the string only once within the assembly and all variables will refer to the same string. That way, if the same string literal containing thousands of characters was placed multiple times into the code, the resultant assembly would reflect the size of only one of them.

Begin 6.0

String Interpolation

As discussed in Chapter 1, strings can support embedded expressions when using the string interpolation format. The string interpolation syntax prefixes a string literal with a dollar symbol and then embeds the expressions within curly brackets. The following is an example:

```
System.Console.WriteLine($"Your full name is {firstName} {lastName}.");
```

where `firstName` and `lastName` are simple expressions that refer to variables.

Note that string literals can be combined with string interpolation by specifying the "`$`" prior to the "`@`" symbol, as in this example:

```
System.Console.WriteLine($@"Your full name is:
    { firstName } { lastName }");
```

Since this is a string literal, the text output on two lines. You can, however, make a similar line break in the code without incurring a line break in the output by placing the line feeds inside the curly braces as follows:

```
System.Console.WriteLine($@"Your full name is: {
    firstName } { lastName }");
```

ADVANCED TOPIC

Understanding the Internals of String Interpolation

String interpolation is a shorthand for invoking the `string.Format()` method. For example, a statement such as

```
System.Console.WriteLine($"Your full name is {firstName} {lastName}.")
```

will be transformed to the C# equivalent of

```
object[] args = new object[] { firstName, lastName };
Console.WriteLine(string.Format("Your full name is {0} {1}.", args));
```

This leaves in place support for localization in the same way it works with composite string and doesn't introduce any post-compile injection of code via strings.

End 6.0

String Methods

The string type, like the `System.Console` type, includes several methods. There are methods, for example, for formatting, concatenating, and comparing strings.

The `Format()` method in Table 2.5 behaves exactly like the `Console.Write()` and `Console.WriteLine()` methods, except that instead of displaying the result in the console window, `string.Format()` returns the result to the caller. Of course, with string interpolation the need for `string.Format()` is significantly reduced (except for localization support). Under the covers, however, string interpolation compiles down to CIL that leverages `string.Format()`.

All of the methods in Table 2.5 are **static.** This means that, to call the method, it is necessary to prefix the method name (for example, `Concat`) with the type that contains the method (for example, `string`). As illustrated below, however, some of the methods in the string class are **instance** methods. Instead of prefixing the method with the type, instance methods use the variable name (or some other reference to an instance). Table 2.6 shows a few of these methods, along with an example.

Table 2.5: string Static Methods

<table>
<tr><th>Statement</th><th>Example</th></tr>
<tr><td><pre>static string string.Format(
    string format,
    ...)</pre></td><td><pre>string text, firstName, lastName;
//...
text = string.Format("Your full name is {0} {1}.",
  firstName, lastName);
// Display
// "Your full name is <firstName> <lastName>."
System.Console.WriteLine(text);</pre></td></tr>
<tr><td><pre>static string string.Concat(
    string str0,
    string str1)</pre></td><td><pre>string text, firstName, lastName;
//...
text = string.Concat(firstName, lastName);
// Display "<firstName><lastName>", notice
// that there is no space between names.
System.Console.WriteLine(text);</pre></td></tr>
<tr><td rowspan="2"><pre>static int string.Compare(
    string strA,
    string strB)
static int string.Compare(
    string strA,
    string strB)
    string ignoreCase)</pre></td><td><pre>string option;
//...
// String comparison in which case matters.
int result = string.Compare(option, "/help");

// Display:
//   0 if equal
//   negative if option < /help
//   positive if option > /help
System.Console.WriteLine(result);</pre></td></tr>
<tr><td><pre>string option;
//...
// Case-insensitive string comparison
int result = string.Compare(
     option, "/Help", true);

// Display:
//   0 if equal
//   < 0 if option < /help
//   > 0 if option > /help
System.Console.WriteLine(result);</pre></td></tr>
</table>

Table 2.6: string Methods

<table>
<tr><th>Statement</th><th>Example</th></tr>
<tr><td><pre>bool StartsWith(
    string value)
bool EndsWith(
    string value)</pre></td><td><pre>string lastName
//...
bool isPhd = lastName.EndsWith("Ph.D.");
bool isDr = lastName.StartsWith("Dr.");</pre></td></tr>
</table>

TABLE 2.6: `string` Methods (*continued*)

Statement	Example

`string ToLower()`
`string ToUpper()`
	`string severity = "warning";`
	`// Display the severity in uppercase`
	`System.Console.WriteLine(severity.ToUpper());`

`string Trim()`
`string Trim(...)`
`string TrimEnd()`
`string TrimStart()`
	`// Remove any whitespace at the start or end.`
	`username = username.Trim();`

`string Replace(`
`    string oldValue,`
`    string newValue)`
	`string filename;`
	`//...`
	`// Remove ?'s from the string`
	`filename = filename.Replace("?", "");;`

Begin 6.0

ADVANCED TOPIC

The using and using static Directives

The invocation of static methods as we have used them so far always involves a prefix of the namespace followed by the type name. When calling `System.Console.WriteLine` for example, even though the method invoked is `WriteLine()` and there is no other method with that name within the context, it is still necessary to prefix the method name with the namespace (`System`) followed by the type name (`Console`). On occasion, you may want a shortcut to avoid such explicitness; to do so, you can leverage the C# 6.0 `using static` directive as shown in Listing 2.13.

LISTING 2.13: The `using static` Directive

```
// The using directives allow you to drop the namespace
using static System.Console;
class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      WriteLine("Hey you!");

      Write("Enter your first name: ");
      firstName = ReadLine();

      Write("Enter your last name: ");
      lastName = ReadLine();
```

```
        WriteLine(
          $"Your full name is {firstName} {lastName}.");
    }
  }
```

The using static directive needs to appear at the top of the file.[1] Each time we use the System.Console class, it is no longer necessary to also use the "System.Console" prefix. Instead, we can simply write the method name. An important point to note about the using static directive is that it works only for static methods and properties, not for instance members.

A similar directive, the using directive, allows for eliminating the namespace prefix—for example, "System." Unlike the using static directive, the using directive applies universally within the file (or namespace) in which it resides (not just to static members). With the using directive, you can (optionally) eliminate all references to the namespace, whether during instantiation, during static method invocation, or even with the nameof operator found in C# 6.0.

End 6.0

String Formatting

Whether you use string.Format() or the C# 6.0 string interpolation feature to construct complex formatting strings, a rich and complex set of formatting patterns is available to display numbers, dates, times, timespans, and so on. For example, if price is a variable of type decimal, then string.Format("{0,20:C2}", price) or the equivalent interpolation $"{price,20:C2}" both convert the decimal value to a string using the default currency formatting rules, rounded to two figures after the decimal place, and right-justified in a 20-character-wide string. Space does not permit a detailed discussion of all the possible formatting strings; consult the MSDN documentation for string.Format() for a complete listing of formatting strings.

If you want an actual left or right curly brace inside an interpolated string or formatted string, you can double the brace to indicate that it is not introducing a pattern. For example, the interpolated string $"{{ {price:C2} }}" might produce the string "{ $1,234.56 }".

1. Or at the top of a namespace declaration.

New Line

When writing out a new line, the exact characters for the new line will depend on the operating system on which you are executing. On Microsoft Windows platforms, the newline is the combination of both the carriage return (`\r`) and line feed (`\n`) characters, while a single line feed is used on UNIX. One way to overcome the discrepancy between platforms is simply to use `System.Console.WriteLine()` to output a blank line. Another approach, which is almost essential for a new line on multiple platforms when you are not outputting to the console, is to use `System.Environment.NewLine`. In other words, `System.Console.WriteLine("Hello  World")` and `System.Console.Write($"Hello World{System.Environment.NewLine}")` are equivalent.

ADVANCED TOPIC

C# Properties

The `Length` member referred to in the following section is not actually a method, as indicated by the fact that there are no parentheses following its call. `Length` is a property of `string`, and C# syntax allows access to a property as though it were a member variable (known in C# as a **field**). In other words, a property has the behavior of special methods called setters and getters, but the syntax for accessing that behavior is that of a field.

Examining the underlying CIL implementation of a property reveals that it compiles into two methods: `set_<PropertyName>` and `get_<PropertyName>`. Neither of these, however, is directly accessible from C# code, except through the C# property constructs. See Chapter 5 for more details on properties.

String Length

To determine the length of a string, you use a string member called `Length`. This particular member is called a **read-only property.** As such, it cannot be set, nor does calling it require any parameters. Listing 2.14 demonstrates how to use the `Length` property, and Output 2.11 shows the results.

LISTING 2.14: Using `string`'s `Length` Member

```
class PalindromeLength
{
  static void Main()
```

```
    {
        string palindrome;

        System.Console.Write("Enter a palindrome: ");
        palindrome = System.Console.ReadLine();

        System.Console.WriteLine(
            $"The palindrome \"{palindrome}\" is"
            + $" {palindrome.Length} characters.");
    }
}
```

Output 2.11

```
Enter a palindrome: Never odd or even
The palindrome "Never odd or even" is 17 characters.
```

The length for a string cannot be set directly; it is calculated from the number of characters in the string. Furthermore, the length of a string cannot change because a string is **immutable.**

Strings Are Immutable

A key characteristic of the `string` type is that it is immutable. A string variable can be assigned an entirely new value but there is no facility for modifying the contents of a `string`. It is not possible, therefore, to convert a `string` to all uppercase letters. It is trivial to create a new string that is composed of an uppercase version of the old string, but the old string is not modified in the process. Consider Listing 2.15 as an example.

Listing 2.15: Error; `string` Is Immutable

```
class Uppercase
{
  static void Main()
  {
      string text;

      System.Console.Write("Enter text: ");
      text = System.Console.ReadLine();

      // UNEXPECTED:  Does not convert text to uppercase
      text.ToUpper();

      System.Console.WriteLine(text);
  }
}
```

Output 2.12 shows the results of Listing 2.15.

OUTPUT 2.12

```
Enter text: This is a test of the emergency broadcast system.
This is a test of the emergency broadcast system.
```

At a glance, it would appear that `text.ToUpper()` should convert the characters within `text` to uppercase. However, strings are immutable and, therefore, `text.ToUpper()` will make no such modification. Instead, `text.ToUpper()` returns a new string that needs to be saved into a variable or passed to `System.Console.WriteLine()` directly. The corrected code is shown in Listing 2.16, and its output is shown in Output 2.13.

LISTING 2.16: Working with Strings

```
class Uppercase
{
  static void Main()
  {
      string text, uppercase;

      System.Console.Write("Enter text: ");
      text = System.Console.ReadLine();

      // Return a new string in uppercase
      uppercase = text.ToUpper();

      System.Console.WriteLine(uppercase);
  }
}
```

OUTPUT 2.13

```
Enter text: This is a test of the emergency broadcast system.
THIS IS A TEST OF THE EMERGENCY BROADCAST SYSTEM.
```

If the immutability of a string is ignored, mistakes similar to those shown in Listing 2.15 can occur with other string methods as well.

To actually change the value of `text`, assign the value from `ToUpper()` back into `text`, as in the following code:

```
text = text.ToUpper();
```

System.Text.StringBuilder

If considerable string modification is needed, such as when constructing a long string in multiple steps, you should use the data type `System.Text.StringBuilder` rather than `string`. The `StringBuilder` type includes methods such as `Append()`, `AppendFormat()`, `Insert()`, `Remove()`, and `Replace()`, some of which are also available with `string`. The key difference, however, is that with `StringBuilder` these methods will modify the data in the `StringBuilder` itself, and will not simply return a new string.

null and void

Two additional keywords relating to types are `null` and `void`. The `null` value identified with the `null` keyword, indicates that the variable does not refer to any valid object. `void` is used to indicate the absence of a type or the absence of any value altogether.

null

`null` can also be used as a type of string "literal." `null` indicates that a variable is set to nothing. Reference types, pointer types, and nullable value types can be assigned the value `null`. The only reference type covered so far in this book is `string`; Chapter 5 covers the topic of creating classes (which are reference types) in detail. For now, suffice it to say that a variable of reference type contains a reference to a location in memory that is different from the value of the variable. Code that sets a variable to `null` explicitly assigns the reference to refer to no valid value. In fact, it is even possible to check whether a reference refers to nothing. Listing 2.17 demonstrates assigning `null` to a `string` variable.

Listing 2.17: Assigning null to a String

```
static void Main()
{
    string faxNumber;
    // ...

    // Clear the value of faxNumber.
    faxNumber = null;

    // ...
}
```

Assigning the value `null` to a reference type is not equivalent to not assigning it at all. In other words, a variable that has been assigned `null` has still been set, whereas a variable with no assignment has not been set and, therefore, will often cause a compile error if used prior to assignment.

Assigning the value `null` to a `string` variable is distinctly different from assigning an empty string, `""`. Use of `null` indicates that the variable has no value, whereas `""` indicates that there is a value—an empty string. This type of distinction can be quite useful. For example, the programming logic could interpret a `faxNumber` of `null` to mean that the fax number is unknown, while a `faxNumber` value of `""` could indicate that there is no fax number.

The void "Type"

Sometimes the C# syntax requires a data type to be specified but no data is actually passed. For example, if no return from a method is needed, C# allows you to specify `void` as the data type instead. The declaration of `Main` within the `HelloWorld` program is an example. The use of `void` as the return type indicates that the method is not returning any data and tells the compiler not to expect a value. `void` is not a data type per se, but rather an indication that there is no data being returned.

Language Contrast: C++

In both C++ and C#, `void` has two meanings: as a marker that a method does not return any data, and to represent a pointer to a storage location of unknown type. In C++ programs it is quite common to see pointer types like `void**`. C# can also represent pointers to storage locations of unknown type using the same syntax, but this usage is comparatively rare in C# and typically encountered only when writing programs that interoperate with unmanaged code libraries.

Language Contrast: Visual Basic—Returning void Is Like Defining a Subroutine

The Visual Basic equivalent of returning a `void` in C# is to define a subroutine (`Sub/End Sub`) rather than a function that returns a value.

Begin 3.0

ADVANCED TOPIC

Implicitly Typed Local Variables

C# 3.0 added a contextual keyword, `var`, for declaring an **implicitly typed local variable.** As long as the code initializes a variable at declaration time with an expression of unambiguous type, C# 3.0 and later allow for the variable data type to be implied rather than stated, as shown in Listing 2.18.

LISTING 2.18: Working with Strings

```
class Uppercase
{
  static void Main()
  {
      System.Console.Write("Enter text: ");
      var text = System.Console.ReadLine();

      // Return a new string in uppercase
      var uppercase = text.ToUpper();

      System.Console.WriteLine(uppercase);
  }
}
```

This listing is different from Listing 2.16 in two ways. First, rather than using the explicit data type `string` for the declaration, Listing 2.18 uses `var`. The resultant CIL code is identical to using `string` explicitly. However, `var` indicates to the compiler that it should determine the data type from the value (`System.Console.ReadLine()`) that is assigned within the declaration.

Second, the variables `text` and `uppercase` are initialized by their declarations. To not do so would result in an error at compile time. As mentioned earlier, the compiler determines the data type of the initializing expression and declares the variable accordingly, just as it would if the programmer had specified the type explicitly.

Although using `var` rather than the explicit data type is allowed, consider avoiding such use when the data type is known—for example, use `string` for the declaration of `text` and `uppercase`. Not only does this make the code more understandable, but it also verifies that the data type returned by the right-hand side expression is the type expected. When using a `var` declared variable, the right-hand side data type should be obvious; if it isn't, consider avoiding the use of the `var` declaration.

Support for var was added to the language in C# 3.0 to permit use of anonymous types. Anonymous types are data types that are declared "on the fly" within a method, rather than through explicit class definitions, as shown in Listing 2.19. (See Chapter 14 for more details on anonymous types.)

Listing 2.19: Implicit Local Variables with Anonymous Types

```
class Program
{
  static void Main()
  {
      var patent1 =
          new { Title = "Bifocals",
          YearOfPublication = "1784" };
      var patent2 =
          new { Title = "Phonograph",
          YearOfPublication = "1877" };

      System.Console.WriteLine(
          $"{ patent1.Title } ({ patent1.YearOfPublication })");
      System.Console.WriteLine(
          $"{ patent2.Title } ({ patent2.YearOfPublication })");
  }
}
```

The corresponding output is shown in Output 2.14.

Output 2.14

```
Bifocals (1784)
Phonograph (1877)
```

Listing 2.19 demonstrates the anonymous type assignment to an implicitly typed (var) local variable. This type of operation provides critical functionality in tandem with C# 3.0 support for joining (associating) data types or reducing the size of a particular type down to fewer data elements.

End 3.0

Categories of Types

All types fall into one of two categories: **value types** and **reference types.** The differences between the types in each category stem from how they are copied: Value type data is always copied by value, while reference type data is always copied by reference.

Value Types

With the exception of `string`, all the predefined types in the book so far have been value types. Variables of value types contain the value directly. In other words, the variable refers to the same location in memory where the value is stored. Because of this, when a different variable is assigned the same value, a copy of the original variable's value is made to the location of the new variable. A second variable of the same value type cannot refer to the same location in memory as the first variable. Consequently, changing the value of the first variable will not affect the value in the second. Figure 2.1 demonstrates this. In the figure, `number1` refers to a particular location in memory that contains the value `42`. After assigning `number1` to `number2`, both variables will contain the value `42`. However, modifying either variable's value will not affect the other.

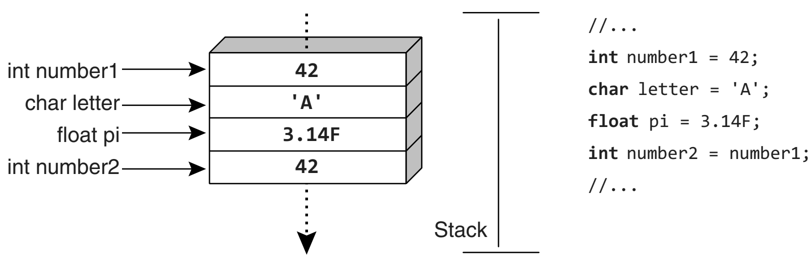


FIGURE 2.1: Value Types Contain the Data Directly

Similarly, passing a value type to a method such as `Console.WriteLine()` will also result in a memory copy, and any changes to the parameter inside the method will not affect the original value within the calling function. Since value types require a memory copy, they generally should be defined to consume a small amount of memory; value types should almost always be less than 16 bytes in size.

Reference Types

By contrast, the value of a reference type is a reference to a storage location that contains data. Reference types store the reference where the data is located instead of storing the data directly, as value types do. Therefore, to access the data, the runtime will read the memory location out of the variable and then "jump" to the location in memory that contains the data.

The memory area of the data a reference type points to is called the **heap** (see Figure 2.2).

A reference type does not require the same memory copy of the data that a value type does, which makes copying reference types far more efficient than copying large value types. When assigning the value of one reference type variable to another reference type variable, only the reference is copied, not the data referred to. In practice, a reference is always the same size as the "native size" of the processor: A 32-bit processor will copy a 32-bit reference and a 64-bit processor will copy a 64-bit reference, and so on. Obviously, copying the small reference to a large block of data is faster than copying the entire block, as a value type would.

Since reference types copy a reference to data, two different variables can refer to the same data. If two variables refer to the same object, changing

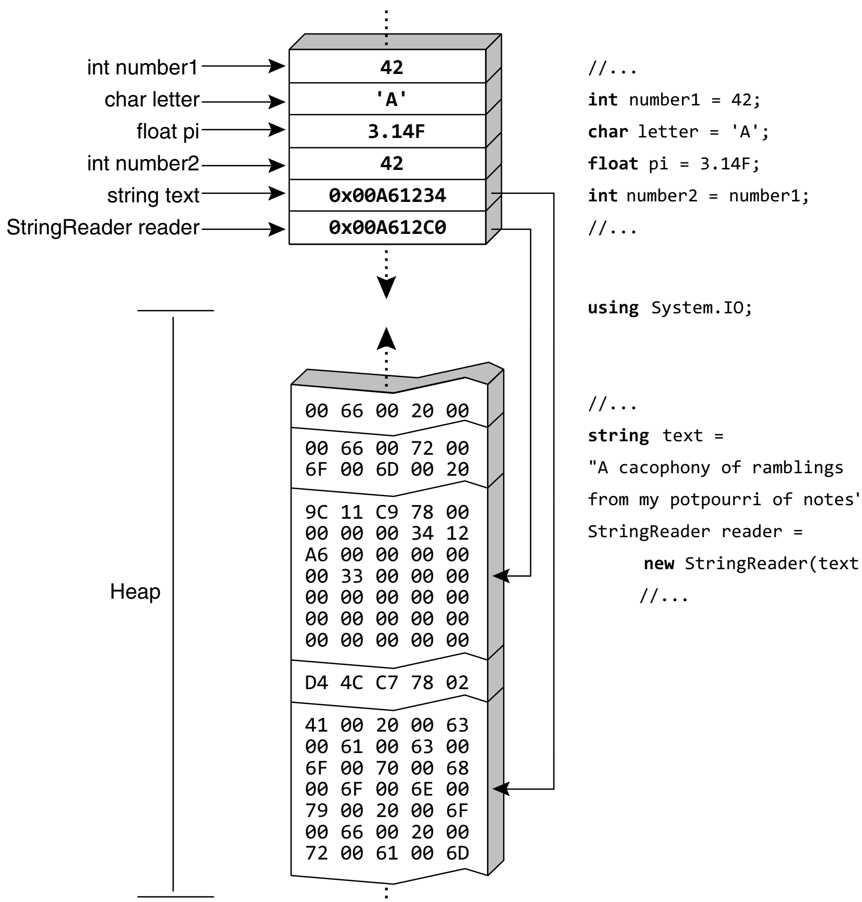


FIGURE 2.2: Reference Types Point to the Heap

a field of the object through one variable causes the effect to be seen when accessing the field via another variable. This happens both for assignment and for method calls. Therefore, a method can affect the data of a reference type, and that change can be observed when control returns to the caller. For this reason, a key factor when choosing between defining a reference type or a value type is whether the object is logically like an immutable value of fixed size (and therefore possibly a value type), or logically a mutable thing that can be referred to (and therefore likely to be a reference type).

Besides `string` and any custom classes such as `Program`, all types discussed so far are value types. However, most types are reference types. Although it is possible to define custom value types, it is relatively rare to do so in comparison to the number of custom reference types.

Begin 2.0

Nullable Modifier

Value types cannot usually be assigned `null` because, by definition, they cannot contain references, including references to nothing. However, this presents a problem because we frequently wish to represent values that are "missing." When specifying a count, for example, what do you enter if the count is unknown? One possible solution is to designate a "magic" value, such as `-1` or `int.MaxValue`, but these are valid integers. Rather, it is desirable to assign `null` to the value type because it is not a valid integer.

To declare variables of value type that can store `null`, you use the nullable modifier, `?`. This feature, which was introduced with C# 2.0, appears in Listing 2.20.

LISTING 2.20: Using the Nullable Modifier

```
static void Main()
{
  int? count = null;
  do
  {
      // ...
  }
  while(count == null);
}
```

Assigning `null` to value types is especially attractive in database programming. Frequently, value type columns in database tables allow `null` values. Retrieving such columns and assigning them to corresponding fields within C# code is problematic, unless the fields can contain `null` as well. Fortunately, the nullable modifier is designed to handle such a scenario specifically.

End 2.0

Conversions between Data Types

Given the thousands of types predefined in the various CLI implementations and the unlimited number of types that code can define, it is important that types support conversion from one type to another where it makes sense. The most common operation that results in a conversion is **casting.**

Consider the conversion between two numerical types: converting from a variable of type `long` to a variable of type `int`. A `long` type can contain values as large as 9,223,372,036,854,775,808; however, the maximum size of an `int` is 2,147,483,647. As such, that conversion could result in a loss of data—for example, if the variable of type `long` contains a value greater than the maximum size of an `int`. Any conversion that could result in a loss of magnitude or an exception because the conversion failed, requires an **explicit cast.** Conversely, a conversion operation that will not lose magnitude and will not throw an exception regardless of the operand types is an **implicit conversion.**

Explicit Cast

In C#, you cast using the **cast operator.** By specifying the type you would like the variable converted to within parentheses, you acknowledge that if an explicit cast is occurring, there may be a loss of precision and data, or an exception may result. The code in Listing 2.21 converts a `long` to an `int` and explicitly tells the system to attempt the operation.

LISTING 2.21: Explicit Cast Example

```
long longNumber = 50918309109;
int intNumber = (int) longNumber;
```

cast operator

With the cast operator, the programmer essentially says to the compiler, "Trust me, I know what I am doing. I know that the value will fit into the target type." Making such a choice will cause the compiler to allow the conversion. However, with an explicit conversion, there is still a chance that an error, in the form of an exception, might occur while executing if the data is not converted successfully. It is, therefore, the programmer's responsibility to ensure the data is successfully converted, or else to provide the necessary error-handling code when the conversion fails.

ADVANCED TOPIC

Checked and Unchecked Conversions

C# provides special keywords for marking a code block to indicate what should happen if the target data type is too small to contain the assigned data. By default, if the target data type cannot contain the assigned data, the data will truncate during assignment. For an example, see Listing 2.22.

Listing 2.22: Overflowing an Integer Value

```
class Program
{
  static void Main()
  {
      // int.MaxValue equals 2147483647
      int n = int.MaxValue;
      n = n + 1 ;
      System.Console.WriteLine(n);
  }
}
```

Output 2.15 shows the results.

Output 2.15

```
-2147483648
```

Listing 2.22 writes the value `-2147483648` to the console. However, placing the code within a checked block, or using the `checked` option when running the compiler, will cause the runtime to throw an exception of type `System.OverflowException`. The syntax for a checked block uses the `checked` keyword, as shown in Listing 2.23.

LISTING 2.23: A Checked Block Example

```
class Program
{
  static void Main()
  {
      checked
      {
          // int.MaxValue equals 2147483647
          int n = int.MaxValue;
          n = n + 1 ;
          System.Console.WriteLine(n);
      }
  }
}
```

Output 2.16 shows the results.

OUTPUT 2.16

```
Unhandled Exception: System.OverflowException: Arithmetic operation
resulted in an overflow at Program.Main() in ...Program.cs:line 12
```

The result is that an exception is thrown if, within the checked block, an overflow assignment occurs at runtime.

The C# compiler provides a command-line option for changing the default checked behavior from unchecked to checked. C# also supports an unchecked block that overflows the data instead of throwing an exception for assignments within the block (see Listing 2.24).

LISTING 2.24: An Unchecked Block Example

```
using System;

class Program
{
  static void Main()
  {
      unchecked
      {
          // int.MaxValue equals 2147483647
          int n = int.MaxValue;
          n = n + 1 ;
          System.Console.WriteLine(n);
      }
  }
}
```

Output 2.17 shows the results.

OUTPUT 2.17

```
-2147483648
```

Even if the checked option is on during compilation, the unchecked keyword in the preceding code will prevent the runtime from throwing an exception during execution.

You cannot convert any type to any other type simply because you designate the conversion explicitly using the cast operator. The compiler will still check that the operation is valid. For example, you cannot convert a `long` to a `bool`. No such conversion is defined, and therefore, the compiler does not allow such a cast.

Language Contrast: Converting Numbers to Booleans

It may be surprising to learn that there is no valid cast from a numeric type to a Boolean type, since this is common in many other languages. The reason no such conversion exists in C# is to avoid any ambiguity, such as whether –1 corresponds to true or false. More importantly, as you will see in the next chapter, this constraint reduces the chance of using the assignment operator in place of the equality operator (avoiding `if(x=42){...}` when `if(x==42){...}` was intended, for example).

Implicit Conversion

In other instances, such as when going from an `int` type to a `long` type, there is no loss of precision and no fundamental change in the value of the type occurs. In these cases, the code needs to specify only the assignment operator; the conversion is **implicit.** In other words, the compiler is able to determine that such a conversion will work correctly. The code in Listing 2.25 converts from an `int` to a `long` by simply using the assignment operator.

Listing 2.25: Not Using the Cast Operator for an Implicit Cast

```
int intNumber = 31416;
long longNumber = intNumber;
```

Even when no explicit cast operator is required (because an implicit conversion is allowed), it is still possible to include the cast operator (see Listing 2.26).

Listing 2.26: Using the Cast Operator for an Implicit Cast

```
int intNumber = 31416;
long longNumber = (long) intNumber;
```

Type Conversion without Casting

No conversion is defined from a string to a numeric type, so methods such as `Parse()` are required. Each numeric data type includes a `Parse()` function that enables conversion from a string to the corresponding numeric type. Listing 2.27 demonstrates this call.

Listing 2.27: Using `int.Parse()` to Convert a `string` to a Numeric Data Type

```
string text = "9.11E-31";
float kgElectronMass = float.Parse(text);
```

Another special type is available for converting one type to the next. This type is `System.Convert`, and an example of its use appears in Listing 2.28.

Listing 2.28: Type Conversion Using `System.Convert`

```
string middleCText = "261.626";
double middleC = System.Convert.ToDouble(middleCText);
bool boolean = System.Convert.ToBoolean(middleC);
```

`System.Convert` supports only a small number of types and is not extensible. It allows conversion from any of the types `bool`, `char`, `sbyte`, `short`, `int`, `long`, `ushort`, `uint`, `ulong`, `float`, `double`, `decimal`, `DateTime`, and `string` to any other of those types.

Furthermore, all types support a `ToString()` method that can be used to provide a string representation of a type. Listing 2.29 demonstrates how to use this method. The resultant output is shown in Output 2.18.

Listing 2.29: Using `ToString()` to Convert to a `string`

```
bool boolean = true;
string text = boolean.ToString();
// Display "True"
System.Console.WriteLine(text);
```

Output 2.18

```
True
```

For the majority of types, the `ToString()` method will return the name of the data type rather than a string representation of the data. The string representation is returned only if the type has an explicit implementation of `ToString()`. One last point to make is that it is possible to code custom conversion methods, and many such methods are available for classes in the runtime.

Begin 2.0

ADVANCED TOPIC

TryParse()

Starting with C# 2.0 (.NET 2.0), all the numeric primitive types include a static `TryParse()` method. This method is very similar to the `Parse()` method, except that instead of throwing an exception if the conversion fails, the `TryParse()` method returns `false`, as demonstrated in Listing 2.30.

Listing 2.30: Using `TryParse()` in Place of an Invalid Cast Exception

```
double number;
string input;

System.Console.Write("Enter a number: ");
input = System.Console.ReadLine();
if (double.TryParse(input, out number))
{
    // Converted correctly, now use number
    // ...
}
else
{
    System.Console.WriteLine(
        "The text entered was not a valid number.");
}
```

Output 2.19 shows the results of Listing 2.30.

OUTPUT 2.19

```
Enter a number: forty-two
The text entered was not a valid number.
```

The resultant value that the code parses from the input `string` is returned via an `out` parameter—in this case, `number`.

The key difference between `Parse()` and `TryParse()` is the fact that `TryParse()` won't throw an exception if it fails. Frequently, the conversion from a `string` to a numeric type depends on a user entering the text. It is expected, in such scenarios, that the user will enter invalid data that will not parse successfully. By using `TryParse()` rather than `Parse()`, you can avoid throwing exceptions in expected situations. (The expected situation in this case is that the user will enter invalid data and we try to avoid throwing exceptions for expected scenarios.)

End 2.0

Arrays

One particular aspect of variable declaration that Chapter 1 didn't cover is array declaration. With array declaration, you can store multiple items of the same type using a single variable and still access them individually using the index when required. In C#, the array index starts at zero. Therefore, arrays in C# are zero based.

BEGINNER TOPIC

Arrays

Arrays provide a means of declaring a collection of data items that are of the same type using a single variable. Each item within the array is uniquely designated using an integer value called the **index.** The first item in a C# array is accessed using index 0. Programmers should be careful to specify an index value that is less than the array size. Since C# arrays are zero-based, the index for the last element in an array is one less than the total number of items in the array.

For beginners, it is helpful sometimes to think of the index as an offset. The first item is zero away from the start of the array. The second item is one away from the start of the array—and so on.

Arrays are a fundamental part of nearly every programming language, so they are required learning for virtually all developers. Although arrays are frequently used in C# programming, and necessary for the beginner to understand, most programs now use generic collection types rather than arrays when storing collections of data. Therefore, readers should skim over the following section, "Declaring an Array," simply to become familiar with their instantiation and assignment rather. Table 2.7 provides the highlights of what to note. Generic collections will be covered in detail in Chapter 14.

In addition, the final section of the chapter, "Common Array Errors," provides a review of some of the array idiosyncrasies.

Declaring an Array

In C#, you declare arrays using square brackets. First, you specify the element type of the array, followed by open and closed square brackets; then you enter the name of the variable. Listing 2.31 declares a variable called `languages` to be an array of strings.

Listing 2.31: Declaring an Array

```
string[] languages;
```

Obviously, the first part of the array identifies the data type of the elements within the array. The square brackets that are part of the declaration identify the **rank,** or the number of dimensions, for the array; in this case, it is an array of rank one. These two pieces form the data type for the variable `languages`.

Language Contrast: C++ and Java—Array Declaration

The square brackets for an array in C# appear immediately following the data type instead of after the variable declaration. This keeps all the type information together instead of splitting it up both before and after the identifier, as occurs in C++ and Java.

TABLE 2.7 Array Highlights

<table>
<tr><th>Description</th><th>Example</th></tr>
<tr><td>

Declaration

Note that the brackets appear with the data type.

Multidimensional arrays are declared using commas where the comma+1 specifies the number of dimensions.

</td><td>

```
string[] languages; // one-dimensional
int[,] cells;       // two-dimensional
```

</td></tr>
<tr><td>

Assignment

The `new` keyword and the corresponding data type are optional at declaration time.

Following declaration, the `new` keyword is required when instantiating an array.

Arrays can be assigned without literal values. As a result, the value of each item in the array is initialized to its default.

If no literal values are provided, the size of the array must be specified. (The size does not have to be a constant; it can be a variable calculated at runtime.)

Starting with C# 3.0, specifying the data type is optional.

</td><td>

```
string[] languages = { "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
languages = new string[9];
languages = new string[]{"C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#" };

// Multidimensional array assignment
// and initialization.
int[,] cells = int[3,3];
cells = {
      {1, 0, 2},
      {1, 2, 0},
      {1, 2, 1}
  };
```

</td></tr>
<tr><td>

`default` *Keyword*

The explicit default of any data type is available using the `default` operator.

</td><td>

```
int count = default(int);
```

</td></tr>
<tr><td>

Accessing an Array

Arrays are zero based, so the first element in an array is at index 0.

The square brackets are used to store and retrieve data from an array.

</td><td>

```
string[] languages = new string[9]{
    "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
// Save "C++" to variable called language.
string language = languages[3];
// Assign "Java" to the C++ position.
languages[3] = languages[2];
// Assign language to location of "Java".
languages[2] = language;
```

</td></tr>
</table>

Listing 2.31 defines an array with a rank of 1. Commas within the square brackets define additional dimensions. Listing 2.32, for example, defines a two-dimensional array of cells for a game of chess or tic-tac-toe.

LISTING 2.32: Declaring a Two-Dimensional Array

```
//    |   |
// ---+---+---
//    |   |
// ---+---+---
//    |   |
int[,] cells;
```

In Listing 2.32, the array has a rank of 2. The first dimension could correspond to cells going across and the second dimension represents cells going down. Additional dimensions are added, with additional commas, and the total rank is one more than the number of commas. Note that the number of items that occur for a particular dimension is not part of the variable declaration. This is specified when creating (instantiating) the array and allocating space for each element.

Instantiating and Assigning Arrays

Once an array is declared, you can immediately fill its values using a comma-delimited list of items enclosed within a pair of curly braces. Listing 2.33 declares an array of strings and then assigns the names of nine languages within curly braces.

LISTING 2.33: Array Declaration with Assignment

```
string[] languages = { "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
```

The first item in the comma-delimited list becomes the first item in the array; the second item in the list becomes the second item in the array, and so on. The curly brackets are the notation for defining an array literal.

The assignment syntax shown in Listing 2.33 is available only if you declare and assign the value within one statement. To assign the value after declaration requires the use of the keyword `new` as shown in Listing 2.34.

Listing 2.34: Array Assignment Following Declaration

```
string[] languages;
languages = new string[]{"C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#" };
```

Starting in C# 3.0, specifying the data type of the array (`string`) following `new` is optional as long as the compiler is able to deduce the element type of the array from the types of the elements in the array initializer. The square brackets are still required.

C# also allows use of the `new` keyword as part of the declaration statement, so it allows the assignment and the declaration shown in Listing 2.35.

Listing 2.35: Array Assignment with `new` during Declaration

```
string[] languages = new string[]{
    "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
```

The use of the `new` keyword tells the runtime to allocate memory for the data type. It instructs the runtime to instantiate the data type—in this case, an array.

Whenever you use the `new` keyword as part of an array assignment, you may also specify the size of the array within the square brackets. Listing 2.36 demonstrates this syntax.

Listing 2.36: Declaration and Assignment with the `new` Keyword

```
string[] languages = new string[9]{
    "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
```

The array size in the initialization statement and the number of elements contained within the curly braces must match. Furthermore, it is possible to assign an array but not specify the initial values of the array, as demonstrated in Listing 2.37.

Listing 2.37: Assigning without Literal Values

```
string[] languages = new string[9];
```

Assigning an array but not initializing the initial values will still initialize each element. The runtime initializes elements to their default values, as follows:

- Reference types (such as `string`) are initialized to `null`.
- Numeric types are initialized to zero.
- `bool` is initialized to `false`.
- `char` is initialized to `\0`.

Nonprimitive value types are recursively initialized by initializing each of their fields to their default values. As a result, it is not necessary to individually assign each element of an array before using it.

Begin 2.0

NOTE

In C# 2.0, it is possible to use the `default()` operator to produce the default value of a data type. `default()` takes a data type as a parameter. `default(int)`, for example, produces `0` and `default(bool)` produces `false`.

End 2.0

Because the array size is not included as part of the variable declaration, it is possible to specify the size at runtime. For example, Listing 2.38 creates an array based on the size specified in the `Console.ReadLine()` call.

LISTING 2.38: Defining the Array Size at Runtime

```
string[] groceryList;
System.Console.Write("How many items on the list? ");
int size = int.Parse(System.Console.ReadLine());
groceryList = new string[size];
// ...
```

C# initializes multidimensional arrays similarly. A comma separates the size of each rank. Listing 2.39 initializes a tic-tac-toe board with no moves.

LISTING 2.39: Declaring a Two-Dimensional Array

```
int[,] cells = int[3,3];
```

Initializing a tic-tac-toe board with a specific position instead could be done as shown in Listing 2.40.

Listing 2.40: Initializing a Two-Dimensional Array of Integers

```
int[,] cells = {
        {1, 0, 2},
        {1, 2, 0},
        {1, 2, 1}
    };
```

The initialization follows the pattern in which there is an array of three elements of type `int[]`, and each element has the same size; in this example, the size is 3. Note that the sizes of each `int[]` element must all be identical. The declaration shown in Listing 2.41, therefore, is not valid.

Listing 2.41: A Multidimensional Array with Inconsistent Size, Causing an Error

```
// ERROR:  Each dimension must be consistently sized.
int[,] cells = {
        {1, 0, 2, 0},
        {1, 2, 0},
        {1, 2}
        {1}
    };
```

Representing tic-tac-toe does not require an integer in each position. One alternative is a separate virtual board for each player, with each board containing a `bool` that indicates which positions the players selected. Listing 2.42 corresponds to a three-dimensional board.

Listing 2.42: Initializing a Three-Dimensional Array

```
bool[,,] cells;
cells = new bool[2,3,3]
  {
     // Player 1 moves                 //  X |   |
     {   {true, false, false},         // ---+---+---
         {true, false, false},         //  X |   |
         {true, false, true} },        // ---+---+---
                                       //  X |   | X

     // Player 2 moves                 //    |   | O
     {   {false, false, true},         // ---+---+---
         {false, true, false},         //    | O |
         {false, true, true} }         // ---+---+---
                                       //    | O |
  };
```

In this example, the board is initialized and the size of each rank is explicitly identified. In addition to identifying the size as part of the `new` expression, the literal values for the array are provided. The literal values of type `bool[,,]` are broken into two arrays of type `bool[,]`, size 3 × 3. Each two-dimensional array is composed of three `bool` arrays, size 3.

As already mentioned, each dimension in a multidimensional array must be consistently sized. However, it is also possible to define a **jagged array,** which is an array of arrays. Jagged array syntax is slightly different from that of a multidimensional array; furthermore, jagged arrays do not need to be consistently sized. Therefore, it is possible to initialize a jagged array as shown in Listing 2.43.

LISTING 2.43: Initializing a Jagged Array

```
int[][] cells = {
    new int[]{1, 0, 2, 0},
    new int[]{1, 2, 0},
    new int[]{1, 2},
    new int[]{1}
};
```

A jagged array doesn't use a comma to identify a new dimension. Rather, a jagged array defines an array of arrays. In Listing 2.43, `[]` is placed after the data type `int[]`, thereby declaring an array of type `int[]`.

Notice that a jagged array requires an array instance (or `null`) for each internal array. In this example, you use `new` to instantiate the internal element of the jagged arrays. Leaving out the instantiation would cause a compile error.

Using an Array

You access a specific item in an array using the square bracket notation, known as the **array accessor.** To retrieve the first item from an array, you specify zero as the index. In Listing 2.44, the value of the fifth item (using the index 4 because the first item is index 0) in the `languages` variable is stored in the variable `language`.

LISTING 2.44: Declaring and Accessing an Array

```
string[] languages = new string[9]{
    "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
// Retrieve fifth item in languages array (Java)
string language = languages[4];
```

The square bracket notation is also used to store data into an array. Listing 2.45 switches the order of `"C++"` and `"Java"`.

LISTING 2.45: Swapping Data between Positions in an Array

```
string[] languages = new string[9]{
    "C#", "COBOL", "Java",
    "C++", "Visual Basic", "Pascal",
    "Fortran", "Lisp", "J#"};
// Save "C++" to variable called language.
string language = languages[3];
// Assign "Java" to the C++ position.
languages[3] = languages[2];
// Assign language to location of "Java".
languages[2] = language;
```

For multidimensional arrays, an element is identified with an index for each dimension, as shown in Listing 2.46.

LISTING 2.46: Initializing a Two-Dimensional Array of Integers

```
int[,] cells = {
        {1, 0, 2},
        {0, 2, 0},
        {1, 2, 1}
    };
// Set the winning tic-tac-toe move to be player 1.
cells[1,0] = 1;
```

Jagged array element assignment is slightly different because it is consistent with the jagged array declaration. The first element is an array within the array of arrays; the second index specifies the item within the selected array element (see Listing 2.47).

LISTING 2.47: Declaring a Jagged Array

```
int[][] cells = {
    new int[]{1, 0, 2},
  new int[]{0, 2, 0},
  new int[]{1, 2, 1}
};

cells[1][0] = 1;
// ...
```

Length

You can obtain the length of an array, as shown in Listing 2.48.

LISTING 2.48: Retrieving the Length of an Array

```
Console.WriteLine(
    $"There are { languages.Length } languages in the array.");
```

Arrays have a fixed length; they are bound such that the length cannot be changed without re-creating the array. Furthermore, overstepping the **bounds** (or length) of the array will cause the runtime to report an error. This can occur when you attempt to access (either retrieve or assign) the array with an index for which no element exists in the array. Such an error frequently occurs when you use the array length as an index into the array, as shown in Listing 2.49.

LISTING 2.49: Accessing Outside the Bounds of an Array, Throwing an Exception

```
string languages = new string[9];
...
// RUNTIME ERROR: index out of bounds – should
// be 8 for the last element
languages[4] = languages[9];
```

> **NOTE**
>
> The `Length` member returns the number of items in the array, not the highest index. The `Length` member for the `languages` variable is `9`, but the highest index for the `languages` variable is `8`, because that is how far it is from the start.

It is a good practice to use `Length` in place of the hardcoded array size. To use `Length` as an index, for example, it is necessary to subtract 1 to avoid an out-of-bounds error (see Listing 2.50).

LISTING 2.50: Using `Length - 1` in the Array Index

```
string languages = new string[9];
...
languages[4] = languages[languages.Length - 1];
```

To avoid overstepping the bounds on an array, use a length check to verify that the array has a length greater than 0 and use `Length - 1` in place of a hardcoded value when accessing the last item in the array (see Listing 2.50).

`Length` returns the total number of elements in an array. Therefore, if you had a multidimensional array such as `bool cells[,,]` of size 2 × 3 × 3, `Length` would return the total number of elements, 18.

For a jagged array, `Length` returns the number of elements in the first array. Because a jagged array is an array of arrays, `Length` evaluates only the outside, containing array and returns its element count, regardless of what is inside the internal arrays.

Language Contrast: C++—Buffer Overflow Bugs

Unmanaged C++ does not always check whether you overstep the bounds on an array. Not only can this be difficult to debug, but making this mistake can also result in a potential security error called a **buffer overrun.** In contrast, the Common Language Runtime protects all C# (and Managed C++) code from overstepping array bounds, virtually eliminating the possibility of a buffer overrun issue in managed code.

More Array Methods

Arrays include additional methods for manipulating the elements within the array—for example, `Sort()`, `BinarySearch()`, `Reverse()`, and `Clear()` (see Listing 2.51).

Listing 2.51: Additional Array Methods

```
class ProgrammingLanguages
{
  static void Main()
  {
      string[] languages = new string[]{
          "C#", "COBOL", "Java",
          "C++", "Visual Basic", "Pascal",
          "Fortran", "Lisp", "J#"};

      System.Array.Sort(languages);

      string searchString = "COBOL";
```

```
        int index = System.Array.BinarySearch(
            languages, searchString);
        System.Console.WriteLine(
            "The wave of the future, "
            + $"{ searchString }, is at index { index }.");

        System.Console.WriteLine();
        System.Console.WriteLine(
            $"{ "First Element",-20 }\t{ "Last Element",-20 }");
        System.Console.WriteLine(
            $"{ "-------------",-20 }\t{ "------------",-20 }");
        System.Console.WriteLine(
                $"{ languages[0],-20 }\t{ languages[languages.Length-1],-20
➥ }");
        System.Array.Reverse(languages);
        System.Console.WriteLine(
                $"{ languages[0],-20 }\t{ languages[languages.Length-1],-20
➥ }");
        // Note this does not remove all items from the array.
        // Rather it sets each item to the type's default value.
        System.Array.Clear(languages, 0, languages.Length);
        System.Console.WriteLine(
                $"{ languages[0],-20 }\t{ languages[languages.Length-1],-20
➥ }");
        System.Console.WriteLine(
            $"After clearing, the array size is: { languages.Length }");
    }
  }
```

The results of Listing 2.51 are shown in Output 2.20.

OUTPUT 2.20

```
The wave of the future, COBOL, is at index 2.

First Element           Last Element
-------------           ------------
C#                      Visual Basic
Visual Basic            C#

After clearing, the array size is: 9
```

Access to these methods is obtained through the `System.Array` class. For the most part, using these methods is self-explanatory, except for two noteworthy items:

- Before using the `BinarySearch()` method, it is important to sort the array. If values are not sorted in increasing order, the incorrect index may be returned. If the search element does not exist, the value returned is negative. (Using the complement operator, `~index`, returns the first index, if any, that is larger than the searched value.)

- The `Clear()` method does not remove elements of the array and does not set the length to zero. The array size is fixed and cannot be modified. Therefore, the `Clear()` method sets each element in the array to its default value (`false`, `0`, or `null`). This explains why `Console.WriteLine()` creates a blank line when writing out the array after `Clear()` is called.

Language Contrast: Visual Basic—Redimensioning Arrays

Visual Basic includes a `Redim` statement for changing the number of items in an array. Although there is no equivalent C#-specific keyword, there is a method available in .NET 2.0 that will re-create the array and then copy all the elements over to the new array. This method is called `System.Array.Resize`.

Array Instance Methods

Like strings, arrays have instance members that are accessed not from the data type, but directly from the variable. `Length` is an example of an instance member because access to `Length` is through the array variable, not the class. Other significant instance members are `GetLength()`, `Rank`, and `Clone()`.

Retrieving the length of a particular dimension does not require the `Length` property. To retrieve the size of a particular rank, an array includes a `GetLength()` instance method. When calling this method, it is necessary to specify the rank whose length will be returned (see Listing 2.52).

LISTING 2.52: Retrieving a Particular Dimension's Size

```
bool[,,] cells;
cells = new bool[2,3,3];
System.Console.WriteLine(cells.GetLength(0));   // Displays 2
```

The results of Listing 2.52 appear in Output 2.21.

OUTPUT 2.21

```
2
```

Listing 2.52 displays `2` because that is the number of elements in the first dimension.

It is also possible to retrieve the entire array's rank by accessing the array's `Rank` member. `cells.Rank`, for example, will return `3`.

By default, assigning one array variable to another copies only the array reference, not the individual elements of the array. To make an entirely new copy of the array, use the array's `Clone()` method. The `Clone()` method will return a copy of the array; changing any of the members of this new array will not affect the members of the original array.

Strings As Arrays

Variables of type `string` are accessible like an array of characters. For example, to retrieve the fourth character of a string called `palindrome` you can call `palindrome[3]`. Note, however, that because strings are immutable, it is not possible to assign particular characters within a string. C#, therefore, would not allow `palindrome[3]='a'`, where `palindrome` is declared as a string. Listing 2.53 uses the array accessor to determine whether an argument on the command line is an option, where an option is identified by a dash as the first character.

LISTING 2.53: Looking for Command-Line Options

```
string[] args;
...
if(args[0][0] == '-')
{
    //This parameter is an option
}
```

This snippet uses the `if` statement, which is covered in Chapter 3. In addition, it presents an interesting example because you use the array accessor to retrieve the first element in the array of strings, `args`. Following the first array accessor is a second one, which retrieves the first character of the string. The code, therefore, is equivalent to that shown in Listing 2.54.

Listing 2.54: Looking for Command-Line Options (Simplified)

```
string[] args;
...
string arg = args[0];
if(arg[0] == '-')
{
    //This parameter is an option
}
```

Not only can string characters be accessed individually using the array accessor, but it is also possible to retrieve the entire string as an array of characters using the string's `ToCharArray()` method. Using this approach, you could reverse the string with the `System.Array.Reverse()` method, as demonstrated in Listing 2.55, which determines whether a string is a palindrome.

Listing 2.55: Reversing a String

```
class Palindrome
{
  static void Main()
  {
      string reverse, palindrome;
      char[] temp;

      System.Console.Write("Enter a palindrome: ");
      palindrome = System.Console.ReadLine();

      // Remove spaces and convert to lowercase
      reverse = palindrome.Replace(" ", "");
      reverse = reverse.ToLower();

      // Convert to an array
      temp = reverse.ToCharArray();

      // Reverse the array
      System.Array.Reverse(temp);

      // Convert the array back to a string and
      // check if reverse string is the same.
      if(reverse == new string(temp))
      {
          System.Console.WriteLine(
              $"\"{palindrome}\" is a palindrome.");
      }
      else
      {
          System.Console.WriteLine(
              $"\"{palindrome}\" is NOT a palindrome.");
```

```
        }
    }
}
```

The results of Listing 2.55 appear in Output 2.22.

OUTPUT 2.22

```
Enter a palindrome: NeverOddOrEven
"NeverOddOrEven" is a palindrome.
```

This example uses the `new` keyword; this time, it creates a new string from the reversed array of characters.

Common Array Errors

This section introduced the three types of arrays: single-dimension, multidimensional, and jagged arrays. Several rules and idiosyncrasies govern array declaration and use. Table 2.8 points out some of the most common errors and helps solidify the rules. Try reviewing the code in the Common Mistake column first (without looking at the Error Description and Corrected Code columns) as a way of verifying your understanding of arrays and their syntax.

TABLE 2.8: Common Array Coding Errors

Common Mistake	Error Description	Corrected Code
`int numbers[];`	The square braces for declaring an array appear after the data type, not after the variable identifier.	`int[] numbers;`

`int[] numbers;`
`numbers = {42, 84, 168 };`
	When assigning an array after declaration, it is necessary to use the `new` keyword and then specify the data type.	`int[] numbers;`
		`numbers = new int[]{`
		`42, 84, 168 }`

`int[3] numbers =` `{ 42, 84, 168 };`	It is not possible to specify the array size as part of the variable declaration.	`int[] numbers =` `{ 42, 84, 168 };`
`int[] numbers =` `new int[];`	The array size is required at initialization time unless an array literal is provided.	`int[] numbers =` `new int[3];`

TABLE 2.8: Common Array Coding Errors (*continued*)

Common Mistake	Error Description	Corrected Code
`int[] numbers = new int[3]{}`	The array size is specified as `3`, but there are no elements in the array literal. The array size must match the number of elements in the array literal.	`int[] numbers = new int[3] { 42, 84, 168 };`
`int[] numbers = new int[3]; Console.WriteLine( numbers[3]);`	Array indexes start at zero. Therefore, the last item is one less than the array size. (Note that this is a runtime error, not a compile-time error.)	`int[] numbers = new int[3]; Console.WriteLine( numbers[2]);`
`int[] numbers = new int[3]; numbers[numbers.Length] = 42;`	Same as previous error: 1 needs to be subtracted from the `Length` to access the last element. (Note that this is a runtime error, not a compile-time error.)	`int[] numbers = new int[3]; numbers[numbers.Length-1] = 42;`
`int[] numbers; Console.WriteLine( numbers[0]);`	`numbers` has not yet been assigned an instantiated array, so it cannot be accessed.	`int[] numbers = {42, 84}; Console.WriteLine( numbers[0]);`
`int[,] numbers = { {42}, {84, 42} };`	Multidimensional arrays must be structured consistently.	`int[,] numbers = { {42, 168}, {84, 42} };`
`int[][] numbers = { {42, 84}, {84, 42} };`	Jagged arrays require instantiated arrays to be specified for the arrays within the array.	`int[][] numbers = { new int[]{42, 84}, new int[]{84, 42} };`

SUMMARY

Even for experienced programmers, C# introduces several new programming constructs. For example, as part of the section on data types, this chapter covered the type `decimal`, which can be used to perform financial calculations without floating point anomalies. In addition, the chapter introduced the fact that the Boolean type, `bool`, does not convert implicitly to or from the integer type, thereby preventing the mistaken use of the assignment operator in a conditional expression. Other characteristics of C# that distinguish it from many of its predecessors are the `@` verbatim string qualifier, which forces a string to ignore the escape character, and the immutable nature of the `string` data type.

C# permits both implicit conversions and explicit conversions (that is, conversions that require a cast operation) to convert expressions to a given data type. In Chapter 9, you will learn how to define customized conversion operators on your own types.

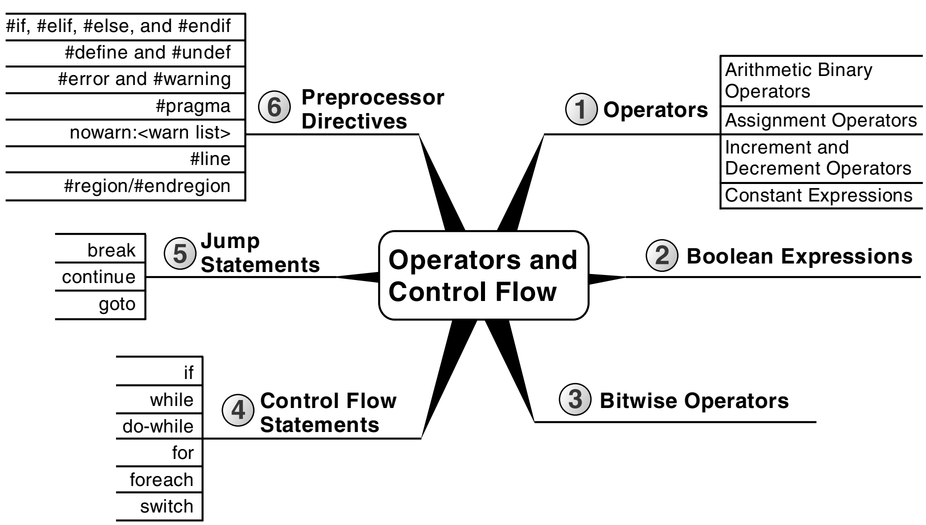
This chapter closed with coverage of C# syntax for arrays, along with the various means of manipulating arrays. For many developers, the syntax can seem rather daunting at first, so the section included a list of the common errors associated with coding arrays.

The next chapter looks at expressions and control flow statements. The `if` statement, which appeared a few times toward the end of this chapter, is discussed as well.

3

Operators and Control Flow

IN THIS CHAPTER, YOU WILL learn about operators, control flow statements, and the C# preprocessor. **Operators** provide syntax for performing different calculations or actions appropriate for the operands within the calculation. **Control flow statements** provide the means for conditional logic within a program or looping over a section of code multiple times. After introducing the `if` control flow statement, the chapter looks at the concept of Boolean expressions, which are embedded within many control flow statements. Included is mention of how integers cannot be converted



(even explicitly) to `bool` and the advantages of this restriction. The chapter ends with a discussion of the C# preprocessor directives.

Operators

Now that you have been introduced to the predefined data types (refer to Chapter 2), you can begin to learn more about how to use these data types in combination with operators to perform calculations. For example, you can make calculations on variables that you have declared.

BEGINNER TOPIC

Operators

Operators are used to perform mathematical or logical operations on values (or variables) called **operands** to produce a new value, called the **result.** For example, in Listing 3.1 the subtraction operator, `-`, is used to subtract two operands, the numbers `4` and `2`. The result of the subtraction is stored in the variable `difference`.

Listing 3.1: A Simple Operator Example

```
int difference = 4 - 2;
```

Operators are generally classified into three categories—unary, binary, and ternary, corresponding to the number of operands (one, two, and three, respectively). This section covers some of the most basic unary and binary operators. The ternary operators are introduced later in the chapter.

Plus and Minus Unary Operators (+, -)

Sometimes you may want to change the sign of a numerical value. In these cases, the unary minus operator (`-`) comes in handy. For example, Listing 3.2 changes the total current U.S. debt to a negative value to indicate that it is an amount owed.

Listing 3.2: Specifying Negative Values[1]

```
//National debt to the penny
decimal debt = -18125876697430.99M;
```

Using the minus operator *is equivalent to subtracting the operand from zero.*

The unary plus operator (+) rarely[2] has any effect on a value. It is a superfluous addition to the C# language and was included for the sake of symmetry.

Arithmetic Binary Operators (+, -, *, /, %)

Binary operators require two operands. C# uses infix notation for binary operators: The operator appears between the left and right operands. The result of every binary operator other than assignment must be used somehow—for example, by using it as an operand in another expression such as an assignment.

> **Language Contrast: C++—Operator-Only Statements**
>
> In contrast to the rule mentioned previously, C++ will allow a single binary expression to form the entirety of a statement, such as 4+5, to compile. In C#, only assignment, call, increment, decrement, and object creation expressions are allowed to be the entirety of a statement.

The subtraction example in Listing 3.3 illustrates the use of a binary operator—more specifically, an arithmetic binary operator. The operands appear on each side of the arithmetic operator, and then the calculated value is assigned. The other arithmetic binary operators are addition (+), division (/), multiplication (*), and remainder (%—sometimes called the mod operator).

---

1. As of February 5, 2015, according to www.treasurydirect.gov.
2. The unary + operator is defined to take operands of type `int`, `uint`, `long`, `ulong`, `float`, `double`, and `decimal` (and nullable versions of those types). Using it on other numeric types such as `short` will convert its operand to one of these types as appropriate.

Listing 3.3: Using Binary Operators

```
class Division
{
  static void Main()
  {
      int numerator;
      int denominator;
      int quotient;
      int remainder;

      System.Console.Write("Enter the numerator: ");
      numerator = int.Parse(System.Console.ReadLine());

      System.Console.Write("Enter the denominator: ");
      denominator = int.Parse(System.Console.ReadLine());

      quotient = numerator / denominator;
      remainder = numerator % denominator;

      System.Console.WriteLine(
          $"{numerator} / {denominator} = {quotient} with remainder
➥{remainder}");
  }
}
```

Output 3.1 shows the results of Listing 3.3.

Output 3.1

```
Enter the numerator: 23
Enter the denominator: 3
23 / 3 = 7 with remainder 2
```

In the highlighted assignment statements, the division and remainder operations are executed before the assignments. The order in which operators are executed is determined by their **precedence** and **associativity.** The precedence for the operators used so far is as follows:

1. `*`, `/`, and `%` have highest precedence.
2. `+` and `-` have lower precedence.
3. `=` has the lowest precedence of these six operators.

Therefore, you can assume that the statement behaves as expected, with the division and remainder operators executing before the assignment.

If you forget to assign the result of one of these binary operators, you will receive the compile error shown in Output 3.2.

OUTPUT 3.2

```
... error CS0201: Only assignment, call, increment, decrement,
and new object expressions can be used as a statement
```

BEGINNER TOPIC

Parentheses, Associativity, Precedence, and Evaluation

When an expression contains multiple operators, it can be unclear precisely what the operands of each operator are. For example, in the expression `x+y*z`, clearly the expression `x` is an operand of the addition and `z` is an operand of the multiplication. But is `y` an operand of the addition or the multiplication?

Parentheses allow you to unambiguously associate an operand with its operator. If you wish `y` to be a summand, you can write the expression as `(x+y)*z`; if you want it to be a multiplicand, you can write `x+(y*z)`.

However, C# does not require you to parenthesize every expression containing more than one operator; instead, the compiler can use associativity and precedence to figure out from the context which parentheses you have omitted. **Associativity** determines how similar operators are parenthesized; **precedence** determines how dissimilar operators are parenthesized.

A binary operator may be "left-associative" or "right-associative," depending on whether the expression "in the middle" belongs to the operator on the left or the right. For example, `a-b-c` is assumed to mean `(a-b)-c`, and not `a-(b-c)`; subtraction is therefore said to be "left-associative." Most operators in C# are left-associative; the assignment operators are right-associative.

When the operators are dissimilar, the **precedence** for those operators is used to determine which side the operand in the middle belongs to. For example, multiplication has higher precedence than addition and, therefore, the expression `x+y*z` is evaluated as `x+(y*z)` rather than `(x+y)*z`.

It is often still a good practice to use parentheses to make the code more readable even when use of parentheses does not change the meaning of the expression. For example, when performing a Celsius-to-Fahrenheit temperature conversion, `(c*9.0/5.0)+32.0` is easier to read than `c*9.0/5.0+32.0`, even though the parentheses are completely unnecessary.

Guidelines

DO use parentheses to make code more readable, particularly if the operator precedence is not clear to the casual reader.

Clearly, operators of higher precedence must execute before adjoining operators of lower precedence: in `x+y*z`, the multiplication must be executed before the addition because the result of the multiplication is the left-hand operand of the addition. However, it is important to realize that precedence and associativity affect only the order in which the *operators* themselves are executed; they do not in any way affect the order in which the *operands* are evaluated.

Operands are always evaluated from left to right in C#. In an expression with three method calls, such as `A()+B()*C()`, first `A()` is evaluated, then `B()`, then `C()`; then the multiplication operator determines the product; and finally the addition operator determines the sum. Just because `C()` is involved in a multiplication and `A()` is involved in a lower-precedence addition does not imply that method invocation `C()` happens before method invocation `A()`.

Language Contrast: C++: Evaluation Order of Operands

In contrast to the rule mentioned here, the C++ specification allows an implementation broad latitude to decide the evaluation order of operands. When given an expression such as `A()+B()*C()`, a C++ compiler can choose to evaluate the function calls in any order, just so long as the product is one of the summands. For example, a legal compiler could evaluate `B()`, then `A()`, then `C()`, then the product, and finally the sum.

Using the Addition Operator with Strings

Operators can also work with non-numeric operands. For example, it is possible to use the addition operator to concatenate two or more strings, as shown in Listing 3.4.

LISTING 3.4: Using Binary Operators with Non-numeric Types

```
class FortyTwo
{
  static void Main()
  {
      short windSpeed = 42;
      System.Console.WriteLine(
          "The original Tacoma Bridge in Washington\nwas "
          + "brought down by a "
          + windSpeed + " mile/hour wind.");
  }
}
```

Output 3.3 shows the results of Listing 3.4.

OUTPUT 3.3

```
The original Tacoma Bridge in Washington
was brought down by a 42 mile/hour wind.
```

Because sentence structure varies among languages in different cultures, developers should be careful not to use the addition operator with strings that possibly will require localization. Similarly, although we can embed expressions within a string using C# 6.0's string interpolation, localization to other languages still requires moving the string to a resource file, neutralizing the string interpolation. For this reason, you should use the addition operator sparingly, favoring composite formatting when localization is a possibility.

Guidelines

DO favor composite formatting over use of the addition operator for concatenating strings when localization is a possibility.

Using Characters in Arithmetic Operations

When introducing the `char` type in Chapter 2, we mentioned that even though it stores characters and not numbers, the `char` type is an **integral** type ("integral" means it is based on an integer). It can participate in arithmetic operations with other integer types. However, interpretation of the value of the `char` type is not based on the character stored within it, but rather on its underlying value. The digit `3`, for example, is represented by the Unicode value `0x33` (hexadecimal), which in base 10 is `51`. The digit `4` is represented by the Unicode value `0x34`, or `52` in base 10. Adding `3` and `4` in Listing 3.5 results in a hexadecimal value of `0x67`, or `103` in base 10, which is the Unicode value for the letter `g`.

Listing 3.5: Using the Plus Operator with the char Data Type

```
int n = '3' + '4';
char c = (char)n;
System.Console.WriteLine(c);  // Writes out g.
```

Output 3.4 shows the result of Listing 3.5.

Output 3.4

```
g
```

You can use this trait of character types to determine how far two characters are from each other. For example, the letter `f` is three characters away from the letter `c`. You can determine this value by subtracting the letter `c` from the letter `f`, as Listing 3.6 demonstrates.

Listing 3.6: Determining the Character Difference between Two Characters

```
int distance = 'f' – 'c';
System.Console.WriteLine(distance);
```

Output 3.5 shows the result of Listing 3.6.

Output 3.5

```
3
```

Special Floating-Point Characteristics

The binary floating-point types, `float` and `double`, have some special characteristics, such as the way they handle precision. This section looks at some specific examples, as well as some unique floating-point type characteristics.

A `float`, with seven decimal digits of precision, can hold the value 1,234,567 and the value 0.1234567. However, if you add these two `floats` together, the result will be rounded to 1234567, because the exact result requires more precision than the seven significant digits that a `float` can hold. The error introduced by rounding off to seven digits can become large compared to the value computed, especially with repeated calculations. (See also the Advanced Topic, "Unexpected Inequality with Floating-Point Types," later in this section.)

Internally, the binary floating-point types actually store a binary fraction, not a decimal fraction. Consequently, "representation error" inaccuracies can occur with a simple assignment, such as `double number = 140.6F`. The exact value of 140.6 is the fraction 703/5, but the denominator of that fraction is not a power of 2, so it cannot be represented exactly by a binary floating-point number. The value actually represented is the closest fraction with a power of 2 in the denominator that will fit into the 16 bits of a `float`.

Since the `double` can hold a more accurate value than the `float` can store, the C# compiler will actually evaluate this expression to `double number = 140.600006103516` because `140.600006103516` is the closest binary fraction to 140.6 as a `float`. This fraction is slightly larger than 140.6 when represented as a `double`.

> ## Guidelines
>
> **AVOID** binary floating-point types when exact decimal arithmetic is required; use the `decimal` floating-point type instead.

ADVANCED TOPIC

Unexpected Inequality with Floating-Point Types

Because floating-point numbers can be unexpectedly rounded off to non-decimal fractions, comparing floating-point values for equality can be quite confusing. Consider Listing 3.7.

Listing 3.7: Unexpected Inequality Due to Floating-Point Inaccuracies

```
decimal decimalNumber = 4.2M;
double doubleNumber1 = 0.1F * 42F;
double doubleNumber2 = 0.1D * 42D;
float floatNumber = 0.1F * 42F;

Trace.Assert(decimalNumber != (decimal)doubleNumber1);
// 1. Displays: 4.2 != 4.20000006258488
System.Console.WriteLine(
    $"{decimalNumber} != {(decimal)doubleNumber1}");

Trace.Assert((double)decimalNumber != doubleNumber1);
// 2. Displays: 4.2 != 4.20000006258488
System.Console.WriteLine(
    $"{(double)decimalNumber} != {doubleNumber1}");

Trace.Assert((float)decimalNumber != floatNumber);
// 3. Displays: (float)4.2M != 4.2F
System.Console.WriteLine(
    $"(float){(float)decimalNumber}M != {floatNumber}F");

Trace.Assert(doubleNumber1 != (double)floatNumber);
// 4. Displays: 4.20000006258488 != 4.20000028610229
System.Console.WriteLine(
    $"{doubleNumber1} != {(double)floatNumber}");

Trace.Assert(doubleNumber1 != doubleNumber2);
// 5. Displays: 4.20000006258488 != 4.2
System.Console.WriteLine(
    $"{doubleNumber1} != {doubleNumber2}");

Trace.Assert(floatNumber != doubleNumber2);
// 6. Displays: 4.2F != 4.2D
System.Console.WriteLine(
    $"{floatNumber}F != {doubleNumber2}D");

Trace.Assert((double)4.2F != 4.2D);
// 7. Displays: 4.19999980926514 != 4.2
System.Console.WriteLine(
    $"{(double)4.2F} != {4.2D}");

Trace.Assert(4.2F != 4.2D);
// 8. Displays: 4.2F != 4.2D
System.Console.WriteLine(
    $"{4.2F}F != {4.2D}D");
```

Output 3.6 shows the results of Listing 3.7.

Output 3.6

```
4.2 != 4.20000006258488
4.2 != 4.20000006258488
(float)4.2M != 4.2F
4.20000006258488 != 4.20000028610229
4.20000006258488 != 4.2
4.2F != 4.2D
4.19999980926514 != 4.2
4.2F != 4.2D
```

The `Assert()` methods alert the developer whenever arguments evaluate to `false`. However, of all the comparisons in this code listing, none of them are in fact equal. In spite of the apparent equality of the values in the code listing, they are not actually equivalent due to the inaccuracies associated with `float` values.

Guidelines

AVOID using equality conditionals with binary floating-point types. Either subtract the two values and see if their difference is less than a tolerance, or use the `decimal` type.

You should be aware of some additional unique floating-point characteristics as well. For instance, you would expect that dividing an integer by zero would result in an error—and it does with data types such as `int` and `decimal`. The `float` and `double` types, however, allow for certain special values. Consider Listing 3.8, and its resultant output, Output 3.7.

Listing 3.8: Dividing a Float by Zero, Displaying NaN

```
float n=0f;
// Displays: NaN
System.Console.WriteLine(n / 0);
```

Output 3.7

```
NaN
```

In mathematics, certain mathematical operations are undefined, including dividing zero by itself. In C#, the result of dividing the `float` zero by zero results in a special "Not a Number" value; all attempts to print the output of such a number will result in `NaN`. Similarly, taking the square root of a negative number with `System.Math.Sqrt(-1)` will result in `NaN`.

A floating-point number could overflow its bounds as well. For example, the upper bound of the `float` type is approximately 3.4×10^{38}. Should the number overflow that bound, the result would be stored as "positive infinity" and the output of printing the number would be `Infinity`. Similarly, the lower bound of a `float` type is -3.4×10^{38}, and computing a value below that bound would result in "negative infinity," which would be represented by the string `-Infinity`. Listing 3.9 produces negative and positive infinity, respectively, and Output 3.8 shows the results.

Listing 3.9: Overflowing the Bounds of a `float`

```
// Displays: -Infinity
System.Console.WriteLine(-1f / 0);
// Displays: Infinity
System.Console.WriteLine(3.402823E+38f * 2f);
```

Output 3.8

```
-Infinity
Infinity
```

Further examination of the floating-point number reveals that it can contain a value very close to zero, without actually containing zero. If the value exceeds the lower threshold for the `float` or `double` type, the value of the number can be represented as "negative zero" or "positive zero," depending on whether the number is negative or positive, and is represented in output as `-0` or `0`.

Compound Assignment Operators (+=, -=, *=, /=, %=)

Chapter 1 discussed the simple assignment operator, which places the value of the right-hand side of the operator into the variable on the left-hand side. Compound assignment operators combine common binary operator calculations with the assignment operator. For example, consider Listing 3.10.

LISTING 3.10: Common Increment Calculation

```
int x = 123;
x = x + 2;
```

In this assignment, first you calculate the value of `x + 2` and then you assign the calculated value back to `x`. Since this type of operation is performed relatively frequently, an assignment operator exists to handle both the calculation and the assignment with one operator. The += operator increments the variable on the left-hand side of the operator with the value on the right-hand side of the operator, as shown in Listing 3.11.

LISTING 3.11: Using the += Operator

```
int x = 123;
x += 2;
```

This code, therefore, is equivalent to Listing 3.10.

Numerous other "compound assignment" operators exist to provide similar functionality. You can also use the assignment operator the with subtraction, multiplication, division, and remainder operators (as demonstrated in Listing 3.12).

LISTING 3.12: Other Assignment Operator Examples

```
x -= 2;
x /= 2;
x *= 2;
x %= 2;
```

Increment and Decrement Operators (++, --)

C# includes special unary operators for incrementing and decrementing counters. The **increment operator,** ++, increments a variable by one each time it is used. In other words, all of the code lines shown in Listing 3.13 are equivalent.

LISTING 3.13: Increment Operator

```
spaceCount = spaceCount + 1;
spaceCount += 1;
spaceCount++;
```

Similarly, you can decrement a variable by one using the **decrement operator**, `--`. Therefore, all of the code lines shown in Listing 3.14 are also equivalent.

LISTING 3.14: Decrement Operator

```
lines = lines - 1;
lines -= 1;
lines--;
```

BEGINNER TOPIC

A Decrement Example in a Loop

The increment and decrement operators are especially prevalent in loops, such as the `while` loop described later in the chapter. For example, Listing 3.15 uses the decrement operator to iterate backward through each letter in the alphabet.

LISTING 3.15: Displaying Each Character's Unicode Value in Descending Order

```
char current;
int unicodeValue;

// Set the initial value of current.
current = 'z';

do
{
  // Retrieve the Unicode value of current.
  unicodeValue = current;
  System.Console.Write($"{current}={unicodeValue}\t");

  // Proceed to the previous letter in the alphabet;
  current--;
}
while(current >= 'a');
```

Output 3.9 shows the results of Listing 3.15.

OUTPUT 3.9

```
z=122   y=121   x=120   w=119   v=118   u=117   t=116   s=115   r=114
q=113   p=112   o=111   n=110   m=109   l=108   k=107   j=106   i=105
h=104   g=103   f=102   e=101   d=100   c=99   b=98   a=97
```

The increment and decrement operators are used in Listing 3.15 to control how many times a particular operation is performed. In this example, notice that the increment operator is also used on a character (`char`) data type. You can use increment and decrement operators on various data types as long as some meaning is assigned to the concept of the "next" or "previous" value for that data type.

We saw that the assignment operator first computes the value to be assigned, and then performs the assignment. The result of the assignment operator is the value that was assigned. The increment and decrement operators are similar: They compute the value to be assigned, perform the assignment, and result in a value. It is therefore possible to use the assignment operator with the increment or decrement operator, though doing so carelessly can be extremely confusing. See Listing 3.16 and Output 3.10 for an example.

LISTING 3.16: Using the Post-Increment Operator

```
int count = 123;
int result;
result = count++;
System.Console.WriteLine(
  $"result = {result} and count = {count}");
```

OUTPUT 3.10

```
result = 123 and count = 124
```

You might be surprised that `result` was assigned the value that was `count` *before* `count` was incremented. Where you place the increment or decrement operator determines whether the assigned value should be the value of the operand before or after the calculation. If you want the value of `result` to be the value assigned to `count`, you need to place the operator before the variable being incremented, as shown in Listing 3.17.

LISTING 3.17: Using the Pre-Increment Operator

```
int count = 123;
int result;
result = ++count;
System.Console.WriteLine(
  $"result = {result} and count = {count}");
```

Output 3.11 shows the results of Listing 3.17.

Output 3.11

```
result = 124 and count = 124
```

In this example, the increment operator appears before the operand, so the result of the expression is the value assigned to the variable after the increment. If `count` is `123`, `++count` will assign `124` to `count` and produce the result `124`. By contrast, the postfix increment operator `count++` assigns `124` to `count` and produces the value that `count` held before the increment: `123`. Regardless of whether the operator is postfix or prefix, the variable `count` will be incremented before the value is produced; the only difference is which value is produced. The difference between prefix and postfix behavior is illustrated in Listing 3.18. The resultant output is shown in Output 3.12.

Listing 3.18: Comparing the Prefix and Postfix Increment Operators

```
class IncrementExample
{
  static void Main()
  {
      int x = 123;
      // Displays 123, 124, 125.
      System.Console.WriteLine($"{x++}, {x++}, {x}");
      // x now contains the value 125.
      // Displays 126, 127, 127.
      System.Console.WriteLine($"{++x}, {++x}, {x}");
      // x now contains the value 127.
  }
}
```

Output 3.12

```
123, 124, 125
126, 127, 127
```

As Listing 3.18 demonstrates, where the increment and decrement operators appear relative to the operand can affect the result produced by the expression. The result of the prefix operators is the value that the variable had before it was incremented or decremented. The result of the postfix operators is the value that the variable had after it was incremented or decremented. Use caution when embedding these operators in the middle of a statement. When in doubt as to what will happen, use these operators independently, placing them within their own statements. This way, the code is also more readable and there is no mistaking the intention.

Language Contrast: C++—Implementation-Defined Behavior

Earlier we discussed how the operands in an expression can be evaluated in any order in C++, whereas they are always evaluated from left to right in C#. Similarly, in C++ an implementation may legally perform the side effects of increments and decrements in any order. For example, in C++ a call of the form `M(x++, x++)`, where `x` begins as `1`, can legally call either `M(1,2)` or `M(2,1)` at the whim of the compiler. In contrast, C# will always call `M(1,2)` because C# makes two guarantees: (1) The arguments to a call are always computed from left to right, and (2) the assignment of the incremented value to the variable always happens before the value of the expression is used. C++ makes neither guarantee.

Guidelines

AVOID confusing usage of the increment and decrement operators.

DO be cautious when porting code between C, C++, and C# that uses increment and decrement operators; C and C++ implementations need not follow the same rules as C#.

ADVANCED TOPIC

Thread-Safe Incrementing and Decrementing

In spite of the brevity of the increment and decrement operators, these operators are not atomic. A thread context switch can occur during the execution of the operator and can cause a race condition. You could use a `lock` statement to prevent the race condition. However, for simple increments and decrements, a less expensive alternative is to use the thread-safe `Increment()` and `Decrement()` methods from the `System.Threading.Interlocked` class. These methods rely on processor functions for performing fast thread-safe increments and decrements. See Chapter 19 for more details.

Constant Expressions and Constant Locals

The preceding chapter discussed literal values, or values embedded directly into the code. It is possible to combine multiple literal values in a **constant expression** using operators. By definition, a constant expression is one that the C# compiler can evaluate at compile time (instead of evaluating it when the program runs) because it is composed entirely of constant operands. Constant expressions can then be used to initialize constant locals, which allow you to give a name to a constant value (similar to the way local variables allow you to give a name to a storage location). For example, the computation of the number of seconds in a day can be a constant expression that is then used in other expressions by name.

The `const` keyword in Listing 3.19 declares a constant local. Since a constant local is by definition the opposite of a **variable**—"constant" means "not able to vary"—any attempt to modify the value later in the code would result in a compile-time error.

Guidelines

DO NOT use a constant for any value that can possibly change over time. The value of pi and the number of protons in an atom of gold are constants; the price of gold, the name of your company, and the version number of your program can change.

Note that the expression assigned to `secondsPerWeek` in Listing 3.19 is a constant expression because all the operands in the expression are also constants.

Listing 3.19: Declaring a Constant

```
// ...
public long Main()
{                                     Constant Expression
    const int secondsPerDay = 60 * 60 * 24;
    const int secondsPerWeek = secondsPerDay * 7;
                   Constant
    // ...
}
```

Introducing Flow Control

Later in this chapter is a code listing (Listing 3.45) that shows a simple way to view a number in its binary form. Even such a simple program, however, cannot be written without using control flow statements. Such statements control the execution path of the program. This section discusses how to change the order of statement execution based on conditional checks. Later on, you will learn how to execute statement groups repeatedly through loop constructs.

A summary of the control flow statements appears in Table 3.1. Note that the General Syntax Structure column indicates common statement use, not the complete lexical structure. An `embedded-statement` in Table 3.1 may be any statement other than a labeled statement or a declaration, but it is typically a block statement.

Each C# control flow statement in Table 3.1 appears in the tic-tac-toe[3] program and is available in Appendix B and for download with the rest of the source code listings from the book. The program displays the tic-tac-toe board, prompts each player, and updates with each move.

The remainder of this chapter looks at each statement in more detail. After covering the `if` statement, it introduces code blocks, scope, Boolean expressions, and bitwise operators before continuing with the remaining control flow statements. Readers who find Table 3.1 familiar because of C#'s similarities to other languages can jump ahead to the section titled "C# Preprocessor Directives" or skip to the "Summary" section at the end of the chapter.

3. Known as noughts and crosses to readers outside the United States.

Table 3.1: Control Flow Statements

Statement	General Syntax Structure	Example

`if` statement	`if(boolean-expression)`
	`  embedded-statement`
		`if (input == "quit")`
		`{`
		`  System.Console.WriteLine(`
		`    "Game end");`
		`  return;`
		`}`

	`if(boolean-expression)`
	`  embedded-statement`
	`else`
	`  embedded-statement`
		`if (input == "quit")`
		`{`
		`  System.Console.WriteLine(`
		`    "Game end");`
		`  return;`
		`}`
		`else`
		`  GetNextMove();`

`while` statement	`while(boolean-expression)`
	`  embedded-statement`
		`while(count < total)`
		`{`
		`  System.Console.WriteLine(`
		`    "count = {count}");`
		`  count++;`
		`}`

`do while` statement	`do`
	`  embedded-statement while(boolean-expression);`
		`do`
		`{`
		`  System.Console.WriteLine(`
		`    "Enter name:");`
		`  input =`
		`    System.Console.ReadLine();`
		`}`
		`while(input != "exit");`

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Table 3.1: Control Flow Statements, (*continued*)

Statement	General Syntax Structure	Example

for statement	for(*for-initializer;*
	    boolean-expression;
	    for-iterator)
	  embedded-statement
		for (int count = 1;
		  count <= 10;
		  count++)
		{
		  System.Console.WriteLine(
		    $"count = {count}");
		}

foreach statement	foreach(*type identifier* in
	     expression)
	  embedded-statement
		foreach (char letter in email)
		{
		  if(!insideDomain)
		  {
		    if (letter == '@')
		    {
		      insideDomain = true;
		    }
		    continue;
		  }
		  System.Console.Write(
		    letter);
		}

continue statement	continue;	

continues

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TABLE 3.1: Control Flow Statements, (*continued*)

Statement	General Syntax Structure	Example

`switch` statement	`switch(governing-type-`*`expression`*`)`
	`{`
	`  ...`
	`  case const-expression:`
	`    statement-list`
	`    jump-statement`
	`  default:`
	`    statement-list`
	`    jump-statement`
	`}`
		`switch(input)`
		`{`
		`  case "exit":`
		`  case "quit":`
		`    System.Console.WriteLine(`
		`      "Exiting app....");`
		`    break;`
		`  case "restart":`
		`    Reset();`
		`    goto case "start";`
		`  case "start":`
		`     GetMove();`
		`     break;`
		`  default:`
		`    System.Console.WriteLine(`
		`      input);`
		`    break;`
		`}`

`break` statement	`break;`	
`goto` statement	`goto` *`identifier`*`;`	
	`goto case` *`const-expression`*`;`	
	`goto default;`	

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`if` Statement

The `if` statement is one of the most common statements in C#. It evaluates a **Boolean expression** (an expression that results in either `true` or `false`) called the **condition.** If the condition is `true`, the **consequence statement** is executed. An `if` statement may optionally have an `else` clause that contains an **alternative statement** to be executed if the condition is `false`. The general form is as follows:

```
if (condition)
  consequence-statement
else
  alternative-statement
```

Listing 3.20: `if/else` Statement Example

```
class TicTacToe      // Declares the TicTacToe class.
{
  static void Main() // Declares the entry point of the program.
  {
      string input;

      // Prompt the user to select a 1- or 2-player game.
      System.Console.Write(
          "1 – Play against the computer\n" +
          "2 – Play against another player.\n" +
          "Choose:"
      );
      input = System.Console.ReadLine();

      if(input=="1")
          // The user selected to play the computer.
          System.Console.WriteLine(
              "Play against computer selected.");
      else
          // Default to 2 players (even if user didn't enter 2).
          System.Console.WriteLine(
              "Play against another player.");
  }
}
```

In Listing 3.20, if the user enters `1`, the program displays `"Play against computer selected."` Otherwise, it displays `"Play against another player."`

Nested `if`

Sometimes code requires multiple `if` statements. The code in Listing 3.21 first determines whether the user has chosen to exit by entering a number less than or equal to `0`; if not, it checks whether the user knows the maximum number of turns in tic-tac-toe.

LISTING 3.21: Nested `if` Statements

```
class TicTacToeTrivia
{
  static void Main()
  {
      int input;    // Declare a variable to store the input.

      System.Console.Write(
          "What is the maximum number " +
          "of turns in tic-tac-toe?" +
          "(Enter 0 to exit.): ");

      // int.Parse() converts the ReadLine()
      // return to an int data type.
      input = int.Parse(System.Console.ReadLine());

      if (input <= 0) // line 16
              // Input is less than or equal to 0.
          System.Console.WriteLine("Exiting...");
      else
          if (input < 9)  // line 20
              // Input is less than 9.
              System.Console.WriteLine(
                  $"Tic-tac-toe has more than {input}" +
                  " maximum turns.");
          else
              if(input > 9) // line 26
                  // Input is greater than 9.
                  System.Console.WriteLine(
                      $"Tic-tac-toe has fewer than {input}" +
                      " maximum turns.");
              else
                  // Input equals 9.
                  System.Console.WriteLine( // line 33
                      "Correct, tic-tac-toe " +
                      "has a maximum of 9 turns.");
  }
}
```

Output 3.13 shows the results of Listing 3.21.

OUTPUT 3.13

```
What is the maximum number of turns in tic-tac-toe? (Enter 0 to exit.): 9
Correct, tic-tac-toe has a maximum of 9 turns.
```

Assume the user enters `9` when prompted at line 14. Here is the execution path:

1. *Line 16:* Check if input is less than 0. Since it is not, jump to line 20.
2. *Line 20:* Check if input is less than 9. Since it is not, jump to line 26.
3. *Line 26:* Check if input is greater than 9. Since it is not, jump to line 33.
4. *Line 33:* Display that the answer was correct.

Listing 3.21 contains nested `if` statements. To clarify the nesting, the lines are indented. However, as you learned in Chapter 1, whitespace does not affect the execution path. If this code was written without the indenting and without the newlines, the execution would be the same. The code that appears in the nested `if` statement in Listing 3.22 is equivalent to Listing 3.21.

LISTING 3.22: `if/else` Formatted Sequentially

```
if (input < 0)
  System.Console.WriteLine("Exiting...");
else if (input < 9)
  System.Console.WriteLine(
      $"Tic-tac-toe has more than {input}" +
      " maximum turns.");
else if(input < 9)
  System.Console.WriteLine(
      $"Tic-tac-toe has less than {input}" +
      " maximum turns.");
else
  System.Console.WriteLine(
      "Correct, tic-tac-toe has a maximum " +
      " of 9 turns.");
```

Although the latter format is more common, in each situation you should use the format that results in the clearest code.

Both of the `if` statement listings omit the braces. However, as discussed next, this is not in accordance with the guidelines, which advocate the use of code blocks except, perhaps, in the simplest of single-line scenarios.

Code Blocks ({})

In the previous `if` statement examples, only one statement follows `if` and `else`: a single `System.Console.WriteLine()`, similar to Listing 3.23.

Listing 3.23: `if` Statement with No Code Block

```
if(input < 9)
  System.Console.WriteLine("Exiting");
```

With curly braces, however, we can combine statements into a single statement called a **block statement** or **code block,** allowing the grouping of multiple statements into a single statement that is the consequence. Take, for example, the highlighted code block in the radius calculation in Listing 3.24.

Listing 3.24: `if` Statement Followed by a Code Block

```
class CircleAreaCalculator
{
  static void Main()
  {
      double radius;  // Declare a variable to store the radius.
      double area;    // Declare a variable to store the area.

      System.Console.Write("Enter the radius of the circle: ");

      // double.Parse converts the ReadLine()
      // return to a double.
      radius = double.Parse(System.Console.ReadLine());
      if(radius >= 0)
      {
          // Calculate the area of the circle.
          area = Math.PI * radius * radius;
          System.Console.WriteLine(
              $"The area of the circle is: { area : 0.00 }");
      }
      else
      {
          System.Console.WriteLine(
              $"{ radius } is not a valid radius.");
      }
  }
}
```

Output 3.14 shows the results of Listing 3.24.

OUTPUT 3.14

```
Enter the radius of the circle: 3
The area of the circle is: 28.27
```

In this example, the `if` statement checks whether the `radius` is positive. If so, the area of the circle is calculated and displayed; otherwise, an invalid radius message is displayed.

Notice that in this example, two statements follow the first `if`. However, these two statements appear within curly braces. The curly braces combine the statements into a **code block, which is itself a single statement.**

If you omit the curly braces that create a code block in Listing 3.24, only the statement immediately following the Boolean expression executes conditionally. Subsequent statements will execute regardless of the `if` statement's Boolean expression. The invalid code is shown in Listing 3.25.

LISTING 3.25: Relying on Indentation, Resulting in Invalid Code

```
if(radius >= 0)
  area = Math.PI * radius *radius;
  System.Console.WriteLine(
      $"The area of the circle is: { area:0.00}");
```

In C#, indentation is used solely to enhance the code readability. The compiler ignores it, so the previous code is semantically equivalent to Listing 3.26.

LISTING 3.26: Semantically Equivalent to Listing 3.25

```
if(radius >= 0)
{
  area = Math.PI * radius * radius;
}
System.Console.WriteLine(
    $"The area of the circle is:{ area:0.00}");
```

Programmers should take great care to avoid subtle bugs such as this, perhaps even going so far as to always include a code block after a control flow statement, even if there is only one statement. A widely accepted coding guideline is to avoid omitting braces, except possibly for the simplest of single-line `if` statements.

Although unusual, it is possible to have a code block that is not lexically a direct part of a control flow statement. In other words, placing curly braces on their own (without a conditional or loop, for example) is legal syntax.

In Listing 3.25 and Listing 3.26, the value of pi was represented by the `PI` constant in the `System.Math` class. Instead of hardcoding a value, such as 3.14 for constants such as pi and Euler's constant (e), code should use `System.Math.PI` and `System.Math.E`.

Guidelines

AVOID omitting braces, except for the simplest of single-line `if` statements.

Code Blocks, Scopes, and Declaration Spaces

Code blocks are often referred to as "scopes," but the two terms are not exactly interchangeable. The **scope** of a named thing is the region of source code in which it is legal to refer to the thing by its unqualified name. The scope of a local variable, for example, is exactly the text of the code block that encloses it, which explains why it is common to refer to code blocks as "scopes."

Scopes are often confused with declaration spaces. A **declaration space** is a logical container of named things in which two things may not have the same name. A code block defines not only a scope, but also a local variable declaration space. It is illegal for two local variable declarations with the same name to appear in the same declaration space. Similarly, it is not possible to declare two methods with the signature of `Main()` within the same class. (This rule is relaxed somewhat for methods: Two methods may have the same name in a declaration space provided that they have different signatures. The signature of a method includes its name and the number and types of its parameters.) Within a block, a local variable can be mentioned by name and must be the unique thing that is declared with that name in the block. Outside the declaring block, there is no way to refer to a local variable by its name; the local variable is said to be "out of scope" outside the block.

In summary, a scope is used to determine what thing a name refers to; a declaration space determines when two things declared with the same name conflict with each other. In Listing 3.27, declaring the local variable `message` inside the block statement embedded in the `if` statement restricts its scope to the block statement only; the local variable is "out of scope" when its name is used later on in the method. To avoid an error, you must declare the variable outside the block.

Listing 3.27: Variables Inaccessible outside Their Scope

```
class Program
{
   static void Main(string[] args)
   {
       int playerCount;
       System.Console.Write(
           "Enter the number of players (1 or 2):");
       playerCount = int.Parse(System.Console.ReadLine());
       if (playerCount != 1 && playerCount != 2)
       {
           string message =
               "You entered an invalid number of players.";
       }
       else
       {
           // ...
       }
       // Error:  message is not in scope.
       System.Console.WriteLine(message);
  }
}
```

Output 3.15 shows the results of Listing 3.27.

Output 3.15

```
...
...\Program.cs(18,26): error CS0103: The name 'message' does not exist
in the current context
```

The declaration space in which a local variable's name must be unique encompasses all the child code blocks textually enclosed within the block that originally declared the local. The C# compiler prevents the name of a local variable declared immediately within a method code block (or as a parameter) from being reused within a child code block. In Listing 3.27, because `args` and `playerCount` are declared within the method code block, they cannot be declared again anywhere within the method.

The name `message` refers to this local variable throughout the scope of the local variable—that is, the block immediately enclosing the declaration. Similarly, `playerCount` refers to the same variable throughout the block containing the declaration, including within both of the child blocks that are the consequence and the alternative of the `if` statement.

Language Contrast: C++—Local Variable Scope

In C++, a local variable declared in a block is in scope from the point of the declaration statement through the end of the block. Thus an attempt to refer to the local variable before its declaration will fail to find the local variable because that variable is not in scope. If there is another thing with that name "in scope," the C++ language will resolve the name to that thing, which might not be what you intended. In C#, the rule is subtly different: A local variable is in scope throughout the entire block in which it is declared, but it is illegal to refer to the local variable before its declaration. That is, the attempt to find the local variable will succeed, and the usage will then be treated as an error. This is just one of C#'s many rules that attempt to prevent errors common in C++ programs.

Boolean Expressions

The parenthesized condition of the `if` statement is a **Boolean expression.** In Listing 3.28, the condition is highlighted.

Listing 3.28: Boolean Expression

```
if (input < 9)
{
    // Input is less than 9.
    System.Console.WriteLine(
        $"Tic-tac-toe has more than { input }" +
         " maximum turns.");
}
// ...
```

Boolean expressions appear within many control flow statements. Their key characteristic is that they always evaluate to `true` or `false`. For `input < 9` to be allowed as a Boolean expression, it must result in a `bool`. The compiler disallows `x = 42`, for example, because this expression assigns `x` and results in the value that was assigned, instead of checking whether the value of the variable is `42`.

Language Contrast: C++—Mistakenly Using = in Place of ==

C# eliminates a coding error commonly found in C and C++. In C++, Listing 3.29 is allowed.

Listing 3.29: C++, But Not C#, Allows Assignment As a Condition

```
if (input = 9)    // Allowed in C++, not in C#.
  System.Console.WriteLine(
      "Correct, tic-tac-toe has a maximum of 9 turns.");
```

Although at first glance this code appears to check whether `input` equals `9`, Chapter 1 showed that `=` represents the assignment operator, not a check for equality. The return from the assignment operator is the value assigned to the variable—in this case, `9`. However, `9` is an `int`, and as such it does not qualify as a Boolean expression and is not allowed by the C# compiler. The C and C++ languages treat integers that are nonzero as `true`, and integers that are zero as `false`. C#, by contrast, requires that the condition actually be of a Boolean type; integers are not allowed.

Relational and Equality Operators

Relational and **equality** operators determine whether a value is greater than, less than, or equal to another value. Table 3.2 lists all the relational and equality operators. All are binary operators.

The C# syntax for equality uses `==`, just as many other programming languages do. For example, to determine whether `input` equals `9`, you use `input == 9`. The equality operator uses two equal signs to distinguish it from the assignment operator, `=`. The exclamation point signifies NOT in C#, so to test for inequality you use the inequality operator, `!=`.

TABLE 3.2: Relational and Equality Operators

Operator	Description	Example
`<`	Less than	`input<9;`
`>`	Greater than	`input>9;`
`<=`	Less than or equal to	`input<=9;`
`>=`	Greater than or equal to	`input>=9;`
`==`	Equality operator	`input==9;`
`!=`	Inequality operator	`input!=9;`

Relational and equality operators always produce a `bool` value, as shown in Listing 3.30.

LISTING 3.30: Assigning the Result of a Relational Operator to a `bool` Variable

```
bool result = 70 > 7;
```

In the tic-tac-toe program (see Appendix B), you use the equality operator to determine whether a user has quit. The Boolean expression of Listing 3.31 includes an OR (`||`) logical operator, which the next section discusses in detail.

LISTING 3.31: Using the Equality Operator in a Boolean Expression

```
if (input == "" || input == "quit")
{
  System.Console.WriteLine($"Player {currentPlayer} quit!!");
  break;
}
```

Logical Boolean Operators

The **logical operators** have Boolean operands and produce a Boolean result. Logical operators allow you to combine multiple Boolean expressions to form more complex Boolean expressions. The logical operators are `|`, `||`, `&`, `&&`, and `^`, corresponding to OR, AND, and exclusive OR. The `|` and `&` versions of OR and AND are rarely used for Boolean logic, for reasons which we discuss in this section.

OR Operator (||)

In Listing 3.31, if the user enters `quit` or presses the Enter key without typing in a value, it is assumed that she wants to exit the program. To enable two ways for the user to resign, you can use the logical OR operator, `||`. The `||` operator evaluates Boolean expressions and results in a `true` value if *either* operand is `true` (see Listing 3.32).

LISTING 3.32: Using the OR Operator

```
if ((hourOfTheDay > 23) || (hourOfTheDay < 0))
  System.Console.WriteLine("The time you entered is invalid.");
```

It is not necessary to evaluate both sides of an OR expression, because if either operand is `true`, the result is known to be `true` regardless of the value of the other operand. Like all operators in C#, the left operand is evaluated before the right one, so if the left portion of the expression evaluates to `true`, the right portion is ignored. In the example in Listing 3.32, if `hourOfTheDay` has the value `33`, then `(hourOfTheDay > 23)` will evaluate to `true` and the OR operator will ignore the second half of the expression, **short-circuiting** it. Short-circuiting an expression also occurs with the Boolean AND operator. (Note that the parentheses are not necessary here; the logical operators are of higher precedence than the relational operators. However, it is clearer to the novice reader to parenthesize the subexpressions for clarity.)

AND Operator (&&)

The Boolean AND operator, `&&`, evaluates to `true` only if both operands evaluate to `true`. If either operand is `false`, the result will be `false`. Listing 3.33 writes a message if the given variable is both greater than 10 and less than 24.[4] Similarly to the OR operator, the AND operator will not always evaluate the right side of the expression. If the left operand is determined to be `false`, the overall result will be `false` regardless of the value of the right operand, so the runtime skips evaluating the right operand.

LISTING 3.33: Using the AND Operator

```
if ((10 < hourOfTheDay) && (hourOfTheDay < 24))
  System.Console.WriteLine(
  "Hi-Ho, Hi-Ho, it's off to work we go.");
```

4. The typical hours that programmers work each day.

Exclusive OR Operator (^)

The caret symbol, `^`, is the "exclusive OR" (XOR) operator. When applied to two Boolean operands, the XOR operator returns `true` only if exactly one of the operands is true, as shown in Table 3.3.

TABLE 3.3: Conditional Values for the XOR Operator

Left Operand	Right Operand	Result
True	True	False
True	False	True
False	True	True
False	False	False

Unlike the Boolean AND and Boolean OR operators, the Boolean XOR operator does not short-circuit: It always checks both operands, because the result cannot be determined unless the values of both operands are known. Note that the XOR operator is exactly the same as the Boolean inequality operator.

Logical Negation Operator (!)

The **logical negation operator, or NOT operator,** `!`, inverts a `bool` value. This operator is a unary operator, meaning it requires only one operand. Listing 3.34 demonstrates how it works, and Output 3.16 shows the result.

LISTING 3.34: Using the Logical Negation Operator

```
bool valid = false;
bool result = !valid;
// Displays "result = True".
System.Console.WriteLine($"result = { result }");
```

OUTPUT 3.16

```
result = True
```

At the beginning of Listing 3.34, `valid` is set to `false`. You then use the negation operator on `valid` and assign the value to `result`.

Conditional Operator (? :)

In place of an `if-else` statement used to select one of two values, you can use the **conditional** operator. The conditional operator uses both a question mark and a colon; the general format is as follows:

```
condition ? consequence : alternative
```

The conditional operator is a "ternary" operator because it has three operands: `condition`, `consequence`, and `alternative`. (As it is the only ternary operator in C#, it is often called "the ternary operator," but it is clearer to refer to it by its name than by the number of operands it takes.) Like the logical operators, the conditional operator uses a form of short-circuiting. If the condition evaluates to `true`, the conditional operator evaluates only `consequence`. If the conditional evaluates to `false`, it evaluates only `alternative`. The result of the operator is the evaluated expression.

Listing 3.35 illustrates the use of the conditional operator. The full listing of this program appears in Appendix B.

Listing 3.35: Conditional Operator

```
class TicTacToe
{
  static string Main()
  {
      // Initially set the currentPlayer to Player 1
      int currentPlayer = 1;

      // ...

      for (int turn = 1; turn <= 10; turn++)
      {
         // ...

         // Switch players
         currentPlayer = (currentPlayer == 2) ? 1 : 2;
      }
  }
}
```

The program swaps the current player. To do so, it checks whether the current value is `2`. This is the "conditional" portion of the conditional expression. If the result of the condition is `true`, the conditional operator results in the "consequence" value `1`. Otherwise, it results in the "alternative" value 2. Unlike an `if` statement, the result of the conditional operator must be assigned (or passed as a parameter); it cannot appear as an entire statement on its own.

Guidelines

CONSIDER using an `if/else` statement instead of an overly complicated conditional expression.

The C# language requires that the consequence and alternative expressions in a conditional operator be typed consistently, and that the consistent type be determined without examination of the surrounding context of the expression. For example, `f ? "abc" : 123` is not a legal conditional expression because the consequence and alternative are a string and a number, neither of which is convertible to the other. Even if you say `object result = f ? "abc" : 123;` the C# compiler will flag this expression as illegal because the type that is consistent with both expressions (that is, `object`) is found outside the conditional expression.

Begin 2.0

Null-Coalescing Operator (??)

The **null-coalescing operator** is a concise way to express "If this value is null, then use this other value." It has the following form:

`expression1` `??` *`expression2`*

The null-coalescing operator also uses a form of short-circuiting. If `expression1` is not null, its value is the result of the operation and the other expression is not evaluated. If `expression1` does evaluate to null, the value of `expression2` is the result of the operator. Unlike the conditional operator, the null-coalescing operator is a binary operator.

Listing 3.36 illustrates the use of the null-coalescing operator.

LISTING 3.36: Null-Coalescing Operator

```
string fileName = GetFileName();
// ...
string fullName = fileName ?? "default.txt";
// ...
```

In this listing, we use the null-coalescing operator to set `fullName` to `"default.txt"` if `fileName` is null. If `fileName` is not null, `fullName` is simply assigned the value of `fileName`.

The null-coalescing operator "chains" nicely. For example, an expression of the form `x ?? y ?? z` results in `x` if `x` is not null; otherwise, it results in `y` if `y` is not null; otherwise, it results in `z`. That is, it goes from left to right and picks out the first non-null expression, or uses the last expression if all the previous expressions were null.

The null-coalescing operator was added to C# in version 2.0, along with nullable value types. This operator works on both operands of nullable value types and reference types.

End 2.0

Null-Conditional Operator (`?.`)

Begin 6.0

Whenever you invoke a method on a value that is null, the runtime will throw a `System.NullReferenceException`, which almost always indicates an error in the programming logic. In recognition of the frequency of this pattern (that is, checking for null before invoking a member), C# 6.0 introduces the "?." operator, known as the null-conditional operator:

Listing 3.37: Null-Conditional Operator

```
class Program
{
  static void Main(string[] args)
  {
      if (args?.Length == 0)
      {
          System.Console.WriteLine(
              "ERROR: File missing. "
              + "Use:\n\tfind.exe file:<filename>");
      }
      else
      {
          if (args[0]?.ToLower().StartsWith("file:")??false)
          {
              string fileName = args[0]?.Remove(0, 5);
              // ...
          }
      }
  }
}
```

The null-conditional operator checks whether the operand (the first `args` in Listing 3.37) is null prior to invoking the method or property (`Length` in the first example in this listing). The logically equivalent explicit code would be the following (although in the C# 6.0 syntax the value of `args` is

6.0 evaluated only once):

```
(args != null) ? (int?)args.Length : null
```

What makes the null-conditional operator especially convenient is that it can be chained. If, for example, you invoke `args[0]?.ToLower().StartsWith("file:")`, both `ToLower()` and `StartsWith()` will be invoked only if `args[0]` is not null. When expressions are chained, if the first operand is null, the expression evaluation is short-circuited, and no further invocation within the expression call chain will occur.

Be careful, however, that you don't unintentionally neglect additional null-conditional operators. Consider, for example, what would happen if (hypothetically, in this case) `args[0]?.ToLower()` could also return null. In this scenario, a `NullReferenceException` would occur upon invocation of `StartsWith()`. This doesn't mean you must use a chain of null-conditional operators, but rather that you should be intentional about the logic. In this example, because `ToLower()` can never be null, no additional null-conditional operator is necessary.

An important thing to note about the null-conditional operator is that, when utilized with a member that returns a value type, it always returns a nullable version of that type. For example, `args?.Length` returns an `int?`, not simply an `int`. Similarly, `args[0]?.ToLower().StartsWith("file:")` returns a `bool?` (a `Nullable<bool>`). Also, because an `if` statement requires a `bool` data type, it is necessary to follow the `StartsWith()` expression with the null-coalescing operator (`??`).

Although perhaps a little peculiar (in comparison to other operator behavior), the return of a nullable value type is produced only at the end of the call chain. Consequently, calling the dot (".") operator on `Length` allows invocation of only `int` (not `int?`) members. However, encapsulating `args?.Length` in parentheses—thereby forcing the `int?` result via parentheses operator precedence—will invoke the `int?` return and make the `Nullable<T>` specific members (`HasValue` and `Value`) available.

Null-conditional operators can also be used in combination with an index operator, as shown in Listing 3.38.

LISTING 3.38: Null-Conditional Operator with Index Operator

```
class Program
{
  public static void Main(string[] args)
  {
      // CAUTION: args?.Length not verified.
      string directoryPath = args?[0];
      string searchPattern = args?[1];
      // ...
  }
}
```

6.0

In this listing, the first and second elements of `args` are assigned to their respective variables only if `args` is not null. If it is, null will be assigned instead.

Unfortunately, this example is naïve, if not dangerous, because the null-conditional operator gives a false sense of security, implying that if `args` isn't null, then the element must exist. Of course, this isn't the case: The element may not exist even if `args` isn't null. Also, because checking for the element count with `args?.Length` verifies that `args` isn't null, you never really need to use the null-conditional operator when indexing the collection after checking the length.

In conclusion, you should avoid using the null-conditional operator in combination with the index operator if the index operator throws an `IndexOutOfRangeException` for nonexistent indexes. Doing so leads to a false sense of code validity.

ADVANCED TOPIC

Leveraging the Null-Conditional Operator with Delegates

The null-conditional operator is a great feature on its own. However, using it in combination with a delegate invocation resolves a C# pain point that has existed since C# 1.0. Notice in the code near the top of the next page how the `PropertyChange` event handler is assigned to a local copy (`propertyChanged`) before we check the value for null and finally fire the event. This is the easiest thread-safe way to invoke events without running the risk that an event unsubscribe will occur between the time when the check for null occurs and the time when the event is fired. Unfortunately, this approach is non-intuitive, and frequently code neglects to follow this pattern—with the result of throwing inconsistent `NullReferenceExceptions`. Fortunately, with the introduction of the null-conditional operator in C# 6.0, this issue has been resolved.

With C# 6.0, the check for a delegate value changes from

```
PropertyChangedEventHandler propertyChanged =
  PropertyChanged;
if (propertyChanged != null)
{
  propertyChanged(this,
      new PropertyChangedEventArgs(nameof(Name)));
}
```

to simply

```
PropertyChanged?.Invoke(propertyChanged(
  this, new PropertyChangedEventArgs(nameof(Name)));
```

End 6.0

Because an event is just a delegate, the pattern of invoking a delegate via the null-conditional operator and an `Invoke()` is always possible.

Bitwise Operators (<<, >>, |, &, ^, ~)

An additional set of operators that is common to virtually all programming languages is the set of operators for manipulating values in their binary formats: the bit operators.

BEGINNER TOPIC

Bits and Bytes

All values within a computer are represented in a binary format of 1s and 0s, called **binary digits** (**bits**). Bits are grouped together in sets of eight, called **bytes**. In a byte, each successive bit corresponds to a value of 2 raised to a power, starting from 2^0 on the right and moving to 2^7 on the left, as shown in Figure 3.1.

0	0	0	0	0	0	0	0
2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0

FIGURE 3.1: Corresponding Placeholder Values

In many scenarios, particularly when dealing with low-level or system services, information is retrieved as binary data. To manipulate these devices and services, you need to perform manipulations of binary data.

In Figure 3.2, each box corresponds to a value of 2 raised to the power shown. The value of the byte (8-bit number) is the sum of the powers of 2 of all of the eight bits that are set to 1.

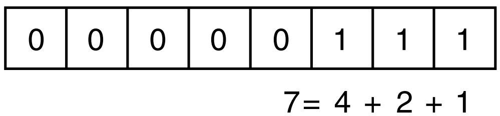


FIGURE 3.2: Calculating the Value of an Unsigned Byte

The binary translation just described is significantly different for signed numbers. Signed numbers (`long`, `short`, `int`) are represented using a "two's complement" notation. This practice ensures that addition continues to work when adding a negative number to a positive number, as though both were positive operands. With this notation, negative numbers behave differently from positive numbers. Negative numbers are identified by a 1 in the leftmost location. If the leftmost location contains a 1, you add the locations with 0s rather than the locations with 1s. Each location corresponds to the negative power of 2 value. Furthermore, from the result, it is also necessary to subtract 1. This is demonstrated in Figure 3.3.

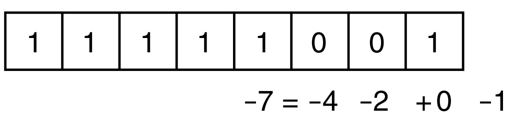


FIGURE 3.3: Calculating the Value of a Signed Byte

Therefore, `1111 1111 1111 1111` corresponds to –1, and `1111 1111 1111 1001` holds the value –7. The binary representation `1000 0000 0000 0000` corresponds to the lowest negative value that a 16-bit integer can hold.

Shift Operators (<<, >>, <<=, >>=)

Sometimes you want to shift the binary value of a number to the right or left. In executing a left shift, all bits in a number's binary representation are shifted to the left by the number of locations specified by the operand on the right of the shift operator. Zeroes are then used to backfill the locations on the right side of the binary number. A right-shift operator does almost the same thing in the opposite direction. However, if the number is a negative value of a signed type, the values used to backfill the left side of the binary number are 1s and not 0s. The shift operators are `>>` and `<<`, known as the right-shift and left-shift operators, respectively. In addition, there are combined shift and assignment operators, `<<=` and `>>=`.

Consider the following example. Suppose you had the `int` value `-7`, which would have a binary representation of `1111 1111 1111 1111 1111 1111 1111 1001`. In Listing 3.39, you right-shift the binary representation of the number –7 by two locations.

Listing 3.39: Using the Right-Shift Operator

```
int x;
x = (-7 >> 2); // 11111111111111111111111111111001 becomes
               // 11111111111111111111111111111110
// Write out "x is -2."
System.Console.WriteLine($"x = { x }.");
```

Output 3.17 shows the results of Listing 3.39.

Output 3.17

```
x = -2.
```

Because of the right shift, the value of the bit in the rightmost location has "dropped off" the edge and the negative bit indicator on the left shifts by two locations to be replaced with 1s. The result is `-2`.

Although legend has it that `x << 2` is faster than `x * 4`, you should not use bit-shift operators for multiplication or division. This difference might have held true for certain C compilers in the 1970s, but modern compilers and modern microprocessors are perfectly capable of optimizing arithmetic. Using shifting for multiplication or division is confusing and frequently leads to errors when code maintainers forget that the shift operators are lower precedence than the arithmetic operators.

Bitwise Operators (&, |, ^)

In some instances, you might need to perform logical operations, such as AND, OR, and XOR, on a bit-by-bit basis for two operands. You do this via the `&`, `|`, and `^` operators, respectively.

BEGINNER TOPIC

Logical Operators Explained

If you have two numbers, as shown in Figure 3.4, the bitwise operations will compare the values of the locations beginning at the leftmost significant value and continuing right until the end. The value of "1" in a location is treated as "true," and the value of "0" in a location is treated as "false."

12:	0	0	0	0	1	1	0	0
7:	0	0	0	0	0	1	1	1

FIGURE 3.4: The Numbers 12 and 7 Represented in Binary

Therefore, the bitwise AND of the two values in Figure 3.4 would entail the bit-by-bit comparison of bits in the first operand (12) with the bits in the second operand (7), resulting in the binary value `000000100`, which is 4. Alternatively, a bitwise OR of the two values would produce `00001111`, the binary equivalent of 15. The XOR result would be `00001011`, or decimal 11.

Listing 3.40 demonstrates the use of these bitwise operators. The results of Listing 3.40 appear in Output 3.18.

LISTING 3.40: Using Bitwise Operators

```
byte and, or, xor;
and = 12 & 7;   // and = 4
or = 12 | 7;    // or = 15
xor = 12 ^ 7;   // xor = 11
System.Console.WriteLine(
    $"and = { and } \nor = { or }\nxor = { xor }");
```

OUTPUT 3.18

```
and = 4
or = 15
xor = 11
```

In Listing 3.40, the value 7 is the **mask**; it is used to expose or eliminate specific bits within the first operand using the particular operator expression. Note that, unlike the AND (&&) operator, the & operator always evaluates *both* sides even if the left portion is false. Similarly, the | version of the OR operator is *not* "short-circuiting." It always evaluates both operands even if the left operand is true. The bit versions of the AND and OR operators, therefore, are not short-circuiting.

To convert a number to its binary representation, you need to iterate across each bit in a number. Listing 3.41 is an example of a program that converts an integer to a string of its binary representation. The results of Listing 3.41 appear in Output 3.19.

LISTING 3.41: Getting a String Representation of a Binary Display

```
class BinaryConverter
{
  static void Main()
  {
      const int size = 64;
      ulong value;
      char bit;

      System.Console.Write ("Enter an integer: ");
      // Use long.Parse()to support negative numbers
      // Assumes unchecked assignment to ulong.
      value = (ulong)long.Parse(System.Console.ReadLine());

      // Set initial mask to 100...
      ulong mask = 1UL << size - 1;
      for (int count = 0; count < size; count++)
      {
          bit = ((mask & value) != 0) ? '1': '0';
          System.Console.Write(bit);
          // Shift mask one location over to the right
          mask >>= 1;
      }
      System.Console.WriteLine();
  }
}
```

Output 3.19

```
Enter an integer: 42
0000000000000000000000000000000000000000000000000000000000101010
```

Within each iteration of the `for` loop in Listing 3.41 (as discussed later in this chapter), we use the right-shift assignment operator to create a mask corresponding to each bit position in `value`. By using the `&` bit operator to mask a particular bit, we can determine whether the bit is set. If the mask test produces a nonzero result, we write `1` to the console; otherwise, we write `0`. In this way, 23 create output describing the binary value of an unsigned `long`.

Note also that the parentheses in `(mask & value) != 0` are necessary because inequality is higher precedence than the AND operator. Without the explicit parentheses, this expression would be equivalent to `mask & (value != 0)`, which does not make any sense; the left side of the `&` is a `ulong` and the right side is a `bool`.

This particular example is provided for learning purposes only. There is actually a built-in CLR method, `System.Convert.ToString(value, 2)` that does such a conversion. In fact, the second argument specifies the base (for example, 2 for binary, 10 for decimal, or 16 for hexadecimal), allowing for more than just conversion to binary.

Bitwise Compound Assignment Operators (&=, |=, ^=)

Not surprisingly, you can combine these bitwise operators with assignment operators as follows: `&=`, `|=`, and `^=`. As a result, you could take a variable, OR it with a number, and assign the result back to the original variable, which Listing 3.42 demonstrates.

Listing 3.42: Using Logical Assignment Operators

```
byte and = 12, or = 12, xor = 12;
and &= 7;   // and = 4
or  |= 7;   // or = 15
xor ^= 7;   // xor = 11
System.Console.WriteLine(
    $"and = { and } \nor = { or }\nxor = { xor }");
```

The results of Listing 3.42 appear in Output 3.20.

OUTPUT 3.20

```
and = 4
or = 15
xor = 11
```

Combining a bitmap with a mask using something like `fields &= mask` clears the bits in `fields` that are not set in the `mask`. The opposite, `fields &= ~mask`, clears out the bits in `fields` that are set in `mask`.

Bitwise Complement Operator (~)

The **bitwise complement operator** takes the complement of each bit in the operand, where the operand can be an `int`, `uint`, `long`, or `ulong`. The expression `~1`, therefore, returns the value with binary notation `1111 1111 1111 1111 1111 1111 1111 1110`, and `~(1<<31)` returns the number with binary notation `0111 1111 1111 1111 1111 1111 1111 1111`.

Control Flow Statements, Continued

Now that we've described Boolean expressions in more detail, we can more clearly describe the control flow statements supported by C#. Many of these statements will be familiar to experienced programmers, so you can skim this section looking for details specific to C#. Note in particular the `foreach` loop, as this may be new to many programmers.

The while and do/while Loops

Thus far you have learned how to write programs that do something only once. However, computers can easily perform similar operations multiple times. To do this, you need to create an instruction loop. The first instruction loop we will discuss is the `while` loop, because it is the simplest conditional loop. The general form of the `while` statement is as follows:

```
while (condition)
  statement
```

The computer will repeatedly execute the statement that is the "body" of the loop as long as the condition (which must be a Boolean expression) evaluates to `true`. If the condition evaluates to `false`, code execution skips the body and executes the code following the loop statement. Note that `statement` will continue to execute even if it causes the condition to become `false`. The loop exits only when the condition is reevaluated "at the top of the loop." The Fibonacci calculator shown in Listing 3.43 demonstrates the `while` loop.

LISTING 3.43: `while` Loop Example

```
class FibonacciCalculator
{
  static void Main()
  {
      decimal current;
      decimal previous;
      decimal temp;
      decimal input;

      System.Console.Write("Enter a positive integer:");

      // decimal.Parse convert the ReadLine to a decimal.
      input = decimal.Parse(System.Console.ReadLine());

      // Initialize current and previous to 1, the first
      // two numbers in the Fibonacci series.
      current = previous = 1;

      // While the current Fibonacci number in the series is
      // less than the value input by the user.
      while (current <= input)
      {
          temp = current;
          current = previous + current;
          previous = temp; // Executes even if previous
          // statement caused current to exceed input
      }

      System.Console.WriteLine(
        $"The Fibonacci number following this is { current }");
  }
}
```

A **Fibonacci number** is a member of the **Fibonacci series,** which includes all numbers that are the sum of the previous two numbers in the series, beginning with 1 and 1. In Listing 3.43, you prompt the user for an integer. Then you use a `while` loop to find the first Fibonacci number that is greater than the number the user entered.

BEGINNER TOPIC

When to Use a while Loop

The remainder of this chapter considers other statements that cause a block of code to execute repeatedly. The term *loop body* refers to the statement (frequently a code block) that is to be executed within the `while` statement, since the code is executed in a "loop" until the exit condition is achieved. It is important to understand which loop construct to select. You use a `while` construct to iterate while the condition evaluates to `true`. A `for` loop is used most appropriately whenever the number of repetitions is known, such as when counting from 0 to *n*. A `do/while` is similar to a `while` loop, except that it will always execute the loop body at least once.

The `do/while` loop is very similar to the `while` loop except that a `do/while` loop is preferred when the number of repetitions is from 1 to *n* and *n* is not known when iterating begins. This pattern frequently occurs when prompting a user for input. Listing 3.44 is taken from the tic-tac-toe program.

LISTING 3.44: do/while Loop Example

```
// Repeatedly request player to move until he
// enters a valid position on the board.
bool valid;
do
{
  valid = false;

  // Request a move from the current player.
  System.Console.Write(
      $"\nPlayer {currentPlayer}: Enter move:");
  input = System.Console.ReadLine();

  // Check the current player's input.
  // ...

} while (!valid);
```

In Listing 3.44, you initialize `valid` to `false` at the beginning of each **iteration,** or loop repetition. Next, you prompt and retrieve the number the user input. Although not shown here, you then check whether the input was correct, and if it was, you assign `valid` equal to `true`. Since the code uses a `do/while` statement rather than a `while` statement, the user will be prompted for input at least once.

The general form of the `do/while` loop is as follows:

```
do
  statement
while (condition);
```

As with all the control flow statements, a code block is generally used as the single statement to allow multiple statements to be executed as the loop body. However, any single statement except for a labeled statement or a local variable declaration can be used.

The for Loop

The for loop iterates a code block until a specified condition is reached. In that way, it is very similar to the while loop. The difference is that the for loop has built-in syntax for initializing, incrementing, and testing the value of a counter, known as the **loop variable.** Because there is a specific location in the loop syntax for an increment operation, the increment and decrement operators are frequently used as part of a for loop.

Listing 3.45 shows the for loop used to display an integer in binary form (functionality the equivalent calling the BCL static function System.Convert.ToString() with a toBase value of 2). The results of this listing appear in Output 3.21.

Listing 3.45: Using the for Loop

```
class BinaryConverter
{
  static void Main()
  {
      const int size = 64;
      ulong value;
      char bit;

      System.Console.Write("Enter an integer: ");
      // Use long.Parse() so as to support negative numbers.
      // Assumes unchecked assignment to ulong.
      value = (ulong)long.Parse(System.Console.ReadLine());

      // Set initial mask to 100....
      ulong mask = 1UL << size - 1;
      for (int count = 0; count < size; count++)
      {
          bit = ((mask & value) > 0) ? '1': '0';
          System.Console.Write(bit);
          // Shift mask one location over to the right
          mask >>= 1;
      }
  }
}
```

OUTPUT 3.21

```
Enter an integer: -42
1111111111111111111111111111111111111111111111111111111111010110
```

Listing 3.45 performs a bit mask 64 times, once for each bit in the number. The three parts of the `for` loop header first declare and initialize the variable `count`, then describe the condition that must be met for the loop body to be executed, and finally describe the operation that updates the loop variable. The general form of the `for` loop is as follows:

```
for (initial ; condition ; loop)
  statement
```

Here is a breakdown of the `for` loop.

- The `initial` section performs operations that precede the first iteration. In Listing 3.45, it declares and initializes the variable `count`. The `initial` expression does not have to be a declaration of a new variable (though it frequently is). It is possible, for example, to declare the variable beforehand and simply initialize it in the `for` loop, or to skip the initialization section entirely by leaving it blank. Variables declared here are in scope throughout the header and body of the `for` statement.
- The `condition` portion of the `for` loop specifies an end condition. The loop exits when this condition is `false` exactly like the `while` loop does. The `for` loop will execute the body only as long as the condition evaluates to `true`. In the preceding example, the loop exits when `count` is greater than or equal to 64.
- The `loop` expression executes after each iteration. In the preceding example, `count++` executes after the right shift of the mask (`mask >>= 1`), but before the condition is evaluated. During the sixty-fourth iteration, `count` is incremented to 64, causing the condition to become `false`, and therefore terminating the loop.
- The `statement` portion of the `for` loop is the "loop body" code that executes while the conditional expression remains `true`.

If you wrote out each `for` loop execution step in pseudocode without using a `for` loop expression, it would look like this:

1. Declare and initialize `count` to 0.
2. If `count` is less than 64, continue to step 3; otherwise, go to step 7.
3. Calculate `bit` and display it.
4. Shift the mask.
5. Increment `count` by 1.
6. Jump back to line 2.
7. Continue the execution of the program after the loop.

The `for` statement doesn't require any of the elements in its header. The expression `for(;;){ ... }` is perfectly valid; although there still needs to be a means to escape from the loop so that it will not continue to execute indefinitely. (If the condition is missing, it is assumed to be the constant `true`.)

The initial and loop expressions have an unusual syntax to support loops that require multiple loop variables, as shown in Listing 3.46.

Listing 3.46: `for` Loop Using Multiple Expressions

```
for (int x = 0, y = 5; ((x <= 5) && (y >=0 )); y--, x++)
{
  System.Console.Write(
      $"{ x }{ ((x > y) ? '>' : '<' )}{ y }\t";
}
```

The results of Listing 3.46 appear in Output 3.22.

Output 3.22

```
0<5     1<4     2<3     3>2     4>1     5>0
```

Here the initialization clause contains a complex declaration that declares and initializes two loop variables, but this is at least similar to a declaration statement that declares multiple local variables. The loop clause is quite unusual, as it can consist of a comma-separated list of expressions, not just a single expression.

Guidelines

CONSIDER refactoring the method to make the control flow easier to understand if you find yourself writing `for` loops with complex conditionals and multiple loop variables.

The `for` loop is little more than a more convenient way to write a `while` loop; you can always rewrite a `for` loop like this:

```
{
  initial;
  while (condition)
  {
    statement;
    loop;
  }
}
```

Guidelines

DO use the `for` loop when the number of loop iterations is known in advance and the "counter" that gives the number of iterations executed is needed in the loop.

DO use the `while` loop when the number of loop iterations is not known in advance and a counter is not needed.

The foreach Loop

The last loop statement in the C# language is `foreach`. The `foreach` loop iterates through a collection of items, setting a loop variable to represent each item in turn. In the body of the loop, operations may be performed on the item. A nice property of the `foreach` loop is that every item is iterated over exactly once; it is not possible to accidentally miscount and iterate past the end of the collection, as can happen with other loops.

The general form of the `foreach` statement is as follows:

```
foreach(type variable in collection)
  statement
```

Here is a breakdown of the `foreach` statement:

- `type` is used to declare the data type of the variable for each item within the collection. It may be `var`, in which case the compiler infers the type of the item from the type of the collection.
- `variable` is a read-only variable into which the `foreach` loop will automatically assign the next item within the collection. The scope of the variable is limited to the body of the loop.

- `collection` is an expression, such as an array, representing any number of items.
- `statement` is the loop body that executes for each iteration of the loop.

Consider the `foreach` loop in the context of the simple example shown in Listing 3.47.

Listing 3.47: Determining Remaining Moves Using the `foreach` Loop

```
class TicTacToe      // Declares the TicTacToe class.
{
  static void Main() // Declares the entry point of the program.
  {
      // Hardcode initial board as follows
      // ---+---+---
      //  1 | 2 | 3
      // ---+---+---
      //  4 | 5 | 6
      // ---+---+---
      //  7 | 8 | 9
      // ---+---+---
      char[] cells = {
        '1', '2', '3', '4', '5', '6', '7', '8', '9'
      };

      System.Console.Write(
          "The available moves are as follows: ");

      // Write out the initial available moves
      foreach (char cell in cells)
      {
        if (cell != 'O' && cell != 'X')
        {
            System.Console.Write($"{ cell } ");
        }
      }
  }
}
```

Output 3.23 shows the results of Listing 3.47.

Output 3.23

```
The available moves are as follows: 1 2 3 4 5 6 7 8 9
```

When the execution engine reaches the `foreach` statement, it assigns to the variable `cell` the first item in the `cells` array—in this case, the value

`'1'`. It then executes the code within the block that makes up the `foreach` loop body. The `if` statement determines whether the value of `cell` is `'O'` or `'X'`. If it is neither, the value of `cell` is written out to the console. The next iteration then assigns the next array value to `cell`, and so on.

Note that the compiler prevents modification of the variable (`cell`) during the execution of a `foreach` loop. Also, the loop variable has a subtly different behavior in C# 5 and higher than it did in previous versions; the difference is apparent only when the loop body contains a lambda expression or anonymous method that uses the loop variable. See Chapter 12 for details.

BEGINNER TOPIC

Where the `switch` Statement Is More Appropriate

Sometimes you might compare the same value in several continuous `if` statements, as shown with the `input` variable in Listing 3.48.

LISTING 3.48: Checking the Player's Input with an `if` Statement

```
// ...

bool valid = false;

// Check the current player's input.
if( (input == "1") ||
  (input == "2") ||
  (input == "3") ||
  (input == "4") ||
  (input == "5") ||
  (input == "6") ||
  (input == "7") ||
  (input == "8") ||
  (input == "9") )
{
    // Save/move as the player directed.
    // ...

    valid = true;
}
else if( (input == "") || (input == "quit") )
{
    valid = true;
}
else
{
    System.Console.WriteLine(
```

```
            "\nERROR:  Enter a value from 1-9. "
            + "Push ENTER to quit");
    }

    // ...
```

This code validates the text entered to ensure that it is a valid tic-tac-toe move. If the value of `input` were `9`, for example, the program would have to perform nine different evaluations. It would be preferable to jump to the correct code after only one evaluation. To enable this, you use a `switch` statement.

The switch Statement

A `switch` statement is simpler to understand than a complex `if` statement when you have a value that must be compared against many different constant values. The `switch` statement looks like this:

```
switch (expression)
{
   case constant:
      statements
    default:
      statements
}
```

Here is a breakdown of the `switch` statement:

- `expression` is the value that is being compared against the different constants. The type of this expression determines the "governing type" of the switch. Allowable governing data types are `bool`, `sbyte`, `byte`, `short`, `ushort`, `int`, `uint`, `long`, `ulong`, `char`, any `enum` type (covered in Chapter 8), the corresponding nullable types of each of those value types, and `string`.
- `constant` is any constant expression compatible with the governing type.
- A group of one or more case labels (or the default label) followed by a group of one or more statements is called a **switch section.** The pattern given previously has two switch sections; Listing 3.49 shows a `switch` statement with three switch sections.

- `statements` is one or more statements to be executed when the expression equals one of the constant values mentioned in a label in the switch section. The end point of the group of statements must not be reachable. Typically the last statement is a jump statement such as a `break`, `return`, or `goto` statement.

Guidelines

DO NOT use `continue` as the jump statement that exits a switch section. This is legal when the `switch` is inside a loop, but it is easy to become confused about the meaning of `break` in a later switch section.

A `switch` statement should have at least one switch section; `switch(x){}` is legal but will generate a warning. Also, the guideline provided earlier (see page 116) was to avoid omitting braces in general. One exception to this rule of thumb is to omit braces for `case` and `break` statements because these keywords serve to indicate the beginning and end of a block, so no braces are needed.

Listing 3.49, with a `switch` statement, is semantically equivalent to the series of `if` statements in Listing 3.48.

Listing 3.49: Replacing the `if` Statement with a `switch` Statement

```
static bool ValidateAndMove(
  int[] playerPositions, int currentPlayer, string input)
{
  bool valid = false;

  // Check the current player's input.
  switch (input)
  {
    case "1" :
    case "2" :
    case "3" :
    case "4" :
    case "5" :
    case "6" :
    case "7" :
    case "8" :
    case "9" :
      // Save/move as the player directed.
      ...
      valid = true;
      break;
```

```
      case "" :
      case "quit" :
        valid = true;
        break;
      default :
        // If none of the other case statements
        // is encountered then the text is invalid.
        System.Console.WriteLine(
          "\nERROR:  Enter a value from 1-9. "
          + "Push ENTER to quit");
        break;
    }

    return valid;
  }
```

In Listing 3.49, `input` is the test expression. Since `input` is a string, the governing type is `string`. If the value of `input` is one of the strings `1`, `2`, `3`, `4`, `5`, `6`, `7`, `8`, or `9`, the move is valid and you change the appropriate cell to match that of the current user's token (X or O). Once execution encounters a `break` statement, control leaves the `switch` statement.

The next switch section describes how to handle the empty string or the string `quit`; it sets `valid` to `true` if `input` equals either value. The `default` switch section is executed if no other switch section had a case label that matched the test expression.

Language Contrast: C++—switch Statement Fall-Through

In C++, if a switch section does not end with a jump statement, control "falls through" to the next switch section, executing its code. Because unintended fall-through is a common error in C++, C# does not allow control to accidentally fall through from one switch section to the next. The C# designers believed it was better to prevent this common source of bugs and encourage better code readability than to match the potentially confusing C++ behavior. If you do want one switch section to execute the statements of another switch section, you may do so explicitly with a `goto` statement, as demonstrated later in this chapter.

There are several things to note about the `switch` statement:

- A `switch` statement with no switch sections will generate a compiler warning, but the statement will still compile.
- Switch sections can appear in any order; the `default` section does not have to appear last. In fact, the `default` switch section does not have to appear at all—it is optional.
- The C# language requires that the end point of every switch section, including the last section, be unreachable. This means that switch sections usually end with a `break`, `return`, `throw`, or `goto`.

Jump Statements

It is possible to alter the execution path of a loop. In fact, with jump statements, it is possible to escape out of the loop or to skip the remaining portion of an iteration and begin with the next iteration, even when the loop condition remains `true`. This section considers some of the ways to jump the execution path from one location to another.

The break Statement

To escape out of a loop or a `switch` statement, C# uses a `break` statement. Whenever the `break` statement is encountered, control immediately leaves the loop or switch. Listing 3.50 examines the `foreach` loop from the tic-tac-toe program.

LISTING 3.50: Using break to Escape Once a Winner Is Found

```
class TicTacToe      // Declares the TicTacToe class.
{
  static void Main() // Declares the entry point of the program.
  {
      int winner = 0;
      // Stores locations each player has moved.
      int[] playerPositions = { 0, 0 };

      // Hardcoded board position.
      //  X | 2 | O
      // ---+---+---
      //  O | O | 6
      // ---+---+---
      //  X | X | X
      playerPositions[0] = 449;
      playerPositions[1] = 28;
```

```
        // Determine if there is a winner.
        int[] winningMasks = {
              7, 56, 448, 73, 146, 292, 84, 273 };

        // Iterate through each winning mask to determine
        // if there is a winner.
        foreach (int mask in winningMasks)
        {
            if ((mask & playerPositions[0]) == mask)
            {
                winner = 1;
                break;
            }
            else if ((mask & playerPositions[1]) == mask)
            {
                winner = 2;
                break;
            }
        }

        System.Console.WriteLine(
            $"Player { winner } was the winner");
    }
  }
```

Output 3.24 shows the results of Listing 3.50.

Output 3.24

```
Player 1 was the winner
```

Listing 3.50 uses a `break` statement when a player holds a winning position. The `break` statement forces its enclosing loop (or a `switch` statement) to cease execution, and control moves to the next line outside the loop. For this listing, if the bit comparison returns `true` (if the board holds a winning position), the `break` statement causes control to jump and display the winner.

Beginner Topic

Bitwise Operators for Positions

The tic-tac-toe example (the full listing is available in Appendix B) uses the bitwise operators to determine which player wins the game. First, the code saves the positions of each player into a bitmap called `playerPositions`. (It uses an array so that the positions for both players can be saved.)

To begin, both `playerPositions` are `0`. As each player moves, the bit corresponding to the move is set. If, for example, the player selects cell 3, `shifter` is set to `3 - 1`. The code subtracts 1 because C# is zero based and you need to adjust for 0 as the first position instead of 1. Next, the code sets `position`, the bit corresponding to cell 3, using the shift operator `000000000000001 << shifter`, where `shifter` now has a value of `2`. Lastly, it sets `playerPositions` for the current player (subtracting 1 again to shift to zero based) to `0000000000000100`. Listing 3.51 uses `|=` so that previous moves are combined with the current move.

LISTING 3.51: Setting the Bit That Corresponds to Each Player's Move

```
int shifter;  // The number of places to shift
              // over to set a bit.
int position;  // The bit that is to be set.

// int.Parse() converts "input" to an integer.
// "int.Parse(input) – 1" because arrays
// are zero based.
shifter = int.Parse(input) - 1;

// Shift mask of 00000000000000000000000000000001
// over by cellLocations.
position = 1 << shifter;

// Take the current player cells and OR them to set the
// new position as well.
// Since currentPlayer is either 1 or 2,
// subtract 1 to use currentPlayer as an
// index in a zero based array.
playerPositions[currentPlayer-1] |= position;
```

Later in the program, you can iterate over each mask corresponding to winning positions on the board to determine whether the current player has a winning position, as shown in Listing 3.50.

The continue Statement

You might have a block containing a series of statements within a loop. If you determine that some conditions warrant executing only a portion of these statements for some iterations, you can use the `continue` statement to jump to the end of the current iteration and begin the next iteration. The `continue` statement exits the current iteration (regardless of whether additional statements remain) and jumps to the loop condition. At that point, if the loop conditional is still `true`, the loop will continue execution.

Listing 3.52 uses the `continue` statement so that only the letters of the domain portion of an email are displayed. Output 3.25 shows the results of Listing 3.52.

LISTING 3.52: Determining the Domain of an Email Address

```
class EmailDomain
{
  static void Main()
  {
      string email;
      bool insideDomain = false;
      System.Console.WriteLine("Enter an email address: ");

      email = System.Console.ReadLine();

      System.Console.Write("The email domain is: ");

      // Iterate through each letter in the email address.
      foreach (char letter in email)
      {
          if (!insideDomain)
          {
              if (letter == '@')
              {
                  insideDomain = true;
              }
              continue;
          }

          System.Console.Write(letter);
      }
  }
}
```

OUTPUT 3.25

```
Enter an email address:
mark@dotnetprogramming.com
The email domain is: dotnetprogramming.com
```

In Listing 3.52, if you are not yet inside the domain portion of the email address, you can use a `continue` statement to move control to the end of the loop, and process the next character in the email address.

You can almost always use an `if` statement in place of a `continue` statement, and this is usually more readable. The problem with the `continue` statement is that it provides multiple flows of control within a single iteration, which compromises readability. In Listing 3.53, the sample has been rewritten, replacing the `continue` statement with the `if/else` construct to demonstrate a more readable version that does not use the `continue` statement.

Listing 3.53: Replacing a `continue` Statement with an `if` Statement

```
foreach (char letter in email)
{
  if (insideDomain)
  {
      System.Console.Write(letter);
  }
  else
  {
      if (letter == '@')
      {
          insideDomain = true;
      }
  }
}
```

The goto Statement

Early programming languages lacked the relatively sophisticated "structured" control flows that modern languages such as C# have as a matter of course, and instead relied upon simple conditional branching (`if`) and unconditional branching (`goto`) statements for most of their control flow needs. The resultant programs were often hard to understand. The continued existence of a `goto` statement within C# seems like an anachronism to many experienced programmers. However, C# supports `goto`, and it is the only method for supporting fall-through within a `switch` statement. In Listing 3.54, if the `/out` option is set, code execution jumps to the `default` case using the `goto` statement, and similarly for `/f`.

Listing 3.54: Demonstrating a `switch` with `goto` Statements

```
// ...
static void Main(string[] args)
{
  bool isOutputSet = false;
```

```
    bool isFiltered = false;

    foreach (string option in args)
    {
        switch (option)
        {
            case "/out":
                isOutputSet = true;
                isFiltered = false;
                goto default;
            case "/f":
                isFiltered = true;
                isRecursive = false;
                goto default;
            default:
                if (isRecursive)
                {
                    // Recurse down the hierarchy
                    // ...

                }
                else if (isFiltered)
                {
                    // Add option to list of filters.
                    // ...
                }
                break;
        }
    }

    // ...

}
```

Output 3.26 shows how to execute the code shown in Listing 3.54.

Output 3.26

```
C:\SAMPLES>Generate /out fizbottle.bin /f "*.xml" "*.wsdl"
```

To branch to a switch section label other than the default label, you can use the syntax `goto case constant;`, where `constant` is the constant associated with the case label you wish to branch to. To branch to a statement that is not associated with a switch section, precede the target statement with any identifier followed by a colon; you can then use that identifier with the `goto` statement. For example, you could have a labeled statement `myLabel : Console.WriteLine();`. The statement `goto myLabel;` would then branch to the labeled statement. Fortunately, C# prevents you from using `goto` to branch *into* a code block; instead, `goto` may be used only to branch within a code block or to an enclosing code block. By making these restrictions, C# avoids most of the serious `goto` abuses possible in other languages.

In spite of the improvements, use of `goto` is generally considered to be inelegant, difficult to understand, and symptomatic of poorly structured code. If you need to execute a section of code multiple times or under different circumstances, either use a loop or extract code to a method of its own.

Guidelines

AVOID using `goto`.

C# Preprocessor Directives

Control flow statements evaluate expressions at runtime. In contrast, the C# preprocessor is invoked during compilation. The preprocessor commands are directives to the C# compiler, specifying the sections of code to compile or identifying how to handle specific errors and warnings within the code. C# preprocessor commands can also provide directives to C# editors regarding the organization of code.

Language Contrast: C++—Preprocessing

Languages such as C and C++ use a **preprocessor** to perform actions on the code based on special tokens. Preprocessor directives generally tell the compiler how to compile the code in a file and do not participate in the compilation process itself. In contrast, the C# compiler handles "preprocessor" directives as part of the regular lexical analysis of the source code. As a result, C# does not support preprocessor macros beyond defining a constant. In fact, the term preprocessor is generally a misnomer for C#.

Each preprocessor directive begins with a hash symbol (#), and all preprocessor directives must appear on one line. A newline rather than a semicolon indicates the end of the directive.

A list of each preprocessor directive appears in Table 3.4.

TABLE 3.4: Preprocessor Directives

Statement or Expression	General Syntax Structure	Example

`#if directive`	`#if preprocessor-expression`
	`  code`
	`#endif`
		`#if CSHARP2PLUS`
		`  Console.Clear();`
		`#endif`

`#elif directive`	`#if preprocessor-expression1`
	`  code`
	`#elif preprocessor-expression2`
	`  code`
	`#endif`
		`#if LINUX`
		`...`
		`#elif WINDOWS`
		`...`
		`#endif`

`#else directive`	`#if`
	`  code`
	`#else`
	`  code`
	`#endif`
		`#if CSHARP1`
		`...`
		`#else`
		`...`
		`#endif`

`#define directive`	`#define conditional-symbol`	`#define CSHARP2PLUS`
`#undef directive`	`#undef conditional-symbol`	`#undef CSHARP2PLUS`
`#error directive`	`#error preproc-message`	`#error Buggy implementation`
`#warning directive`	`#warning preproc-message`	`#warning Needs code review`
`#pragma directive`	`#pragma warning`	`#pragma warning disable 1030`

`#line directive`	`#line org-line new-line`
	`#line default`
		`#line 467 "TicTacToe.cs"`
		`...`
		`#line default`

`#region directive`	`#region pre-proc-message`
	`  code`
	`#endregion`
		`#region Methods`
		`  ...`
		`#endregion`

Excluding and Including Code (#if, #elif, #else, #endif)

Perhaps the most common use of preprocessor directives is in controlling when and how code is included. For example, to write code that could be compiled by both C# 2.0 and later compilers and the prior version 1.0 compilers, you would use a preprocessor directive to exclude C# 2.0–specific code when compiling with a version 1.0 compiler. You can see this in the tic-tac-toe example and in Listing 3.55.

Listing 3.55: Excluding C# 2.0 Code from a C# 1.x Compiler

```
#if CSHARP2PLUS
System.Console.Clear();
#endif
```

In this case, you call the `System.Console.Clear()` method, which is available only in CLI 2.0 and later versions. Using the `#if` and `#endif` preprocessor directives, this line of code will be compiled only if the preprocessor symbol `CSHARP2PLUS` is defined.

Another use of the preprocessor directive would be to handle differences among platforms, such as surrounding Windows- and Linux-specific APIs with `WINDOWS` and `LINUX` `#if` directives. Developers often use these directives in place of multiline comments (`/*...*/`) because they are easier to remove by defining the appropriate symbol or via a search and replace.

A final common use of the directives is for debugging. If you surround code with an `#if DEBUG`, you will remove the code from a release build on most IDEs. The IDEs define the `DEBUG` symbol by default in a debug compile and `RELEASE` by default for release builds.

To handle an else-if condition, you can use the `#elif` directive within the `#if` directive, instead of creating two entirely separate `#if` blocks, as shown in Listing 3.56.

Listing 3.56: Using #if, #elif, and #endif Directives

```
#if LINUX
...
#elif WINDOWS
...
#endif
```

Defining Preprocessor Symbols (#define, #undef)

You can define a preprocessor symbol in two ways. The first is with the `#define` directive, as shown in Listing 3.57.

Listing 3.57: A #define Example

```
#define CSHARP2PLUS
```

The second method uses the `define` option when compiling for .NET, as shown in Output 3.27.

Output 3.27

```
>csc.exe /define:CSHARP2PLUS TicTacToe.cs
```

Output 3.28 shows the same functionality using the Mono compiler.

Output 3.28

```
>mcs.exe -define:CSHARP2PLUS TicTacToe.cs
```

To add multiple definitions, separate them with a semicolon. The advantage of the `define` compiler option is that no source code changes are required, so you may use the same source files to produce two different binaries.

To undefine a symbol, you use the `#undef` directive in the same way you use `#define`.

Emitting Errors and Warnings (#error, #warning)

Sometimes you may want to flag a potential problem with your code. You do this by inserting `#error` and `#warning` directives to emit an error or a warning, respectively. Listing 3.58 uses the tic-tac-toe sample to warn that the code does not yet prevent players from entering the same move multiple times. The results of Listing 3.58 appear in Output 3.29.

Listing 3.58: Defining a Warning with #warning

```
#warning    "Same move allowed multiple times."
```

OUTPUT 3.29

```
Performing main compilation...
...\tictactoe.cs(471,16): warning CS1030: #warning: '"Same move
allowed multiple times."'

Build complete -- 0 errors, 1 warnings
```

By including the #warning directive, you ensure that the compiler will report a warning, as shown in Output 3.29. This particular warning is a way of flagging the fact that there is a potential enhancement or bug within the code. It could be a simple way of reminding the developer of a pending task.

Begin 2.0

Turning Off Warning Messages (#pragma)

Warnings are helpful because they point to code that could potentially be troublesome. However, sometimes it is preferred to turn off particular warnings explicitly because they can be ignored legitimately. C# 2.0 and later compilers provide the preprocessor #pragma directive for just this purpose (see Listing 3.59).

LISTING 3.59: Using the Preprocessor #pragma Directive to Disable the #warning Directive

```
#pragma warning disable  1030
```

Note that warning numbers are prefixed with the letters *CS* in the compiler output. However, this prefix is not used in the #pragma warning directive. The number corresponds to the warning error number emitted by the compiler when there is no preprocessor command.

To reenable the warning, #pragma supports the restore option following the warning, as shown in Listing 3.60.

LISTING 3.60: Using the Preprocessor #pragma Directive to Restore a Warning

```
#pragma warning restore  1030
```

In combination, these two directives can surround a particular block of code where the warning is explicitly determined to be irrelevant.

Perhaps one of the most common warnings to disable is CS1591. This warning appears when you elect to generate XML documentation using the

/doc compiler option, but you neglect to document all of the public items within your program.

nowarn:<warn list> Option

In addition to the #pragma directive, C# compilers generally support the nowarn:<warn list> option. This achieves the same result as #pragma, except that instead of adding it to the source code, you can insert the command as a compiler option. The nowarn option affects the entire compilation, whereas the #pragma option affects only the file in which it appears. Turning off the CS1591 warning, for example, would appear on the command line as shown in Output 3.30.

Output 3.30

```
> csc /doc:generate.xml /nowarn:1591 /out:generate.exe Program.cs
```

End 2.0

Specifying Line Numbers (#line)

The #line directive controls on which line number the C# compiler reports an error or warning. It is used predominantly by utilities and designers that emit C# code. In Listing 3.61, the actual line numbers within the file appear on the left.

Listing 3.61: The #line Preprocessor Directive

```
124        #line 113 "TicTacToe.cs"
125        #warning "Same move allowed multiple times."
126        #line default
```

Including the #line directive causes the compiler to report the warning found on line 125 as though it was on line 113, as shown in the compiler error message in Output 3.31.

Output 3.31

```
Performing main compilation...
...\tictactoe.cs(113,18): warning CS1030: #warning: '"Same move
allowed multiple times."'

Build complete -- 0 errors, 1 warnings
```

Following the #line directive with default reverses the effect of all prior #line directives and instructs the compiler to report true line numbers rather than the ones designated by previous uses of the #line directive.

Hints for Visual Editors (#region, #endregion)

C# contains two preprocessor directives, #region and #endregion, that are useful only within the context of visual code editors. Code editors, such as Microsoft Visual Studio, can search through source code and find these directives to provide editor features when writing code. C# allows you to declare a region of code using the #region directive. You must pair the #region directive with a matching #endregion directive, both of which may optionally include a descriptive string following the directive. In addition, you may nest regions within one another.

Listing 3.62 shows the tic-tac-toe program as an example.

LISTING 3.62: #region and #endregion Preprocessor Directives

```
...
#region Display Tic-tac-toe Board

#if CSHARP2PLUS
  System.Console.Clear();
#endif

// Display the current board;
border = 0;   //  set the first border (border[0] = "|")

// Display the top line of dashes.
// ("\n---+---+---\n")
System.Console.Write(borders[2]);
foreach (char cell in cells)
{
  // Write out a cell value and the border that comes after it.
  System.Console.Write($" { cell } { borders[border] }");

  // Increment to the next border.
  border++;

  // Reset border to 0 if it is 3.
  if (border == 3)
  {
      border = 0;
  }
}
#endregion Display Tic-tac-toe Board
...
```

These preprocessor directives are used, for example, with Microsoft Visual Studio. Visual Studio examines the code and provides a tree control to open and collapse the code (on the left-hand side of the code editor window) that matches the region demarcated by the `#region` directives (see Figure 3.5).

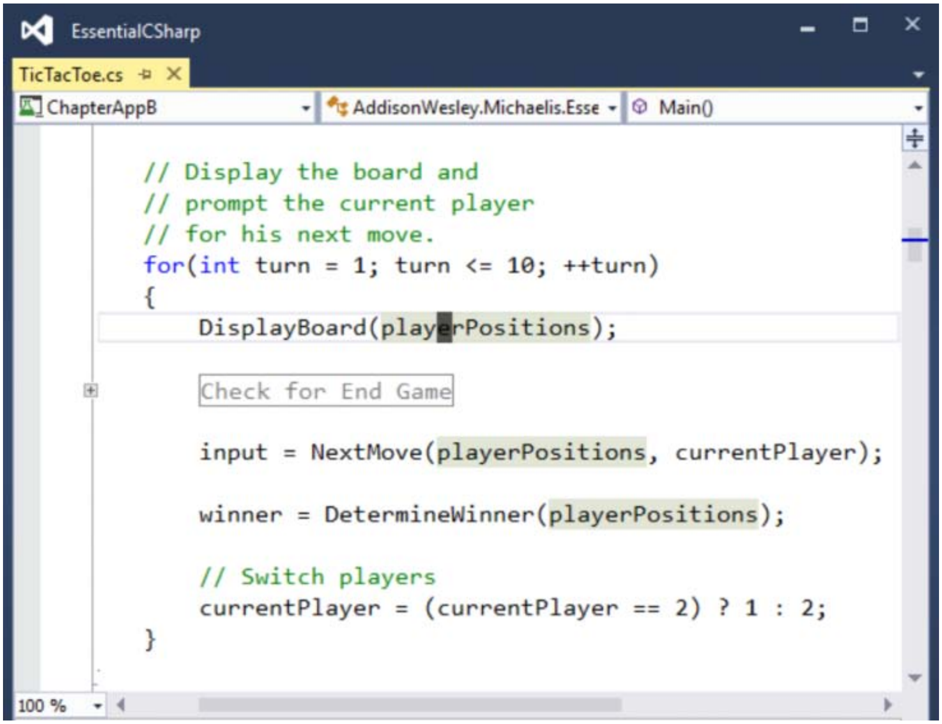


FIGURE 3.5: Collapsed Region in Microsoft Visual Studio .NET

SUMMARY

This chapter began by introducing the C# operators related to assignment and arithmetic. Next, we used the operators along with the `const` keyword to declare constants. Coverage of all the C# operators was not sequential, however. Before discussing the relational and logical comparison operators, the chapter introduced the `if` statement and the important concepts of code blocks and scope. To close out the coverage of operators, we discussed the bitwise operators, especially regarding masks. We also discussed other control flow statements such as loops, `switch`, and `goto`, and ended the chapter with a discussion of the C# preprocessor directives.

Operator precedence was discussed earlier in the chapter; Table 3.5 summarizes the order of precedence across all operators, including several that are not yet covered.

TABLE 3.5: Operator Order of Precedence*

Category	Operators
Primary	`x.y  f(x)  a[x]  x++  x--  new  typeof(T)  checked(x)  unchecked(x)  default(T)  nameof(x)  delegate{}  ()`
Unary	`+  -  !  ~  ++x  --x  (T)x  await x`
Multiplicative	`*  /  %`
Additive	`+  -`
Shift	`<<  >>`
Relational and type testing	`<  >  <=  >=  is  as`
Equality	`==  !=`
Logical AND	`&`
Logical XOR	`^`
Logical OR	`|`
Conditional AND	`&&`
Conditional OR	`||`
Null coalescing	`??`
Conditional	`?:`
Assignment and lambda	`= *=  /=  %=  +=  -=  <<=  >>=  &=  ^=  |=  =>`

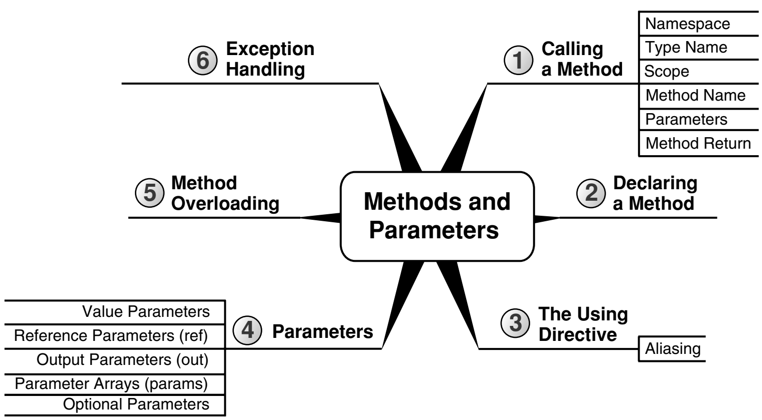
* Rows appear in order of precedence from highest to lowest.

Perhaps one of the best ways to review all of the content covered in Chapters 1–3 is to look at the tic-tac-toe program found in Appendix B. By reviewing this program, you can see one way in which you can combine all that you have learned into a complete program.

4

Methods and Parameters

FROM WHAT YOU HAVE LEARNED about C# programming so far, you should be able to write straightforward programs consisting of a list of statements, similar to the way programs were created in the 1970s. Programming has come a long way since the 1970s; however, as programs have become more complex, new paradigms have emerged to manage that complexity. "Procedural" or "structured" programming provides constructs by which statements are grouped together to form units. Furthermore, with structured programming, it is possible to pass data to a group of statements and then have data returned once the statements have executed.



Besides the basics of calling and defining methods, this chapter covers some slightly more advanced concepts—namely, recursion, method overloading, optional parameters, and named arguments. All method calls discussed so far and through the end of this chapter are static (a concept that Chapter 5 explores in detail).

Even as early as the `HelloWorld` program in Chapter 1, you learned how to define a method. In that example, you defined the `Main()` method. In this chapter, you will learn about method creation in more detail, including the special C# syntaxes (`ref` and `out`) for parameters that pass variables rather than values to methods. Lastly, we will touch on some rudimentary error handling.

Calling a Method

BEGINNER TOPIC

What Is a Method?

Up to this point, all of the statements in the programs you have written have appeared together in one grouping called a `Main()` method. When programs become any more complex than those we have seen thus far, a single method implementation quickly becomes difficult to maintain and complex to read through and understand.

A **method** is a means of grouping together a sequence of statements to perform a particular action or compute a particular result. This provides greater structure and organization for the statements that comprise a program. Consider, for example, a `Main()` method that counts the lines of source code in a directory. Instead of having one large `Main()` method, you can provide a shorter version that allows you to hone in on the details of each method implementation as necessary. Listing 4.1 shows an example.

Listing 4.1: Grouping Statements into Methods

```
class LineCount
{
  static void Main()
  {
      int lineCount;
      string files;
```

```
        DisplayHelpText();
        files = GetFiles();
        lineCount = CountLines(files);
        DisplayLineCount(lineCount);
    }
    // ...
}
```

Instead of placing all of the statements into `Main()`, the listing breaks them into groups called methods. The `System.Console.WriteLine()` statements that display the help text have been moved to the `DisplayHelpText()` method. All of the statements used to determine which files to count appear in the `GetFiles()` method. To actually count the files, the code calls the `CountLines()` method before displaying the results using the `DisplayLineCount()` method. With a quick glance, it is easy to review the code and gain an overview, because the method name describes the purpose of the method.

Guidelines

DO give methods names that are verbs or verb phrases.

A method is always associated with a type—usually a **class**—that provides a means of grouping related methods together.

Methods can receive data via **arguments** that are supplied for their **parameters**. Parameters are variables used for passing data from the **caller** (the code containing the method call) to the invoked method (`Write()`, `WriteLine()`, `GetFiles()`, `CountLines()`, and so on). In Listing 4.1, `files` and `lineCount` are examples of arguments passed to the `CountLines()` and `DisplayLineCount()` methods via their parameters. Methods can also return data back to the caller via a **return value** (in Listing 4.1, the `GetFiles()` method call has a return value that is assigned to `files`).

To begin, we will reexamine `System.Console.Write()`, `System.Console.WriteLine()`, and `System.Console.ReadLine()` from Chapter 1. This time we will look at them as examples of method calls in general, instead of looking at the specifics of printing and retrieving data from the console. Listing 4.2 shows each of the three methods in use.

Listing 4.2: A Simple Method Call

```
class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      System.Console.WriteLine("Hey you!");

      System.Console.Write("Enter your first name: ");

      firstName = System.Console.ReadLine();
      System.Console.Write("Enter your last name: ");
      lastName = System.Console.ReadLine();
      System.Console.WriteLine(
          $"Your full name is { firstName } { lastName }.");
  }
}
```

The parts of the method call include the method name, argument list, and returned value. A fully qualified method name includes a namespace, type name, and method name; a period separates each part of a fully qualified method name. As we will see, methods are often called with only a part of their fully qualified name.

Namespaces

Namespaces are a categorization mechanism for grouping all types related to a particular area of functionality. Namespaces are hierarchical, and can have arbitrarily many levels in the hierarchy, though namespaces with more than half a dozen levels are rare. Typically the hierarchy begins with a company name, and then a product name, and then the functional area. For example, in `Microsoft.Win32.Networking`, the outermost namespace is `Microsoft`, which contains an inner namespace `Win32`, which in turn contains an even more deeply nested `Networking` namespace.

Namespaces are primarily used to organize types by area of functionality so that they can be more easily found and understood. However, they can also be used to avoid type name collisions. For example, the compiler can distinguish between two types with the name `Button` as long as each type has a different namespace. Thus you can disambiguate types `System.Web.UI.WebControls.Button` and `System.Windows.Controls.Button`.

In Listing 4.2, the `Console` type is found within the `System` namespace. The `System` namespace contains the types that enable the programmer to perform many fundamental programming activities. Almost all C# programs use types within the `System` namespace. Table 4.1 provides a listing of other common namespaces.

TABLE 4.1: Common Namespaces

Begin 4.0

Namespace	Description
`System`	Contains the fundamental types, and types for conversion between types, mathematics, program invocation, and environment management.
`System.Collections`	Contains types for working with collections of objects such as lists and dictionaries.
`System.Collections.Generics`	Contains strongly typed collections that use generics.
`System.Data`	Contains types used for working with databases.
`System.Drawing`	Contains types for drawing to the display device and working with images.
`System.IO`	Contains types for working with directories and manipulating, loading, and saving files.
`System.Linq`	Contains classes and interfaces for querying data in collections using a Language Integrated Query.
`System.Text`	Contains types for working with strings and various text encodings, and for converting between those encodings.
`System.Text.RegularExpressions`	Contains types for working with regular expressions.
`System.Threading`	Contains types for multithreaded programming.
`System.Threading.Tasks`	Contains types for task-based asynchrony.
`System.Web`	Contains types that enable browser-to-server communication, generally over HTTP. The functionality within this namespace is used to support ASP.NET.

continues

TABLE 4.1: Common Namespaces (*continued*)

Namespace	Description
`System.ServiceModel`	The Windows Communication Foundation (WCF) that contains types for sending and retrieving data between service and client applications, enabling the distributed communication between both .NET and non-.NET technologies.
`System.Windows`	Contains types for creating rich user interfaces starting with .NET 3.0 using a UI technology called Windows Presentation Framework (WPF) that leverages Extensible Application Markup Language (XAML) for declarative design of the UI.
`System.Windows.Forms`	Contains types for creating rich user interfaces and the components within them.
`System.Xml`	Contains standards-based support for XML processing.

End 4.0

It is not always necessary to provide the namespace when calling a method. For example, if the call expression appears in a type in the same namespace as the called method, the compiler can infer the namespace to be the namespace that contains the type. Later in this chapter, you will see how the `using` directive eliminates the need for a namespace qualifier as well.

Guidelines

DO use PascalCasing for namespace names.

CONSIDER organizing the directory hierarchy for source code files to match the namespace hierarchy.

Type Name

Calls to static methods require the type name qualifier as long as the target method is not within the same type.[1] (As discussed later in the chapter, a "using static" directive allows you to omit the type name.) For example, a call expression of `Console.WriteLine()` found in the method `HelloWorld.Main()` requires the type, `Console`, to be stated. However, just

1. Or base class.

as with the namespace, C# allows the omission of the type name from a method call whenever the method is a member of the type containing the call expression. (Examples of method calls such as this appear in Listing 4.4.) The type name is unnecessary in such cases because the compiler infers the type from the location of the call. If the compiler can make no such inference, the name must be provided as part of the method call.

At their core, types are a means of grouping together methods and their associated data. For example, `Console` is the type that contains the `Write()`, `WriteLine()`, and `ReadLine()` methods (among others). All of these methods are in the same "group" because they belong to the `Console` type.

Scope

In the previous chapter you learned that the "scope" of a program element is the region of text in which it can be referred to by its unqualified name. A call that appears inside a type declaration to a method declared in that type does not require the type qualifier because the method is "in scope" throughout its containing type. Similarly, a type is "in scope" throughout the namespace that declares it; therefore, a method call that appears in a type in a particular namespace need not specify that namespace in the method call name.

Method Name

Every method call contains a method name, which might or might not be qualified with a namespace and type name, as we have discussed. After the method name comes the argument list; the argument list is a parenthesized, comma-separated list of the values that correspond to the parameters of the method.

Parameters and Arguments

A method can take any number of parameters, and each parameter is of a specific data type. The values that the caller supplies for parameters are called the **arguments;** every argument must correspond to a particular parameter. For example, the following method call has three arguments:

```
System.IO.File.Copy(
    oldFileName, newFileName, false)
```

The method is found on the class `File`, which is located in the namespace `System.IO`. It is declared to have three parameters, with the first and second being of type `string` and the third being of type `bool`. In this example, we use variables (`oldFileName` and `newFileName`) of type `string` for the old and new filenames, and then specify `false` to indicate that the copy should fail if the new filename already exists.

Method Return Values

In contrast to `System.Console.WriteLine()`, the method call `System.Console.ReadLine()` in Listing 4.2 does not have any arguments because the method is declared to take no parameters. However, this method happens to have a **method return value.** The method return value is a means of transferring results from a called method back to the caller. Because `System.Console.ReadLine()` has a return value, it is possible to assign the return value to the variable `firstName`. In addition, it is possible to pass this method return value itself as an argument to another method call, as shown in Listing 4.3.

LISTING 4.3: Passing a Method Return Value As an Argument to Another Method Call

```
class Program
{
  static void Main()
  {
      System.Console.Write("Enter your first name: ");
      System.Console.WriteLine("Hello {0}!",
          System.Console.ReadLine());
  }
}
```

Instead of assigning the returned value to a variable and then using that variable as an argument to the call to `System.Console.WriteLine()`, Listing 4.3 calls the `System.Console.ReadLine()` method within the call to `System.Console.WriteLine()`. At execution time, the `System.Console.ReadLine()` method executes first and its return value is passed directly into the `System.Console.WriteLine()` method, rather than into a variable.

Not all methods return data. Both versions of `System.Console.Write()` and `System.Console.WriteLine()` are examples of such methods. As you will see shortly, these methods specify a return type of `void` just as the `HelloWorld` declaration of `Main` returned `void`.

Statement versus Method Call

Listing 4.3 provides a demonstration of the difference between a statement and a method call. Although `System.Console.WriteLine("Hello {0}!", System.Console.ReadLine());` is a single statement, it contains two method calls. A statement often contains one or more expressions, and in this example, two of those expressions are method calls. Therefore, method calls form parts of statements.

Although coding multiple method calls in a single statement often reduces the amount of code, it does not necessarily increase the readability and seldom offers a significant performance advantage. Developers should favor readability over brevity.

> **NOTE**
>
> In general, developers should favor readability over brevity. Readability is critical to writing code that is self-documenting and, therefore, more maintainable over time.

Declaring a Method

Begin 6.0

This section expands on the explanation of declaring a method to include parameters or a return type. Listing 4.4 contains examples of these concepts, and Output 4.1 shows the results.

LISTING 4.4: Declaring a Method

```
class IntroducingMethods
{
  public static void Main()
  {
      string firstName;
      string lastName;
      string fullName;
      string initials;
```

```
        System.Console.WriteLine("Hey you!");

        firstName = GetUserInput("Enter your first name: ");
        lastName = GetUserInput("Enter your last name: ");

        fullName = GetFullName(firstName, lastName);
        initials = GetInitials(firstName, lastName);
        DisplayGreeting(fullName, initials);
    }

    static string GetUserInput(string prompt)
    {
        System.Console.Write(prompt);
        return System.Console.ReadLine();
    }

    static string GetFullName(  // C# 6.0 expression-bodied method
        string firstName, string lastName) =>
            $"{ firstName } { lastName }";

    static void DisplayGreeting(string fullName, string initials)
    {
        System.Console.WriteLine(
            $"Hello { fullName }! Your initials are { initials }");
        return;
    }

    static string GetInitials(string firstName, string lastName)
    {
        return $"{ firstName[0] }. { lastName[0] }.";
    }
  }
```

Output 4.1

```
Hey you!
Enter your first name: Inigo
Enter your last name: Montoya
Your full name is Inigo Montoya.
```

Five methods are declared in Listing 4.4. From `Main()` the code calls `GetUserInput()`, followed by a call to `GetFullName()` and `GetInitials()`. All of the last three methods return a value and take arguments. One declaration, `GetFullName()`, leverages the C# 6.0 styled expression-bodied method syntax discussed shortly. In addition, the listing calls `DisplayGreeting()`, which doesn't return any data. No method in C# can exist outside the confines of an enclosing type; in this case, the enclosing type is the `IntroducingMethods` class. Even the `Main` method examined in Chapter 1 must be within a type.

End 6.0

Language Contrast: C++/Visual Basic—Global Methods

C# provides no global method support; everything must appear within a type declaration. This is why the `Main()` method was marked as `static`—the C# equivalent of a C++ global and Visual Basic "shared" method.

BEGINNER TOPIC

Refactoring into Methods

Moving a set of statements into a method instead of leaving them inline within a larger method is a form of **refactoring.** Refactoring reduces code duplication, because you can call the method from multiple places instead of duplicating the code. Refactoring also increases code readability. As part of the coding process, it is a best practice to continually review your code and look for opportunities to refactor. This involves looking for blocks of code that are difficult to understand at a glance and moving them into a method with a name that clearly defines the code's behavior. This practice is often preferred over commenting a block of code, because the method name serves to describe what the implementation does.

For example, the `Main()` method that is shown in Listing 4.4 results in the same behavior as does the `Main()` method that is shown in Listing 1.15 in Chapter 1. Perhaps even more noteworthy is that although both listings are trivial to follow, Listing 4.4 is easier to grasp at a glance by just viewing the `Main()` method and not worrying about the details of each called method's implementation.

In earlier versions of Visual Studio, you can select a group of statements, right-click on it, and then select the Extract Method refactoring from the Refactoring section of the context menu to automatically move a group of statements to a new method. In Visual Studio 2015, the refactorings are available from the Quick Actions section of the context menu.

Formal Parameter Declaration

Consider the declarations of the `DisplayGreeting()`, `GetFullName()`, and the `GetInitials()` methods. The text that appears between the parentheses of a method declaration is the **formal parameter list.** (As we will see when we discuss generics, methods may also have a **type parameter list.** When it is clear from context which kind of parameters we are discussing, we will simply refer to them as "parameters" in a "parameter list.") Each parameter in the parameter list includes the type of the parameter along with the parameter name. A comma separates each parameter in the list.

Behaviorally, most parameters are virtually identical to local variables, and the naming convention of parameters follows accordingly. Therefore, parameter names use camelCase. Also, it is not possible to declare a local variable (a variable declared inside a method) with the same name as a parameter of the containing method, because this would create two "local variables" of the same name.

Guidelines

DO use "camelCasing" for parameter names.

Method Return Type Declaration

In addition to `GetUserInput()`, `GetFullName()`, and the `GetInitials()` methods requiring parameters to be specified, each of these methods also includes a **method return type.** You can tell that a method returns a value because a data type appears immediately before the method name in the method declaration. Each of these method examples specifies a `string` return type. Unlike with parameters, of which there can be any number, only one method return type is allowable.

As with `GetUserInput()` and `GetInitials()`, methods with a return type almost always contain one or more "return statements" that return control to the caller. A `return` statement consists of the `return` keyword followed by an expression that computes the value the method is returning. For example, the `GetInitials()` method's return statement is `return $"{ firstName[0] }. { lastName[0] }.";`. The expression (an interpolated string in this case) following the `return` keyword must be compatible with the stated return type of the method.

If a method has a return type, the block of statements that makes up the body of the method must have an "unreachable end point." That is, there must be no way for control to "fall off the end" of a method without it returning a value. Often the easiest way to ensure that this condition is met is to make the last statement of the method a `return` statement. However, `return` statements can appear in locations other than at the end of a method implementation. For example, an `if` or `switch` statement in a method implementation could include a `return` statement within it; see Listing 4.5 for an example.

LISTING 4.5: A `return` Statement before the End of a Method

```
class Program
{
  static bool MyMethod()
  {
      string command = ObtainCommand();
      switch(command)
      {
          case "quit":
              return false;
          // ... omitted, other cases
          default:
              return true;
      }
  }
}
```

(Note that a `return` statement transfers control out of the `switch`, so no `break` statement is required to prevent illegal fall-through in a switch section that ends with a return statement.)

In Listing 4.5, the last statement in the method is not a `return` statement; it is a `switch` statement. However, the compiler can deduce that every possible code path through the method results in a `return`, so that the end point of the method is not reachable. Thus this method is legal, even though it does not end with a `return` statement.

If particular code paths include unreachable statements following the `return`, the compiler will issue a warning that indicates the additional statements will never execute.

Though C# allows a method to have multiple return statements, code is generally more readable and easier to maintain if there is a single exit location rather than multiple returns sprinkled through various code paths of the method.

Specifying `void` as a return type indicates that there is no return value from the method. As a result, a call to the method may not be assigned to a variable or used as a parameter type at the call site. A void method call may be used only as a statement. Furthermore, within the body of the method the `return` statement becomes optional, and when it is specified, there must be no value following the `return` keyword. For example, the return of `Main()` in Listing 4.4 is `void` and there is no `return` statement within the method. However, `DisplayGreeting()` includes an (optional) `return` statement that is not followed by any returned result.

Begin 6.0

Expression Bodied Methods

To support the simplest of method declarations without the formality of a method body, C# 6.0 introduced **expression bodied methods,** which are declared using an expression rather than a full method body. Listing 4.4's `GetFullName()` method provides an example of the expression bodied method:

```
static string GetFullName( string firstName, string lastName) =>
        $"{ firstName } { lastName }";
```

In place of the curly brackets typical of a method body, an expression bodied method uses the "goes to" operator (fully introduced in Chapter 12), for which the resulting data type must match the return type of the method. In other words, even though there is no explicit return statement in the expression bodied method implementation, it is still necessary that the return type from the expression match the method declaration's return type.

Expression boded methods are syntactic shortcuts to the fuller method body declaration. As such, their use should be limited to the simplest of method implementations—generally expressible on a single line.

End 6.0

Language Contrast: C++—Header Files

Unlike in C++, C# classes never separate the implementation from the declaration. In C#, there is no header (`.h`) file or implementation (`.cpp`) file. Instead, declaration and implementation appear together in the same file. (C# does support an advanced feature called "partial methods," in which the method's defining declaration is separate from its implementation, but for the purposes of this chapter we will consider only nonpartial methods.) The lack of separate declaration and implementation in C# removes the requirement to maintain redundant declaration information in two places found in languages that have separate header and implementation files, such as C++.

BEGINNER TOPIC

Namespaces

As described earlier, **namespaces** are an organizational mechanism for categorizing and grouping together related types. Developers can discover related types by examining other types within the same namespace as a familiar type. Additionally, through namespaces, two or more types may have the same name as long as they are disambiguated by different namespaces.

The using Directive

Fully qualified namespace names can become quite long and unwieldy. It is possible, however, to "import" all the types from one or more namespaces into a file so that they can be used without full qualification. To achieve this, the C# programmer includes a `using` directive, generally at the top of the file. For example, in Listing 4.6, `Console` is not prefixed with `System`. The namespace may be omitted because of the `using System` directive that appears at the top of the listing.

LISTING 4.6: using Directive Example

```
// The using directive imports all types from the
// specified namespace into the entire file.
using System;

class HelloWorld
{
  static void Main()
  {
      // No need to qualify Console with System
      // because of the using directive above.
      Console.WriteLine("Hello, my name is Inigo Montoya");
  }
}
```

The results of Listing 4.6 appear in Output 4.2.

OUTPUT 4.2

```
Hello, my name is Inigo Montoya
```

A `using` directive such as `using System` does not enable you to omit `System` from a type declared within a child namespace of `System`.

For example, if your code accessed the `StringBuilder` type from the `System.Text` namespace, you would have to either include an additional `using System.Text;` directive or fully qualify the type as `System.Text.StringBuilder`, not just `Text.StringBuilder`. In short, a `using` directive does not "import" types from any **nested namespaces.** Nested namespaces, which are identified by the period in the namespace, always need to be imported explicitly.

Language Contrast: Java—Wildcards in `import` Directive

Java allows for importing namespaces using a wildcard such as the following:

```
import javax.swing.*;
```

In contrast, C# does not support a wildcard `using` directive, but instead requires each namespace to be imported explicitly.

Language Contrast: Visual Basic .NET—Project Scope `Imports` Directive

Unlike C#, Visual Basic .NET supports the ability to specify the `using` directive equivalent, `Imports`, for an entire project, rather than just for a specific file. In other words, Visual Basic .NET provides a command-line means of the `using` directive that will span an entire compilation.

Frequent use of types within a particular namespace implies that the addition of a `using` directive for that namespace is a good idea, instead of fully qualifying all types within the namespace. Accordingly, almost all C# files include the `using System` directive at the top. Throughout the remainder of this book, code listings will often omit the `using System` directive. Other namespace directives will be included explicitly, however.

One interesting effect of the `using System` directive is that the string data type can be identified with varying case: `String` or `string`. The former version relies on the `using System` directive and the latter uses the `string` keyword. Both are valid C# references to the `System.String` data type, and the resultant CIL code is unaffected by which version is chosen.[2]

ADVANCED TOPIC

Nested using Directives

Not only can you have `using` directives at the top of a file, but you also can include them at the top of a namespace declaration. For example, if a new namespace, `EssentialCSharp`, were declared, it would be possible to add a `using` declarative at the top of the namespace declaration (see Listing 4.7).

Listing 4.7: Specifying the using Directive inside a Namespace Declaration

```
namespace EssentialCSharp
{
  using System;

  class HelloWorld
  {
    static void Main()
    {
        // No need to qualify Console with System
        // because of the using directive above.
        Console.WriteLine("Hello, my name is Inigo Montoya");
    }
  }
}
```

The results of Listing 4.7 appear in Output 4.3.

Output 4.3

```
Hello, my name is Inigo Montoya
```

The difference between placing the `using` directive at the top of a file and placing it at the top of a namespace declaration is that the directive is active only within the namespace declaration. If the code includes a new

2. I prefer the `string` keyword, but whichever representation a programmer selects, the code within a project ideally should be consistent.

namespace declaration above or below the `EssentialCSharp` declaration, the `using System` directive within a different namespace would not be active. Code seldom is written this way, especially given the standard practice of providing a single type declaration per file.

Begin 6.0

The using static Directive

The `using` directive allows you to abbreviate a type name by omitting the namespace portion of the name—such that just the type name can be specified for any type within the stated namespace. In contrast, the `using static` directive allows you to omit both the namespace and the type name from any member of the stated type. A `using static System.Console` directive, for example, allows you to specify `WriteLine()` rather than the fully qualified method name of `System.Console.WriteLine()`. Continuing with this example, we can update Listing 4.2 to leverage the `using static System.Console` directive to create Listing 4.8.

Listing 4.8: The using static Directive

```
using static System.Console;

class HeyYou
{
  static void Main()
  {
      string firstName;
      string lastName;

      WriteLine("Hey you!");

      Write("Enter your first name: ");

      firstName = ReadLine();
      Write("Enter your last name: ");
      lastName = ReadLine();
      WriteLine(
          $"Your full name is { firstName } { lastName }.");
  }
}
```

In this case, there is no loss of readability of the code: `WriteLine()`, `Write()`, and `ReadLine()` all clearly relate to a console directive. In fact, one could argue that the resulting code is simpler and, therefore, clearer than before.

However, sometimes this is not the case. For example, if your code uses classes that have overlapping behavior names, such as an `Exists()` method on a file and an `Exists()` method on a directory, then perhaps a `using static` directive would reduce clarity when you invoke `Exists()`. Similarly, if the class you were writing had its own members with overlapping behavior names to those imported with a `using static` statement—for example, `Display()` and `Write()`—then perhaps clarity would be lost to the reader.

This ambiguity would not be allowed by the compiler. If two members with the same signature were available (through either `using static` directives or separately declared members), any invocation of them that was ambiguous would result in a compile error.

End 6.0

Aliasing

The `using` directive also allows **aliasing** a namespace or type. An alias is an alternative name that you can use within the text to which the `using` directive applies. The two most common reasons for aliasing are to disambiguate two types that have the same name and to abbreviate a long name. In Listing 4.9, for example, the `CountDownTimer` alias is declared as a means of referring to the type `System.Timers.Timer`. Simply adding a `using System.Timers` directive will not sufficiently enable the code to avoid fully qualifying the `Timer` type. The reason is that `System.Threading` also includes a type called `Timer`; therefore, just using `Timer` within the code will be ambiguous.

LISTING 4.9: Declaring a Type Alias

```
using System;
using System.Threading;
using CountDownTimer = System.Timers.Timer;

class HelloWorld
{
  static void Main()
  {
      CountDownTimer timer;

      // ...
  }
}
```

Listing 4.9 uses an entirely new name, `CountDownTimer`, as the alias. It is possible, however, to specify the alias as `Timer`, as shown in Listing 4.10.

LISTING 4.10: Declaring a Type Alias with the Same Name

```
using System;
using System.Threading;

// Declare alias Timer to refer to System.Timers.Timer to
// avoid code ambiguity with System.Threading.Timer
using Timer = System.Timers.Timer;

class HelloWorld
{
  static void Main()
  {
      Timer timer;

      // ...
  }
}
```

Because of the alias directive, "Timer" is not an ambiguous reference. Furthermore, to refer to the `System.Threading.Timer` type, you will have to either qualify the type or define a different alias.

Returns and Parameters on `Main()`

So far, declaration of an executable's `Main()` method has been the simplest declaration possible. You have not included any parameters or non-void return type in your `Main()` method declarations. However, C# supports the ability to retrieve the command-line arguments when executing a program, and it is possible to return a status indicator from the `Main()` method.

The runtime passes the command-line arguments to `Main()` using a single `string` array parameter. All you need to do to retrieve the parameters is to access the array, as demonstrated in Listing 4.11. The purpose of this program is to download a file whose location is given by a URL. The first command-line argument identifies the URL, and the optional second argument is the filename to which to save the file. The listing begins with a `switch` statement that evaluates the number of parameters (`args.Length`) as follows:

1. If there are not two parameters, display an error indicating that it is necessary to provide the URL and filename.
2. The presence of two arguments indicates the user has provided both the URL of the resource and the download target filename.

Listing 4.11: Passing Command-Line Arguments to Main

```
using System;
using System.Net;
using System.Net;

class Program
{
  static int Main(string[] args)
  {
      int result;
      string targetFileName;
      string url;
      switch (args.Length)
      {
          default:
              // Exactly two arguments must be specified; give an error.
              Console.WriteLine(
                  "ERROR:  You must specify the "
                  + "URL and the file name");
              targetFileName = null;
              url = null;
              break;
          case 2:
              url = args[0];
              targetFileName = args[1];
              break;
      }

      if (targetFileName != null && url != null)
      {
          WebClient webClient = new WebClient();
          webClient.DownloadFile(url, targetFileName);
          result = 0;
      }
      else
      {
          Console.WriteLine(
              "Usage: Downloader.exe <URL> <TargetFileName>");
          result = 1;
      }
      return result;
  }

 }
```

The results of Listing 4.11 appear in Output 4.4.

Output 4.4

```
>Downloader.exe
ERROR:  You must specify the URL to be downloaded
Downloader.exe <URL> <TargetFileName>
```

If you were successful in calculating the target filename, you would use it to save the downloaded file. Otherwise, you would display the help text. The `Main()` method also returns an `int` rather than a `void`. This is optional for a `Main()` declaration, but if it is used, the program can return a status code to a caller (such as a script or a batch file). By convention, a return other than zero indicates an error.

Although all command-line arguments can be passed to `Main()` via an array of strings, sometimes it is convenient to access the arguments from inside a method other than `Main()`. The `System.Environment.GetCommandLineArgs()` method returns the command-line arguments array in the same form that `Main(string[] args)` passes the arguments into `Main()`.

ADVANCED TOPIC

Disambiguate Multiple `Main()` Methods

If a program includes two classes with `Main()` methods, it is possible to specify on the command line which class to use for the `Main()` declaration. `csc.exe` includes an `/m` option to specify the fully qualified class name of `Main()`.

BEGINNER TOPIC

Call Stack and Call Site

As code executes, methods call more methods, which in turn call additional methods, and so on. In the simple case of Listing 4.4, `Main()` calls `GetUserInput()`, which in turn calls `System.Console.ReadLine()`, which in turn calls even more methods internally. Every time a new method is invoked, the runtime creates an "activation frame" that contains information about the arguments passed to the new call, the local variables of the new call, and information about where control should resume when the new method returns. The set of calls within calls within calls, and so on, produces a series of activation frames that is termed the **call stack.** As program complexity increases, the call stack generally gets larger and larger as each method calls another method. As calls complete, however, the call stack shrinks until another method is invoked. The process of removing activation frames from the call stack is termed **stack unwinding.** Stack unwinding always occurs in the reverse order of the method calls. When the method completes, execution will return to the **call site**—that is, the location from which the method was invoked.

Advanced Method Parameters

So far this chapter's examples have returned data via the method return value. This section demonstrates how methods can return data via their method parameters and shows how a method may take a variable number of arguments.

Value Parameters

Arguments to method calls are usually **passed by value,** which means the value of the argument expression is copied into the target parameter. For example, in Listing 4.12, the value of each variable that `Main()` uses when calling `Combine()` will be copied into the parameters of the `Combine()` method. Output 4.5 shows the results of this listing.

LISTING 4.12: Passing Variables by Value

```
class Program
{
  static void Main()
  {
      // ...
      string fullName;
      string driveLetter = "C:";
      string folderPath  = "Data";
      string fileName    = "index.html";

      fullName = Combine(driveLetter, folderPath, fileName);

      Console.WriteLine(fullName);
      // ...
  }

  static string Combine(
      string driveLetter, string folderPath, string fileName)
  {
      string path;
      path = string.Format("{1}{0}{2}{0}{3}",
          System.IO.Path.DirectorySeparatorChar,
          driveLetter, folderPath, fileName);
      return path;
  }
}
```

Output 4.5

```
C:\Data\index.html
```

Even if the `Combine()` method assigns `null` to `driveLetter`, `folderPath`, and `fileName` before returning, the corresponding variables within `Main()` will maintain their original values because the variables are copied when calling a method. When the call stack unwinds at the end of a call, the copied data is thrown away.

BEGINNER TOPIC

Matching Caller Variables with Parameter Names

In Listing 4.12, the variable names in the caller exactly matched the parameter names in the called method. This matching is provided simply for readability purposes; whether names match is entirely irrelevant to the behavior of the method call. The parameters of the called method and the local variables of the calling method are found in different declaration spaces and have nothing to do with each other.

ADVANCED TOPIC

Reference Types versus Value Types

For the purposes of this section, it is inconsequential whether the parameter passed is a value type or a reference type. Rather, the important issue is whether the called method can write a value into the caller's original variable. Since a copy of the caller variable's value is made, the caller's variable cannot be reassigned. Nevertheless, it is helpful to understand the difference between a variable that contains a value type and a variable that contains a reference type.

The value of a reference type variable is, as the name implies, a reference to the location where the data associated with the object is stored. How the runtime chooses to represent the value of a reference type variable is an implementation detail of the runtime; typically it is represented as the address of the memory location in which the object's data is stored, but it need not be.

If a reference type variable is passed by value, the reference itself is copied from the caller to the method parameter. As a result, the target method cannot update the caller variable's value but it may update the data referred to by the reference.

Alternatively, if the method parameter is a value type, the value itself is copied into the parameter, and changing the parameter in the called method will not affect the original caller's variable.

Reference Parameters (ref)

Consider Listing 4.13, which calls a function to swap two values, and Output 4.6, which shows the results.

Listing 4.13: Passing Variables by Reference

```
class Program
{
  static void Main()
  {
      // ...
      string first = "hello";
      string second = "goodbye";
      Swap(ref first, ref second);

      Console.WriteLine(
          $@"first = ""{ first }"", second = ""{ second }""" );
      // ...
  }

  static void Swap(ref string x, ref string y)
  {
      string temp = x;
      x = y;
      y = temp;
  }
}
```

Output 4.6

```
first = "goodbye", second = "hello"
```

The values assigned to `first` and `second` are successfully switched. To do this, the variables are **passed by reference.** The obvious difference between the call to `Swap()` and Listing 4.12's call to `Combine()` is the inclusion of the keyword `ref` in front of the parameter's data type. This keyword changes the call such that the variables used as arguments are passed by reference, so the called method can update the original caller's variables with new values.

When the called method specifies a parameter as `ref`, the caller is required to supply a variable, not a value, as an argument, and to place `ref` in front of the variables passed. In so doing, the caller explicitly recognizes that the target method could reassign the values of the variables associated with any `ref` parameters it receives. Furthermore, it is necessary to initialize any local variables passed as `ref` because target methods could read data from `ref` parameters without first assigning them. In Listing 4.13, for example, `temp` is assigned the value of `first`, assuming that the variable passed in `first` was initialized by the caller. Effectively, a `ref` parameter is an alias for the variable passed. In other words, it is essentially giving a parameter name to an existing variable, rather than creating a new variable and copying the value of the argument into it.

Output Parameters (out)

As mentioned earlier, a variable used as a `ref` parameter must be assigned before it is passed to the called method, because the called method might read from the variable. The "swap" example given previously must read and write from both variables passed to it. However, it is often the case that a method that takes a reference to a variable intends to write to the variable, but not to read from it. In such cases, clearly it could be safe to pass an uninitialized local variable by reference.

To achieve this, code needs to decorate parameter types with the keyword `out`. This is demonstrated in the `TryGetPhoneButton()` method in Listing 4.14, which returns the phone button corresponding to a character.

LISTING 4.14: Passing Variables Out Only

```
class ConvertToPhoneNumber
{
  static int Main(string[] args)
  {
      char button;

      if(args.Length == 0)
```

```
        {
            Console.WriteLine(
                "ConvertToPhoneNumber.exe <phrase>");
            Console.WriteLine(
                "'_' indicates no standard phone button");
            return 1;
        }
        foreach(string word in args)
        {
            foreach(char character in word)
            {
                if(TryGetPhoneButton(character, out button))
                {
                    Console.Write(button);
                }
                else
                {
                    Console.Write('_');
                }
            }
        }
        Console.WriteLine();
        return 0;
    }

    static bool TryGetPhoneButton(char character, out char button)
    {
        bool success = true;
        switch( char.ToLower(character) )
        {
            case '1':
                button = '1';
                break;
            case '2': case 'a': case 'b': case 'c':
                button = '2';
                break;

            // ...

            case '-':
                button = '-';
                break;
            default:
                  // Set the button to indicate an invalid value
                  button = '_';
                success = false;
                break;
        }
        return success;
    }
}
```

Output 4.7 shows the results of Listing 4.14.

Output 4.7

```
>ConvertToPhoneNumber.exe CSharpIsGood
274277474663
```

In this example, the `TryGetPhoneButton()` method returns `true` if it can successfully determine the `character`'s corresponding phone button. The function also returns the corresponding button by using the `button` parameter, which is decorated with `out`.

An `out` parameter is functionally identical to a `ref` parameter; the only difference is which requirements the language enforces regarding how the aliased variable is read from and written to. Whenever a parameter is marked with `out`, the compiler will check that the parameter is set for all code paths within the method that return normally (that is, the code paths that do not throw an exception). If, for example, the code does not assign `button` a value in some code path, the compiler will issue an error indicating that the code didn't initialize `button`. Listing 4.14 assigns `button` to the underscore character because even though it cannot determine the correct phone button, it is still necessary to assign a value.

The developer of a method may declare one or more `out` parameters to get around the restriction that a method may have only one return type; a method that needs to return two values can do so by returning one value normally, as the return value of the method, and a second value by writing it into an aliased variable passed as an `out` parameter. Although this pattern is both common and legal, there are usually better ways to achieve that aim. For example, if you are considering returning two or more values from a method, you might actually be better off writing two methods, one for each value. If the method must return two values, use of tuple types (to represent multiple values) or nullable value types (to represent a value that might not be "valid," as in the earlier example) can eliminate the need to pass variables by reference.

NOTE

Each and every normal code path must result in the assignment of all `out` parameters.

Parameter Arrays (params)

In the examples so far, the number of arguments that must be passed has been fixed by the number of parameters declared in the target method declaration. However, sometimes it is convenient if the number of arguments may vary. Consider the `Combine()` method from Listing 4.12. In that method, you passed the drive letter, folder path, and filename. What if the path had more than one folder, and the caller wanted the method to join additional folders to form the full path? Perhaps the best option would be to pass an array of strings for the folders. However, this would make the calling code a little more complex, because it would be necessary to construct an array to pass as an argument.

To make it easier on the callers of such a method, C# provides a keyword that enables the number of arguments to vary in the calling code instead of being set by the target method. Before we discuss the method declaration, observe the calling code declared within `Main()`, as shown in Listing 4.15.

Listing 4.15: Passing a Variable Parameter List

```
using System;
using System.IO;
class PathEx
{
  static void Main()
  {
      string fullName;

      // ...

      // Call Combine() with four arguments
      fullName = Combine(
          Directory.GetCurrentDirectory(),
          "bin", "config", "index.html");
      Console.WriteLine(fullName);

      // ...

      // Call Combine() with only three arguments
      fullName = Combine(
          Environment.SystemDirectory,
          "Temp", "index.html");
      Console.WriteLine(fullName);

      // ...

      // Call Combine() with an array
      fullName = Combine(
```

```
            new string[] {
                "C:\\", "Data",
                "HomeDir", "index.html"} );
        Console.WriteLine(fullName);
        // ...
    }

    static string Combine(params string[] paths)
    {
        string result = string.Empty;
        foreach (string path in paths)
        {
            result = System.IO.Path.Combine(result, path);
        }
        return result;
    }
}
```

Output 4.8 shows the results of Listing 4.15.

Output 4.8

```
C:\Data\mark\bin\config\index.html
C:\WINDOWS\system32\Temp\index.html
C:\Data\HomeDir\index.html
```

In the first call to `Combine()`, four arguments are specified. The second call contains only three arguments. In the final call, a single argument is passed using an array. In other words, the `Combine()` method takes a variable number of arguments—presented either as any number of string arguments separated by commas or as a single array of strings. The former syntax is called the "expanded" form of the method call, and the second form is called the "normal" form.

To allow this, the `Combine()` method does the following:

1. Places `params` immediately before the last parameter in the method declaration
2. Declares the last parameter as an array

With a **parameter array** declaration, it is possible to access each corresponding argument as a member of the `params` array. In the `Combine()` method implementation, you iterate over the elements of the `paths` array and call `System.IO.Path.Combine()`. This method automatically combines the parts of the path, appropriately using the platform-specific directory-separator character. Note that `PathEx.Combine()` is identical to `Path.Combine()`, except that `PathEx.Combine()` handles a variable number of parameters rather than simply two.

There are a few notable characteristics of the parameter array:

- The parameter array is not necessarily the only parameter on a method. The parameter array must be the last parameter in the method declaration. Since only the last parameter may be a parameter array, a method cannot have more than one parameter array.
- The caller can specify zero arguments that correspond to the parameter array parameter, which will result in an array of zero items being passed as the parameter array.
- Parameter arrays are type-safe. The arguments given must be compatible with the element type of the parameter array.
- The caller can use an explicit array rather than a comma-separated list of parameters. The resulting IL code is identical.
  - If the target method implementation requires a minimum number of parameters, those parameters should appear explicitly within the method declaration, forcing a compile error instead of relying on runtime error handling if required parameters are missing. For example, if you have a method that requires one or more integer arguments, declare the method `int Max(int first, params int[] operands)` rather than `int Max(params int[] operands)` so that at least one value is passed to `Max()`.

Using a parameter array, you can pass a variable number of arguments of the same type into a method. The section "Method Overloading," which appears later in this chapter, discusses a means of supporting a variable number of arguments that are not necessarily of the same type.

Guidelines

DO use parameter arrays when a method can handle any number—including zero—of additional arguments.

Recursion

Calling a method **recursively** or implementing the method using **recursion** refers to use of a method that calls itself. Recursion is sometimes the simplest way to implement a particular algorithm. Listing 4.16 counts the lines of all the C# source files (`*.cs`) in a directory and its subdirectory.

Listing 4.16: Counting the Lines within `*.cs` Files, Given a Directory

```
using System.IO;

public static class LineCounter
{
  // Use the first argument as the directory
  // to search, or default to the current directory.
  public static void Main(string[] args)
  {
      int totalLineCount = 0;
      string directory;
      if (args.Length > 0)
      {
          directory = args[0];
      }
      else
      {
          directory = Directory.GetCurrentDirectory();
      }
      totalLineCount = DirectoryCountLines(directory);
      System.Console.WriteLine(totalLineCount);
    }

  static int DirectoryCountLines(string directory)
  {
      int lineCount = 0;
      foreach (string file in
          Directory.GetFiles(directory, "*.cs"))
      {
            lineCount += CountLines(file);
        }

      foreach (string subdirectory in
          Directory.GetDirectories(directory))
      {
          lineCount += DirectoryCountLines(subdirectory);
      }

      return lineCount;
  }

  private static int CountLines(string file)
  {
      string line;
```

```
        int lineCount = 0;
        FileStream stream =
            new FileStream(file, FileMode.Open);3
        StreamReader reader = new StreamReader(stream);
        line = reader.ReadLine();

         while(line != null)
         {
             if (line.Trim() != "")
             {
                 lineCount++;
             }
             line = reader.ReadLine();
         }

        reader.Close();  // Automatically closes the stream
        return lineCount;
    }
}
```

Output 4.9 shows the results of Listing 4.16.

Output 4.9

```
104
```

The program begins by passing the first command-line argument to `DirectoryCountLines()`, or by using the current directory if no argument is provided. This method first iterates through all the files in the current directory and totals the source code lines for each file. After processing each file in the directory, the code processes each subdirectory by passing the subdirectory back into the `DirectoryCountLines()` method, rerunning the method using the subdirectory. The same process is repeated recursively through each subdirectory until no more directories remain to process.

Readers unfamiliar with recursion may find it confusing at first. Regardless, it is often the simplest pattern to code, especially with hierarchical type data such as the filesystem. However, although it may be the most readable approach, it is generally not the fastest implementation. If performance becomes an issue, developers should seek an alternative solution to a recursive implementation. The choice generally hinges on balancing readability with performance.

3. This code could be improved with a `using` statement, a construct that we have avoided because it has not yet been introduced.

BEGINNER TOPIC

Infinite Recursion Error

A common programming error in recursive method implementations appears in the form of a stack overflow during program execution. This usually happens because of **infinite recursion,** in which the method continually calls back on itself, never reaching a point that triggers the end of the recursion. It is a good practice for programmers to review any method that uses recursion and to verify that the recursion calls are finite.

A common pattern for recursion using pseudocode is as follows:

```
M(x)
{
  if x is trivial
    return the result
  else
    a. Do some work to make the problem smaller
    b. Recursively call M to solve the smaller problem
    c. Compute the result based on a. and b.
    return the result
}
```

Things go wrong when this pattern is not followed. For example, if you don't make the problem smaller or if you don't handle all possible "smallest" cases, the recursion never terminates.

Method Overloading

Listing 4.16 called `DirectoryCountLines()`, which counted the lines of `*.cs` files. However, if you want to count code in `*.h/*.cpp` files or in `*.vb` files, `DirectoryCountLines()` will not work. Instead, you need a method that takes the file extension, but still keeps the existing method definition so that it handles `*.cs` files by default.

All methods within a class must have a unique signature, and C# defines uniqueness by variation in the method name, parameter data types, or number of parameters. This does not include method return data types; defining two methods that differ only in their return data types will cause a compile error. **Method overloading** occurs when a class has two or more methods with the same name and the parameter count and/or data types vary between the overloaded methods.

NOTE

A method is considered unique as long as there is variation in the method name, parameter data types, or number of parameters.

Method overloading is a type of **operational polymorphism**. Polymorphism occurs when the same logical operation takes on many ("poly") forms ("morphs") because the data varies. Calling `WriteLine()` and passing a format string along with some parameters is implemented differently than calling `WriteLine()` and specifying an integer. However, logically, to the caller, the method takes care of writing the data and it is somewhat irrelevant how the internal implementation occurs. Listing 4.17 provides an example, and Output 4.10 shows the results.

LISTING 4.17: Counting the Lines within `*.cs` Files Using Overloading

```
using System.IO;

public static class LineCounter
{
  public static void Main(string[] args)
  {
      int totalLineCount;

      if (args.Length > 1)
      {
          totalLineCount =
              DirectoryCountLines(args[0], args[1]);
      }
      if (args.Length > 0)
      {
          totalLineCount = DirectoryCountLines(args[0]);
      }
      else
      {
          totalLineCount  = DirectoryCountLines();
      }

      System.Console.WriteLine(totalLineCount);
  }

  static int DirectoryCountLines()
  {
      return DirectoryCountLines(
          Directory.GetCurrentDirectory());
  }

  static int DirectoryCountLines(string directory)
```

```
    {
        return DirectoryCountLines(directory, "*.cs");
    }

    static int DirectoryCountLines(
        string directory, string extension)
    {
        int lineCount = 0;
        foreach (string file in
            Directory.GetFiles(directory, extension))
        {
            lineCount += CountLines(file);
        }

        foreach (string subdirectory in
            Directory.GetDirectories(directory))
        {
            lineCount += DirectoryCountLines(subdirectory);
        }

        return lineCount;
    }

    private static int CountLines(string file)
    {
        int lineCount = 0;
        string line;
        FileStream stream =
            new FileStream(file, FileMode.Open);[4]
        StreamReader reader = new StreamReader(stream);
        line = reader.ReadLine();
        while(line != null)
        {
            if (line.Trim() != "")
            {
                lineCount++;
            }
            line = reader.ReadLine();
        }

        reader.Close();  // Automatically closes the stream
        return lineCount;
    }
  }
```

Output 4.10

```
>LineCounter.exe .\ *.cs
28
```

4. This code could be improved with a `using` statement, a construct that we have avoided because it has not yet been introduced.

The effect of method overloading is to provide optional ways to call the method. As demonstrated inside `Main()`, you can call the `DirectoryCountLines()` method with or without passing the directory to search and the file extension.

Notice that the parameterless implementation of `DirectoryCountLines()` was changed to call the single-parameter version (`int DirectoryCountLines (string directory)`). This is a common pattern when implementing overloaded methods. The idea is that developers implement only the core logic in one method and all the other overloaded methods will call that single method. If the core implementation changes, it needs to be modified in only one location rather than within each implementation. This pattern is especially prevalent when using method overloading to enable optional parameters that do not have values determined at compile time, so they cannot be specified using optional parameters.

> **NOTE**
>
> Placing the core functionality into a single method that all other overloading methods invoke means that you can make changes in implementation in just the core method, which the other methods will automatically take advantage of.

Optional Parameters

Begin 4.0

Starting with C# 4.0, the language designers added support for **optional parameters.** By allowing the association of a parameter with a constant value as part of the method declaration, it is possible to call a method without passing an argument for every parameter of the method (see Listing 4.18).

LISTING 4.18: Methods with Optional Parameters

```
using System.IO;

public static class LineCounter
{
  public static void Main(string[] args)
  {
      int totalLineCount;
```

```
        if (args.Length > 1)
        {
            totalLineCount =
                DirectoryCountLines(args[0], args[1]);
        }
        if (args.Length > 0)
        {
            totalLineCount = DirectoryCountLines(args[0]);
        }
        else
        {
            totalLineCount  = DirectoryCountLines();
        }

        System.Console.WriteLine(totalLineCount);
    }

    static int DirectoryCountLines()
    {
        // ...
    }

  /*
    static int DirectoryCountLines(string directory)
    { ... }
  */

    static int DirectoryCountLines(
        string directory, string extension = "*.cs")
    {
        int lineCount = 0;
        foreach (string file in
            Directory.GetFiles(directory, extension))
        {
            lineCount += CountLines(file);
        }

        foreach (string subdirectory in
            Directory.GetDirectories(directory))
        {
            lineCount += DirectoryCountLines(subdirectory);
        }

        return lineCount;
    }

    private static int CountLines(string file)
    {
        // ...
    }
  }
```

4.0

In Listing 4.18, the `DirectoryCountLines()` method declaration with a single parameter has been removed (commented out), but the call from `Main()` (specifying one parameter) remains. When no `extension` parameter is specified in the call, the value assigned to `extension` within the declaration (`*.cs` in this case) is used. This allows the calling code to not specify a value if desired, and it eliminates the additional overload that would be required in C# 3.0 and earlier. Note that optional parameters must appear after all required parameters (those that don't have default values). Also, the fact that the default value needs to be a constant, compile-time–resolved value is fairly restrictive. You cannot, for example, declare a method like this:

```
DirectoryCountLines(
  string directory = Environment.CurrentDirectory,
  string extension = "*.cs")
```

because `Environment.CurrentDirectory` is not a constant. In contrast, because `"*.cs"` is a constant, C# does allow it for the default value of an optional parameter.

4.0

Guidelines

DO provide good defaults for all parameters where possible.

DO provide simple method overloads that have a small number of required parameters.

CONSIDER organizing overloads from the simplest to the most complex.

A second method call feature made available in C# 4.0 is the use of **named arguments.** With named arguments, it is possible for the caller to explicitly identify the name of the parameter to be assigned a value, rather than relying solely on parameter and argument order to correlate them (see Listing 4.19).

Listing 4.19: Specifying Parameters by Name

```
class Program
{
  static void Main()
  {
      DisplayGreeting(
          firstName: "Inigo", lastName: "Montoya");
  }
```

```
  public static void DisplayGreeting(
      string firstName,
      string middleName = default(string),
      string lastName = default(string))
  {

      // ...

  }
}
```

In Listing 4.19, the call to `DisplayGreeting()` from within `Main()` assigns a value to a parameter by name. Of the two optional parameters (`middleName` and `lastName`), only `lastName` is given as an argument. For cases where a method has lots of parameters and many of them are optional (a common occurrence when accessing Microsoft COM libraries), using the named argument syntax is certainly a convenience. However, along with the convenience comes an impact on the flexibility of the method interface. In the past, parameter names could be changed without causing other calling C# code to no longer compile. With the addition of named parameters, the parameter name becomes part of the interface because changing the name would cause code that uses the named parameter to no longer compile.

4.0

Guidelines

DO treat parameter names as part of the API, and avoid changing the names if version compatibility between APIs is important.

For many experienced C# developers, this is a surprising restriction. However, the restriction has been imposed as part of the Common Language Specification ever since .NET 1.0. Moreover, Visual Basic has always supported calling methods with named arguments. Therefore, library developers should already be following the practice of not changing parameter names to successfully interoperate with other .NET languages from version to version. In essence, C# 4.0 now imposes the same restriction on changing parameter names that many other .NET languages already require.

Given the combination of method overloading, optional parameters, and named parameters, resolving which method to call becomes less obvious.

A call is **applicable** (compatible) with a method if all parameters have exactly one corresponding argument (either by name or by position) that is type compatible, unless the parameter is optional (or is a parameter array). Although this restricts the possible number of methods that will be called, it doesn't identify a unique method. To further distinguish which specific method will be called, the compiler uses only explicitly identified parameters in the caller, ignoring all optional parameters that were not specified at the caller. Therefore, if two methods are applicable because one of them has an optional parameter, the compiler will resolve to the method without the optional parameter.

End 4.0

ADVANCED TOPIC

Method Resolution

When the compiler must choose which of several applicable methods is the best one for a particular call, the one with the "most specific" parameter types is chosen. Assuming there are two applicable methods, each requiring an implicit conversion from an argument to a parameter type, the method whose parameter type is the more derived type will be used.

For example, a method that takes a `double` parameter will be chosen over a method that takes an `object` parameter if the caller passes an argument of type `int`. This is because `double` is more specific than `object`. There are objects that are not doubles, but there are no doubles that are not objects, so `double` must be more specific.

If more than one method is applicable and no unique best method can be determined, the compiler will issue an error indicating that the call is ambiguous.

For example, given the following methods:

```
static void Method(object thing){}
static void Method(double thing){}
static void Method(long thing){}
static void Method(int thing){}
```

a call of the form `Method(42)` will resolve as `Method(int thing)` because that is an exact match from the argument type to the parameter type. Were that method to be removed, overload resolution would choose the `long` version, because `long` is more specific than either `double` or `object`.

The C# specification includes additional rules governing implicit conversion between byte, ushort, uint, ulong, and the other numeric types. In general, though, it is better to use a cast to make the intended target method more recognizable.

Basic Error Handling with Exceptions

This section examines how to handle error reporting via a mechanism known as **exception handling.**

With exception handling, a method is able to pass information about an error to a calling method without using a return value or explicitly providing any parameters to do so. Listing 4.20 contains a slight modification to the HeyYou program from Chapter 1. Instead of requesting the last name of the user, it prompts for the user's age.

Listing 4.20: Converting a string to an int

```
using System;

class ExceptionHandling
{
  static void Main()
  {
      string firstName;
      string ageText;
      int age;

      Console.WriteLine("Hey you!");

      Console.Write("Enter your first name: ");
      firstName = System.Console.ReadLine();

      Console.Write("Enter your age: ");
      ageText = Console.ReadLine();
      age = int.Parse(ageText);

      Console.WriteLine(
          $"Hi { firstName }!  You are { age*12 } months old.");
  }
}
```

Output 4.11 shows the results of Listing 4.20.

Output 4.11

```
Hey you!
Enter your first name: Inigo
Enter your age: 42
Hi Inigo!  You are 504 months old.
```

The return value from `System.Console.ReadLine()` is stored in a variable called `ageText` and is then passed to a method with the `int` data type, called `Parse()`. This method is responsible for taking a string value that represents a number and converting it to an `int` type.

BEGINNER TOPIC

42 As a String versus 42 As an Integer

C# requires that every non-null value have a well-defined type associated with it. Therefore, not only is the data value important, but also the type associated with the data. A string value of 42, therefore, is distinctly different from an integer value of 42. The string is composed of the two characters 4 and 2, whereas the `int` is the number 42.

Given the converted string, the final `System.Console.WriteLine()` statement will print the age in months by multiplying the age value by 12.

But what happens if the user does not enter a valid integer string? For example, what happens if the user enters "forty-two"? The `Parse()` method cannot handle such a conversion. It expects the user to enter a string that contains only digits. If the `Parse()` method is sent an invalid value, it needs some way to report this fact back to the caller.

Trapping Errors

To indicate to the calling method that the parameter is invalid, `int.Parse()` will **throw an exception.** Throwing an exception halts further execution in the current control flow and instead jumps into the first code block within the call stack that handles the exception.

Since you have not yet provided any such handling, the program reports the exception to the user as an **unhandled exception.** Assuming there is no registered debugger on the system, the error will appear on the console with a message such as that shown in Output 4.12.

Output 4.12

```
Hey you!
Enter your first name: Inigo
Enter your age: forty-two

Unhandled Exception: System.FormatException: Input string was
        not in a correct format.
    at System.Number.ParseInt32(String s, NumberStyles style,
        NumberFormatInfo info)
    at ExceptionHandling.Main()
```

Obviously, such an error is not particularly helpful. To fix this, it is necessary to provide a mechanism that handles the error, perhaps reporting a more meaningful error message back to the user.

This process is known as **catching an exception.** The syntax is demonstrated in Listing 4.21, and the output appears in Output 4.13.

Listing 4.21: Catching an Exception

```
using System;

class ExceptionHandling
{
  static int Main()
  {
      string firstName;
      string ageText;
      int age;
      int result = 0;

      Console.Write("Enter your first name: ");
      firstName = Console.ReadLine();

      Console.Write("Enter your age: ");
      ageText = Console.ReadLine();

      try
      {
          age = int.Parse(ageText);
          Console.WriteLine(
              $"Hi { firstName }! You are { age*12 } months old.");
      }
      catch (FormatException )
      {
          Console.WriteLine(
```

```
                $"The age entered, { ageText }, is not valid.");
            result = 1;
        }
        catch(Exception exception)
        {
            Console.WriteLine(
                $"Unexpected error:  { exception.Message }");
            result = 1;
        }
        finally
        {
            Console.WriteLine($"Goodbye { firstName }");
        }

        return result;
    }
}
```

Output 4.13

```
Enter your first name: Inigo
Enter your age: forty-two
The age entered, forty-two, is not valid.
Goodbye Inigo
```

To begin, surround the code that could potentially throw an exception (`age = int.Parse()`) with a **try block.** This block begins with the `try` keyword. It indicates to the compiler that the developer is aware of the possibility that the code within the block might throw an exception, and if it does, one of the **catch blocks** will attempt to handle the exception.

One or more catch blocks (or the finally block) must appear immediately following a try block. The catch block header (see the Advanced Topic titled "General `catch`," later in this chapter) optionally allows you to specify the data type of the exception, and as long as the data type matches the exception type, the catch block will execute. If, however, there is no appropriate catch block, the exception will fall through and go unhandled as though there were no exception handling. The resultant control flow appears in Figure 4.1 on the next page.

For example, assume the user enters "forty-two" for the age in the previous example. In this case, `int.Parse()` will throw an exception of type `System.FormatException`, and control will jump to the set of catch blocks. (`System.FormatException` indicates that the string was not of the correct format to be parsed appropriately.) Since the first catch block matches the type of exception that `int.Parse()` threw, the code inside this block will execute. If a statement within the try block throws a different exception, the second catch block would execute because all exceptions are of type `System.Exception`.

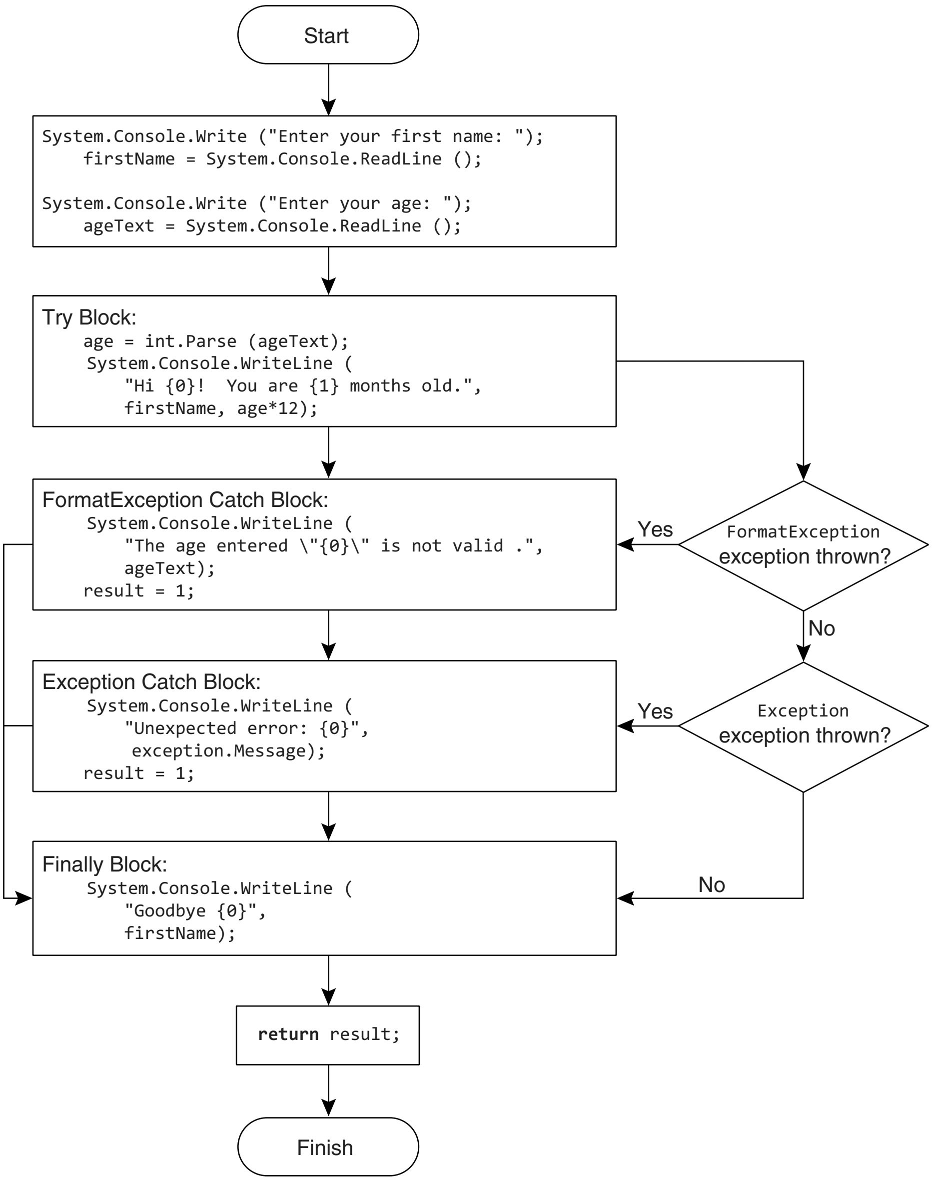


FIGURE 4.1: Exception-Handling Program Flow

If there were no `System.FormatException` catch block, the `System.Exception` catch block would execute even though `int.Parse` throws a `System.FormatException`. This is because a `System.FormatException` is also of type `System.Exception`. (`System.FormatException` is a more specific implementation of the generic exception, `System.Exception`.)

The order in which you handle exceptions is significant. Catch blocks must appear from most specific to least specific. The `System.Exception` data type is least specific, so it appears last. `System.FormatException` appears first because it is the most specific exception that Listing 4.21 handles.

Regardless of whether control leaves the try block normally or because the code in the try block throws an exception, the **finally block** of code will execute after control leaves the try-protected region. The purpose of the finally block is to provide a location to place code that will execute regardless of how the try/catch blocks exit—with or without an exception. Finally blocks are useful for cleaning up resources regardless of whether an exception is thrown. In fact, it is possible to have a try block with a finally block and no catch block. The finally block executes regardless of whether the try block throws an exception or whether a catch block is even written to handle the exception. Listing 4.22 demonstrates the try/finally block and Output 4.14 shows the results.

LISTING 4.22: Finally Block without a Catch Block

```
using System;

class ExceptionHandling
{
  static int Main()
  {
      string firstName;
      string ageText;
      int age;
      int result = 0;

      Console.Write("Enter your first name: ");
      firstName = Console.ReadLine();

      Console.Write("Enter your age: ");
      ageText = Console.ReadLine();

      try
```

```
        {
            age = int.Parse(ageText);
            Console.WriteLine(
                $"Hi { firstName }! You are { age*12 } months old.");
        }
        finally
        {
            Console.WriteLine($"Goodbye { firstName }");
        }

        return result;
    }
}
```

Output 4.14

```
Enter your first name: Inigo
Enter your age: forty-two

Unhandled Exception: System.FormatException: Input string was not in a
correct format.
   at System.Number.StringToNumber(String str, NumberStyles options,
NumberBuffer& number, NumberFormatInfo info, Boolean parseDecimal)
   at System.Number.ParseInt32(String s, NumberStyles style,
NumberFormatInfo info)
   at ExceptionHandling.Main()
Goodbye Inigo
```

The attentive reader will have noticed something interesting here: The runtime first reported the unhandled exception, and then ran the finally block. What explains this unusual behavior?

First, the behavior is legal because when an exception is unhandled, the behavior of the runtime is implementation defined; any behavior is legal! The runtime chooses this particular behavior because it knows before it chooses to run the finally block that the exception will be unhandled; the runtime has already examined all of the activation frames on the call stack and determined that none of them is associated with a catch block that matches the thrown exception.

As soon as the runtime determines that the exception will be unhandled, it checks whether a debugger is installed on the machine, because you might be the software developer who is analyzing this failure. If a debugger is present, it offers the user the chance to attach the debugger to the process *before* the finally block runs. If there is no debugger installed or if the user declines to debug the problem, the default behavior is to print the unhandled exception to the console, and then see if there are any finally blocks that could run. Due to the "implementation-defined" nature of the situation, the runtime is not required to run finally blocks in this situation; an implementation may choose to do so or not.

Guidelines

AVOID explicitly throwing exceptions from finally blocks. (Implicitly thrown exceptions resulting from method calls are acceptable.)

DO favor try/finally and avoid using try/catch for cleanup code.

DO throw exceptions that describe which exceptional circumstance occurred, and if possible, how to prevent it.

ADVANCED TOPIC

Exception Class Inheritance

Starting in C# 2.0, all objects thrown as exceptions derive from `System.Exception`. (Objects thrown from other languages that do not derive from `System.Exception` are automatically "wrapped" by an object that does.) Therefore, they can be handled by the `catch(System.Exception  exception)` block. It is preferable, however, to include a catch block that is specific to the most derived type (`System.FormatException`, for example), because then it is possible to get the most information about an exception and handle it less generically. In so doing, the `catch` statement that uses the most derived type is able to handle the exception type specifically, accessing data related to the exception thrown, and avoiding conditional logic to determine what type of exception occurred.

This is why C# enforces the rule that catch blocks appear from most derived to least derived. For example, a `catch` statement that catches `System.Exception` cannot appear before a statement that catches `System.FormatException` because `System.FormatException` derives from `System.Exception`.

A method could throw many exception types. Table 4.2 lists some of the more common ones within the framework.

TABLE 4.2: Common Exception Types

Exception Type	Description
`System.Exception`	The "base" exception from which all other exceptions derive.
`System.ArgumentException`	Indicates that one of the arguments passed into the method is invalid.
`System.ArgumentNullException`	Indicates that a particular argument is `null` and that this is not a valid value for that parameter.
`System.ApplicationException`	To be avoided. The original idea was that you might want to have one kind of handling for "system" exceptions and another for "application" exceptions, although plausible, doesn't actually work well in the real world.
`System.FormatException`	Indicates that the string format is not valid for conversion.
`System.IndexOutOfRangeException`	Indicates that an attempt was made to access an array or other collection element that does not exist.
`System.InvalidCastException`	Indicates that an attempt to convert from one data type to another was not a valid conversion.
`System.InvalidOperationException`	Indicates that an unexpected scenario has occurred such that the application is no longer in a valid state of operation.
`System.NotImplementedException`	Indicates that although the method signature exists, it has not been fully implemented.
`System.NullReferenceException`	Thrown when code tries to find the object referred to by a reference that is null.
`System.ArithmeticException`	Indicates an invalid math operation, not including divide by zero.
`System.ArrayTypeMismatchException`	Occurs when attempting to store an element of the wrong type into an array.
`System.StackOverflowException`	Indicates an unexpectedly deep recursion.

ADVANCED TOPIC

General catch

It is possible to specify a catch block that takes no parameters, as shown in Listing 4.23.

LISTING 4.23: General Catch Blocks

```
...
try
{
    age = int.Parse(ageText);
    System.Console.WriteLine(
        $"Hi { firstName }!  You are { age*12 } months old.");
}
catch (System.FormatException exception)
{
    System.Console.WriteLine(
        $"The age entered ,{ ageText }, is not valid.");
    result = 1;
}
catch(System.Exception exception)
{
    System.Console.WriteLine(
        $"Unexpected error:  { exception.Message }");
    result = 1;
}
catch
{
    System.Console.WriteLine("Unexpected error!");
    result = 1;
}
finally
{
    System.Console.WriteLine($"Goodbye { firstName }");
}
...
```

A catch block with no data type, called a **general catch block,** is equivalent to specifying a catch block that takes an `object` data type—for instance, `catch(object exception){...}`. Because all classes ultimately derive from `object`, a catch block with no data type must appear last.

General catch blocks are rarely used because there is no way to capture any information about the exception. In addition, C# doesn't support the ability to throw an exception of type `object`. (Only libraries written in languages such as C++ allow exceptions of any type.)

Begin 2.0

The behavior starting in C# 2.0 varies slightly from the earlier C# behavior. In C# 2.0, if a language allows throwing non-`System.Exception`s, the object of the thrown exception will be wrapped in a `System.Runtime.CompilerServices.RuntimeWrappedException` that does derive from `System.Exception`. Therefore, all exceptions, whether derived from `System.Exception` or not, will propagate into C# assemblies as if they were derived from `System.Exception`.

The result is that `System.Exception` catch blocks will catch all exceptions not caught by earlier blocks, and a general catch block, following a `System.Exception` catch block, will never be invoked. Consequently, following a `System.Exception` catch block with a general catch block in C# 2.0 or later will result in a compiler warning indicating that the general catch block will never execute.

End 2.0

Guidelines

AVOID general catch blocks and replace them with a catch of `System.Exception`.

AVOID catching exceptions for which the appropriate action is unknown. It is better to let an exception go unhandled than to handle it incorrectly.

AVOID catching and logging an exception before rethrowing it. Instead, allow the exception to escape until it can be handled appropriately.

Reporting Errors Using a throw Statement

C# allows developers to throw exceptions from their code, as demonstrated in Listing 4.24 and Output 4.15.

Listing 4.24: Throwing an Exception

```
using System;
public class ThrowingExceptions
{
  public static void Main()
  {
      try
      {
          Console.WriteLine("Begin executing");
          Console.WriteLine("Throw exception");
```

```
                throw new Exception("Arbitrary exception");
            Console.WriteLine("End executing");
        }
        catch(FormatException exception)
        {
            Console.WriteLine(
                "A FormateException was thrown");
        }
        catch(Exception exception)
        {
            Console.WriteLine(
                $"Unexpected error: { exception.Message }");
        }
        catch
        {
            Console.WriteLine("Unexpected error!");
        }

        Console.WriteLine(
            "Shutting down...");
    }
}
```

Output 4.15

```
Begin executing
Throw exception...
Unexpected error:  Arbitrary exception
Shutting down...
```

As the arrows in Listing 4.24 depict, throwing an exception causes execution to jump from where the exception is thrown into the first catch block within the stack that is compatible with the thrown exception type.[5] In this case, the second catch block handles the exception and writes out an error message. In Listing 4.24, there is no finally block, so execution falls through to the `System.Console.WriteLine()` statement following the try/catch block.

To throw an exception, it is necessary to have an instance of an exception. Listing 4.24 creates an instance using the keyword `new` followed by the type of the exception. Most exception types allow a message to be generated as part of throwing the exception, so that when the exception occurs, the message can be retrieved.

5. Technically, it could be caught by a compatible catch filter as well.

Sometimes a catch block will trap an exception but be unable to handle it appropriately or fully. In these circumstances, a catch block can rethrow the exception using the `throw` statement without specifying any exception, as shown in Listing 4.25.

Listing 4.25: Rethrowing an Exception

```
...
      catch(Exception exception)
      {
          Console.WriteLine(
              $@"Rethrowing unexpected error:  {
                  exception.Message }");
          throw;
      }
...
```

In Listing 4.25, the `throw` statement is "empty" rather than specifying that the exception referred to by the `exception` variable is to be thrown. This illustrates a subtle difference: `throw;` preserves the "call stack" information in the exception, whereas `throw exception;` replaces that information with the current call stack information. For debugging purposes, it is usually better to know the original call stack.

Guidelines

DO prefer using an empty throw when catching and rethrowing an exception so as to preserve the call stack.

DO report execution failures by throwing exceptions rather than returning error codes.

DO NOT have public members that return exceptions as return values or an `out` parameter. Throw exceptions to indicate errors; do not use them as return values to indicate errors.

Avoid Using Exception Handling to Deal with Expected Situations

Developers should make an effort to avoid throwing exceptions for expected conditions or normal control flow. For example, developers should not expect users to enter valid text when specifying their age.[6] Therefore,

6. In general, developers should expect their users to perform unexpected actions, and therefore they should code defensively to handle "stupid user tricks."

instead of relying on an exception to validate data entered by the user, developers should provide a means of checking the data before attempting the conversion. (Better yet, they should prevent the user from entering invalid data in the first place.) Exceptions are designed specifically for tracking exceptional, unexpected, and potentially fatal situations. Using them for an unintended purpose such as expected situations will cause your code to be hard to read, understand, and maintain.

Additionally, like most languages, C# incurs a slight performance hit when throwing an exception—taking microseconds compared to the nanoseconds most operations take. This delay is generally not noticeable in human time—except when the exception goes unhandled. For example, when Listing 4.20 is executed and the user enters an invalid age, the exception is unhandled and there is a noticeable delay while the runtime searches the environment to see whether there is a debugger to load. Fortunately, slow performance when a program is shutting down isn't generally a factor to be concerned with.

Guidelines

DO NOT use exceptions for handling normal, expected conditions; use them for exceptional, unexpected conditions.

ADVANCED TOPIC

Begin 2.0

Numeric Conversion with `TryParse()`

One of the problems with the `Parse()` method is that the only way to determine whether the conversion will be successful is to attempt the cast and then catch the exception if it doesn't work. Because throwing an exception is a relatively expensive operation, it is better to attempt the conversion without exception handling. In the first release of C#, the only data type that enabled this behavior was a `double` method called `double.TryParse()`. However, the CLI added this method to all numeric primitive types in version 2.0. It requires the use of the `out` keyword because the return from the `TryParse()` function is a `bool` rather than the converted value. Listing 4.26 is a code snippet that demonstrates the conversion using `int.TryParse()`.

LISTING 4.26: Conversion Using `int.TryParse()`

```
if (int.TryParse(ageText, out age))
{
    Console.WriteLine(
        $"Hi { firstName }!  "
        + $"You are { age*12 } months old.");
}
else
{
    Console.WriteLine(
        $"The age entered, { ageText }, is not valid.");
}
```

With the .NET Framework 4, a `TryParse()` method was also added to enum types.

With the `TryParse()` method, it is no longer necessary to include a try/catch block simply for the purpose of handling the string-to-numeric conversion.

End 2.0

SUMMARY

This chapter discussed the details of declaring and calling methods, including the use of the keywords `out` and `ref` to pass variables rather than their values. In addition to method declaration, this chapter introduced exception handling.

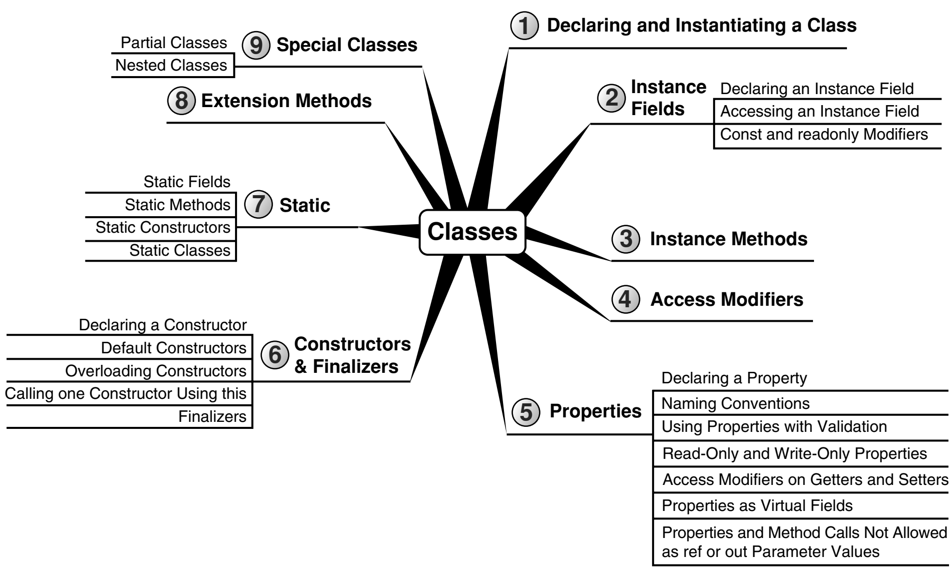
Methods are a fundamental construct that is a key to writing readable code. Instead of writing large methods with lots of statements, you should use methods to create “paragraphs” within your code, whose lengths are roughly 10 or fewer statements. The process of breaking large functions into smaller pieces is one of the ways you can refactor your code to make it more readable and maintainable.

The next chapter considers the class construct and describes how it encapsulates methods (behavior) and fields (data) into a single unit.

5

Classes

YOU BRIEFLY SAW IN CHAPTER 1 how to declare a new class called `HelloWorld`. In Chapter 2, you learned about the built-in primitive types included with C#. Since you have now also learned about control flow and how to declare methods, it is time to discuss defining your own types. This is the core construct of any C# program; this support for classes and the objects created from them is what makes C# an object-oriented language.



This chapter introduces the basics of object-oriented programming using C#. A key focus is on how to define **classes,** which are the templates for objects themselves.

All of the constructs of structured programming from the previous chapters still apply within object-oriented programming. However, by wrapping those constructs within classes, you can create larger, more organized programs that are more maintainable. The transition from structured, control-flow-based programs to object-oriented programs revolutionized programming because it provided an extra level of organization. The result was that smaller programs were simplified somewhat. Even more importantly, it was easier to create much larger programs because the code within those programs was better organized.

One of the key advantages of object-oriented programming is that instead of creating new programs entirely from scratch, you can assemble a collection of existing objects from prior work, extending the classes with new features, adding more classes, and thereby providing new functionality.

Readers unfamiliar with object-oriented programming should read the Beginner Topic blocks for an introduction. The general text outside the Beginner Topics focuses on using C# for object-oriented programming with the assumption that readers are already familiar with object-oriented concepts.

This chapter delves into how C# supports encapsulation through its support of constructs such as classes, properties, and access modifiers; we covered methods in the preceding chapter. The next chapter builds on this foundation with the introduction of inheritance and the polymorphism that object-oriented programming enables.

BEGINNER TOPIC

Object-Oriented Programming

The key to programming successfully today lies in the ability to provide organization and structure to the implementation of the complex requirements of large applications. Object-oriented programming provides one of the key methodologies in accomplishing this goal, to the point that it is difficult for object-oriented programmers to envision transitioning back to structured programming, except for the most trivial programs.

The most fundamental construct in object-oriented programming is the class. A group of classes form a programming abstraction, model, or template of what is often a real-world concept. The class `OpticalStorageMedia`, for example, may have an `Eject()` method on it that causes a disk to eject from the player. The `OpticalStorageMedia` class is the programming abstraction of the real-world object of a CD or DVD player.

Classes exhibit the three principal characteristics of object-oriented programming: encapsulation, inheritance, and polymorphism.

Encapsulation

Encapsulation allows you to hide details. The details can still be accessed when necessary, but by intelligently encapsulating the details, large programs are made easier to understand, data is protected from inadvertent modification, and code becomes easier to maintain because the effects of a code change are limited to the scope of the encapsulation. Methods are examples of encapsulation. Although it is possible to take the code from a method and embed it directly inline with the caller's code, refactoring of code into a method provides encapsulation benefits.

Inheritance

Consider the following example: A DVD drive is a type of optical media device. It has a specific storage capacity along with the ability to hold a digital movie. A CD drive is also a type of optical media device, but it has different characteristics. The copy protection on CDs is different from DVD copy protection, and the storage capacity is different as well. Both CD drives and DVD drives are different from hard drives, USB drives, and floppy drives (remember those?). All fit into the category of storage devices, but each has special characteristics, even for fundamental functions such as the supported filesystems and whether instances of the media are read-only or read/write.

Inheritance in object-oriented programming allows you to form "is a kind of" relationships between these similar but different items. It is reasonable to say that a DVD drive "is a kind of" storage media and that a CD drive "is a kind of" storage media, and as such, that each has storage capacity. We could also reasonably say that both have an "is a kind of" relationship with "optical storage media," which in turn "is a kind of" storage media.

If you define classes corresponding to each type of storage device mentioned, you will have defined a **class hierarchy,** which is a series of "is a kind of" relationships. The base class, from which all storage devices derive, could be the class `StorageMedia`. As such, classes that represent CD drives, DVD drives, hard drives, USB drives, and floppy drives are derived from the class `StorageMedia`. However, the classes for CD and DVD drives don't need to derive from `StorageMedia` directly. Instead, they can derive from an intermediate class, `OpticalStorageMedia`. You can view the class hierarchy graphically using a Unified Modeling Language (UML)–like class diagram, as shown in Figure 5.1.

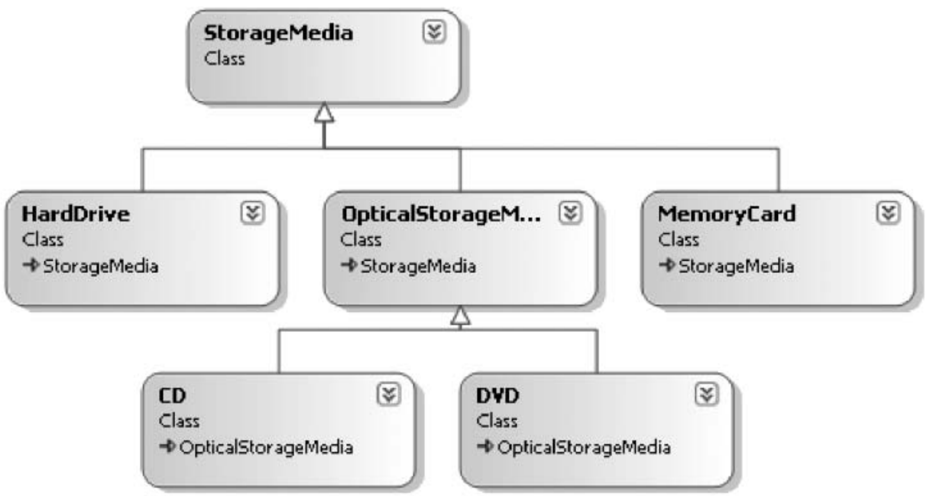


FIGURE 5.1: Class Hierarchy

The inheritance relationship involves a minimum of two classes, such that one class is a more specific kind of the other; in Figure 5.1, `HardDrive` is a more specific kind of `StorageMedia`. Although the more specialized type, `HardDrive`, is a kind of `StorageMedia`, the reverse is not true—that is, an instance of `StorageMedia` is not necessarily a `HardDrive`. As Figure 5.1 shows, inheritance can involve more than two classes.

The more specialized type is called the **derived type** or the **subtype.** The more general type is called the **base type** or the **super type.** The base type is also often called the "parent" type and its derived types are often called its "child" types. Though this usage is common, it can be confusing: After all, a child is not a kind of parent! In this book we will stick to "derived type" and "base type."

To **derive** or **inherit** from another type is to **specialize** that type, which means to customize the base type so that it is more suitable for a specific purpose. The base type may contain those implementation details that are common to all of the derived types.

The key feature of inheritance is that all derived types inherit the members of the base type. Often, the implementation of the base members can be modified, but regardless, the derived type contains the base type's members in addition to any other members that the derived type contains explicitly.

Derived types allow you to organize your classes into a coherent hierarchy where the derived types have greater specificity than their base types.

Polymorphism

Polymorphism is formed from *poly*, meaning "many," and *morph*, meaning "form." In the context of objects, polymorphism means that a single method or type can have many forms of implementation.

Suppose you have a media player that can play both CD music discs and DVDs containing MP3s. However, the exact implementation of the `Play()` method will vary depending on the media type. Calling `Play()` on an object representing a music CD or on an object representing a music DVD will play music in both cases, because each object's type understands the intricacies of playing. All that the media player knows about is the common base type, `OpticalStorageMedia`, and the fact that it defines the `Play()` method. Polymorphism is the principle that a type can take care of the exact details of a method's implementation because the method appears on multiple derived types, each of which shares a common base type (or interface) that also contains the same method signature.

Declaring and Instantiating a Class

Defining a class involves first specifying the keyword `class`, followed by an identifier, as shown in Listing 5.1.

LISTING 5.1: Defining a Class

```
class Employee
{
}
```

All code that belongs to the class will appear between the curly braces following the class declaration. Although not a requirement, generally you place each class into its own file. This makes it easier to find the code that defines a particular class, because the convention is to name the file using the class name.

Guidelines

DO NOT place more than one class in a single source file.

DO name the source file with the name of the public type it contains.

Once you have defined a new class, you can use that class as though it were built into the framework. In other words, you can declare a variable of that type or define a method that takes a parameter of the new class type. Listing 5.2 demonstrates such declarations.

Listing 5.2: Declaring Variables of the Class Type

```
class Program
{
  static void Main()
  {
      Employee employee1, employee2;
      // ...
  }

  static void IncreaseSalary(Employee employee)
  {
      // ...
  }
}
```

BEGINNER TOPIC

Objects and Classes Defined

In casual conversation, the terms *class* and *object* appear interchangeably. However, object and class have distinct meanings. A **class** is a template for what an object will look like at instantiation time. An **object,** therefore, is an instance of a class. Classes are like the mold for what a widget will look like. Objects correspond to widgets created by the mold. The process of creating an object from a class is called **instantiation** because an object is an instance of a class.

Now that you have defined a new class type, it is time to instantiate an object of that type. Mimicking its predecessors, C# uses the `new` keyword to instantiate an object (see Listing 5.3).

Listing 5.3: Instantiating a Class

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();
      Employee employee2;
      employee2 = new Employee();

      IncreaseSalary(employee1);
  }
}
```

Not surprisingly, the assignment can occur in the same statement as the declaration, or in a separate statement.

Unlike the primitive types you have worked with so far, there is no literal way to specify an `Employee`. Instead, the `new` operator provides an instruction to the runtime to allocate memory for an `Employee` object, instantiate the object, and return a reference to the instance.

Although an explicit operator for allocating memory exists, there is no such operator for de-allocating the memory. Instead, the runtime automatically reclaims the memory sometime after the object becomes inaccessible. The **garbage collector** is responsible for the automatic de-allocation. It determines which objects are no longer referenced by other active objects and then de-allocates the memory for those objects. The result is that there is no compile-time–determined program location where the memory will be collected and restored to the system.

In this trivial example, no explicit data or methods are associated with an `Employee`, which renders the object essentially useless. The next section focuses on adding data to an object.

BEGINNER TOPIC

Encapsulation Part 1: Objects Group Data with Methods

If you received a stack of index cards with employees' first names, a stack of index cards with their last names, and a stack of index cards with their salaries, the cards would be of little value unless you knew that the cards were in the same order in each stack. Even so, the data would be difficult to work with because determining a person's full name would require searching through two stacks. Worse, if you dropped one of the stacks, there would be no way to reassociate the first name with the last name and the salary. Instead, you would need one stack of employee cards in which all of the data is grouped on one card. With this approach, first names, last names, and salaries will be encapsulated together.

Outside the object-oriented programming context, to **encapsulate** a set of items is to enclose those items within a capsule. Similarly, object-oriented programming encapsulates methods and data together into an object. This provides a grouping of all of the class **members** (the data and methods within a class) so that they no longer need to be handled individually. Instead of passing a first name, a last name, and a salary as three separate parameters to a method, objects enable a call to pass a reference to an employee object. Once the called method receives the object reference, it can send a message (it can call a method such as AdjustSalary(), for example) to the object to perform a particular operation.

Language Contrast: C++—`delete` Operator

C# programmers should view the `new` operator as a call to instantiate an object, not as a call to allocate memory. Both objects allocated on the heap and objects allocated on the stack support the `new` operator, emphasizing the point that `new` is not about how memory allocation should take place and whether de-allocation is necessary.

Thus C# does not need the `delete` operator found in C++. Memory allocation and de-allocation are details that the runtime manages, allowing the developer to focus more on domain logic. However, though memory is managed by the runtime, the runtime does not manage other resources such as database connections, network ports, and so on. Unlike C++, C# does not support **implicit deterministic resource cleanup** (the occurrence of implicit object destruction at a compile-time–defined location in the code). Fortunately, C# does support **explicit deterministic resource cleanup** via a `using` statement, and **implicit nondeterministic resource cleanup** using finalizers.

Instance Fields

One of the key aspects of object-oriented design is the grouping of data to provide structure. This section discusses how to add data to the `Employee` class. The general object-oriented term for a variable that stores data within a class is **member variable.** This term is well understood in C#, but the more standard term and the one used in the specification is **field,** which is a named unit of storage associated with the containing type. **Instance fields** are variables declared at the class level to store data associated with an object. Hence, **association** is the relationship between the field data type and the containing field.

Declaring an Instance Field

In Listing 5.4, the class `Employee` has been modified to include three fields: `FirstName`, `LastName`, and `Salary`.

LISTING 5.4: Declaring Fields

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;
}
```

With these fields added, it is possible to store some fundamental data with every `Employee` instance. In this case, you prefix the fields with an access modifier of `public`. The use of `public` on a field indicates that the data within the field is accessible from classes other than `Employee` (see the section "Access Modifiers," later in this chapter).

As with local variable declarations, a field declaration includes the data type to which the field refers. Furthermore, it is possible to assign fields an initial value at declaration time, as demonstrated with the `Salary` field in Listing 5.5.

LISTING 5.5: Setting Initial Values of Fields at Declaration Time

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary = "Not enough";
}
```

We delay the guidelines of naming and coding fields until later in the chapter, after C# properties have been introduced. Suffice it to say, Listing 5.5 does *not* follow the general convention.

Accessing an Instance Field

You can set and retrieve the data within fields. However, the fact that a field does not include a `static` modifier indicates that it is an instance field. You can access an instance field only from an instance of the containing class (an object). You cannot access it from the class directly (without first creating an instance, in other words).

Listing 5.6 shows an updated look at the `Program` class and its utilization of the `Employee` class, and Output 5.1 shows the results.

Listing 5.6: Accessing Fields

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();
      Employee employee2;
      employee2 = new Employee();

      employee1.FirstName = "Inigo";
      employee1.LastName = "Montoya";
      employee1.Salary = "Too Little";
      IncreaseSalary(employee1);
      Console.WriteLine(
          "{0} {1}: {2}",
          employee1.FirstName,
          employee1.LastName,
          employee1.Salary);
      // ...
  }

  static void IncreaseSalary(Employee employee)
  {
      employee.Salary = "Enough to survive on";
  }
}
```

Output 5.1

```
Inigo Montoya: Enough to survive on
```

Listing 5.6 instantiates two `Employee` objects, as you saw before. Next, it sets each field, calls `IncreaseSalary()` to change the salary, and then displays each field associated with the object referenced by `employee1`.

Notice that you first have to specify which `Employee` instance you are working with. Therefore, the `employee1` variable appears as a prefix to the field name when assigning and accessing the field.

Instance Methods

One alternative to formatting the names in the `WriteLine()` method call within `Main()` is to provide a method in the `Employee` class that takes care of the formatting. Changing the functionality to be within the `Employee` class rather than a member of `Program` is consistent with the encapsulation of a class. Why not group the methods relating to the employee's full name with the class that contains the data that forms the name?

Listing 5.7 demonstrates the creation of such a method.

LISTING 5.7: Accessing Fields from within the Containing Class

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;

  public string GetName()
  {
      return $"{ FirstName }  { LastName }";
  }
}
```

There is nothing particularly special about this method compared to what you learned in Chapter 4, except that now the `GetName()` method accesses fields on the object instead of just local variables. In addition, the method declaration is not marked with `static`. As you will see later in this chapter, static methods cannot directly access instance fields within a class. Instead, it is necessary to obtain an instance of the class to call any instance member, whether a method or a field.

Given the addition of the `GetName()` method, you can update `Program.Main()` to use the method, as shown in Listing 5.8 and Output 5.2.

Listing 5.8: Accessing Fields from outside the Containing Class

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();
      Employee employee2;
      employee2 = new Employee();

      employee1.FirstName = "Inigo";
      employee1.LastName = "Montoya";
      employee1.Salary = "Too Little";
      IncreaseSalary(employee1);
      Console.WriteLine(
          $"{ employee1.GetName() }: { employee1.Salary }");
      // ...
  }
  // ...
}
```

Output 5.2

```
Inigo Montoya: Enough to survive on
```

Using the this Keyword

You can obtain the reference to a class from within instance members that belong to the class. To indicate explicitly that the field or method accessed is an instance member of the containing class in C#, you use the keyword `this`. Use of `this` is implicit when calling any instance member, and it returns an instance of the object itself.

For example, consider the `SetName()` method shown in Listing 5.9.

Listing 5.9: Using this to Identify the Field's Owner Explicitly

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;

  public string GetName()
  {
      return $"{ FirstName }  { LastName }";
  }

  public void SetName(
```

```
        string newFirstName, string newLastName)
    {
        this.FirstName = newFirstName;
        this.LastName = newLastName;
    }
}
```

This example uses the keyword `this` to indicate that the fields `FirstName` and `LastName` are instance members of the class.

Although the `this` keyword can prefix any and all references to local class members, the general guideline is not to clutter code when there is no additional value. Therefore, you should avoid using the `this` keyword unless it is required. Listing 5.12 (later in this chapter) is an example of one of the few circumstances when such a requirement exists. Listings 5.9 and 5.10, however, are not good examples. In Listing 5.9, `this` can be dropped entirely without changing the meaning of the code. And in Listing 5.10 (presented next), by changing the naming convention for fields, we can avoid any ambiguity between local variables and fields.

BEGINNER TOPIC

Relying on Coding Style to Avoid Ambiguity

In the `SetName()` method, you did not have to use the `this` keyword because `FirstName` is obviously different from `newFirstName`. But suppose that, instead of calling the parameter “newFirstName,” you called it “FirstName” (using PascalCase), as shown in Listing 5.10.

LISTING 5.10: Using this to Avoid Ambiguity

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;

  public string GetName()
  {
      return $"{ FirstName }  { LastName }";
  }

  // Caution:  Parameter names use PascalCase
  public void SetName(string FirstName, string LastName)
  {
```

```
        this.FirstName = FirstName;
        this.LastName = LastName;
    }
  }
```

In this example, it is not possible to refer to the FirstName field without explicitly indicating that the Employee object owns the variable. this acts just like the employee1 variable prefix used in the Program.Main() method (see Listing 5.8); it identifies the reference as the one on which SetName() was called.

Listing 5.10 does not follow the C# naming convention in which parameters are declared like local variables, using camelCase. This can lead to subtle bugs, because assigning FirstName (intending to refer to the field) to FirstName (the parameter) will lead to code that still compiles and even runs. To avoid this problem, it is a good practice to have a different naming convention for parameters and local variables than the naming convention for fields. We demonstrate one such convention later in this chapter.

Language Contrast: Visual Basic—Accessing a Class Instance with Me

The C# keyword this is identical to the Visual Basic keyword Me.

In Listing 5.9 and Listing 5.10, the this keyword is not used in the GetName() method—it is optional. However, if local variables or parameters exist with the same name as the field (see the SetName() method in Listing 5.10), omitting this would result in accessing the local variable/parameter when the intention was the field; given this scenario, use of this is required.

You also can use the keyword this to access a class's methods explicitly. For example, this.GetName() is allowed within the SetName() method, permitting you to print out the newly assigned name (see Listing 5.11 and Output 5.3).

Listing 5.11: Using this with a Method

```
class Employee
{
  // ...
```

```
  public string GetName()
  {
      return $"{ FirstName }  { LastName }";
  }

  public void SetName(string newFirstName, string newLastName)
  {
      this.FirstName = newFirstName;
      this.LastName = newLastName;
      Console.WriteLine(
          $"Name changed to ‘{ this.GetName() }’");
  }
}
```

```
class Program
{
  static void Main()
  {
      Employee employee = new Employee();

      employee.SetName("Inigo", "Montoya");
      // ...
  }
  // ...
}
```

Output 5.3

```
Name changed to 'Inigo Montoya'
```

Sometimes it may be necessary to use `this` to pass a reference to the currently executing object. Consider the `Save()` method in Listing 5.12.

Listing 5.12: Passing this in a Method Call

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;

  public void Save()
  {
      DataStorage.Store(this);
  }
}
```

```
class DataStorage
{
  // Save an employee object to a file
  // named with the Employee name.
  public static void Store(Employee employee)
  {
      // ...
  }
}
```

The `Save()` method in Listing 5.12 calls a method on the `DataStorage` class, called `Store()`. The `Store()` method, however, needs to be passed the `Employee` object, which needs to be persisted. This is done using the keyword `this`, which passes the instance of the `Employee` object on which `Save()` was called.

ADVANCED TOPIC

Storing and Loading with Files

The actual implementation of the `Store()` method inside `DataStorage` involves classes within the `System.IO` namespace, as shown in Listing 5.13. Inside `Store()`, you begin by instantiating a `FileStream` object that you associate with a file corresponding to the employee's full name. The `FileMode.Create` parameter indicates that you want a new file to be created if there isn't already one with the `<firstname><lastname>.dat` name; if the file exists already, it will be overwritten. Next, you create a `StreamWriter` class. The `StreamWriter` class is responsible for writing text into the `FileStream`. You write the data using `WriteLine()` methods, just as though writing to the console.

Listing 5.13: Data Persistence to a File

```
using System;
// IO namespace
using System.IO;

class DataStorage
{
  // Save an employee object to a file
  // named with the Employee name.
  // Error handling not shown.
  public static void Store(Employee employee)
  {
```

```
        // Instantiate a FileStream using FirstNameLastName.dat
        // for the filename. FileMode.Create will force
        // a new file to be created or override an
        // existing file.
        FileStream stream = new FileStream(
            employee.FirstName + employee.LastName + ".dat",
            FileMode.Create);1

        // Create a StreamWriter object for writing text
        // into the FileStream.
        StreamWriter writer = new StreamWriter(stream);

        // Write all the data associated with the employee.
        writer.WriteLine(employee.FirstName);
        writer.WriteLine(employee.LastName);
        writer.WriteLine(employee.Salary);

        // Close the StreamWriter and its stream.
        writer.Close();  // Automatically closes the stream
    }
    // ...
}
```

Once the write operations are completed, both the `FileStream` and the `StreamWriter` need to be closed so that they are not left open indefinitely while waiting for the garbage collector to run. Listing 5.13 does not include any error handling, so if an exception is thrown, neither `Close()` method will be called.

The load process is similar (see Listing 5.14).

LISTING 5.14: Data Retrieval from a File

```
class Employee
{
  // ...
}
```

```
// IO namespace
using System;
using System.IO;

class DataStorage
{
  // ...

  public static Employee Load(string firstName, string lastName)
```

1. This code could be improved with a `using` statement, a construct that we have avoided because it has not yet been introduced.

```
    {
        Employee employee = new Employee();

        // Instantiate a FileStream using FirstNameLastName.dat
        // for the filename. FileMode.Open will open
        // an existing file or else report an error.
        FileStream stream = new FileStream(
            firstName + lastName + ".dat", FileMode.Open);[2]

        // Create a SteamReader for reading text from the file.
        StreamReader reader = new StreamReader(stream);

        // Read each line from the file and place it into
        // the associated property.
        employee.FirstName = reader.ReadLine();
        employee.LastName = reader.ReadLine();
        employee.Salary = reader.ReadLine();

        // Close the StreamReader and its stream.
        reader.Close();  // Automatically closes the stream

        return employee;
    }
}
```

```
class Program
{
    static void Main()
    {
          Employee employee1;

          Employee employee2 = new Employee();
          employee2.SetName("Inigo", "Montoya");
          employee2.Save();

         // Modify employee2 after saving.
          IncreaseSalary(employee2);

          // Load employee1 from the saved version of employee2
          employee1 = DataStorage.Load("Inigo", "Montoya");

          Console.WriteLine(
              $"{ employee1.GetName() }: { employee1.Salary }");

          // ...
    }
    // ...
}
```

2. This code could be improved with a `using` statement, a construct that we have avoided because it has not yet been introduced.

Output 5.4 shows the results.

Output 5.4

```
Name changed to 'Inigo Montoya'
Inigo Montoya:
```

The reverse of the save process appears in Listing 5.14, which uses a `StreamReader` rather than a `StreamWriter`. Again, `Close()` needs to be called on both `FileStream` and `StreamReader` once the data has been read.

Output 5.4 does not show any salary after `Inigo Montoya:` because `Salary` was not set to `Enough to survive on` by a call to `IncreaseSalary()` until after the call to `Save()`.

Notice in `Main()` that we can call `Save()` from an instance of an employee, but to load a new employee we call `DataStorage.Load()`. To load an employee, we generally don't already have an employee instance to load into, so an instance method on `Employee` would be less than ideal. An alternative to calling `Load` on `DataStorage` would be to add a static `Load()` method (see the section "Static Members," later in this chapter) to `Employee` so that it would be possible to call `Employee.Load()` (using the `Employee` class, not an instance of `Employee`).

Notice the inclusion of the `using System.IO` directive at the top of the listing. This makes each `IO` class accessible without prefixing it with the full namespace.

Access Modifiers

When declaring a field earlier in the chapter, you prefixed the field declaration with the keyword `public`. `public` is an **access modifier** that identifies the level of encapsulation associated with the member it decorates. Five access modifiers are available: `public`, `private`, `protected`, `internal`, and `protected internal`. This section considers the first two.

BEGINNER TOPIC

Encapsulation Part 2: Information Hiding

Besides wrapping data and methods together into a single unit, encapsulation deals with hiding the internal details of an object's data and behavior.

To some degree, methods do this; from outside a method, all that is visible to a caller is the method declaration. None of the internal implementation is visible. Object-oriented programming enables this further, however, by providing facilities for controlling the extent to which members are visible from outside the class. Members that are not visible outside the class are **private members.**

In object-oriented programming, *encapsulation* is the term for not only grouping data and behavior, but also hiding data and behavior implementation details within a class (the capsule) so that the inner workings of a class are not exposed. This reduces the chance that callers will modify the data inappropriately or program according to the implementation, only to have it change in the future.

The purpose of an access modifier is to provide encapsulation. By using `public`, you explicitly indicate that it is acceptable that the modified fields are accessible from outside the `Employee` class—in other words, that they are accessible from the `Program` class, for example.

Consider an `Employee` class that includes a `Password` field, however. It should be possible to call an `Employee` object and verify the password using a `Logon()` method. Conversely, it should not be possible to access the `Password` field on an `Employee` object from outside the class.

To define a `Password` field as hidden and inaccessible from outside the containing class, you use the keyword `private` for the access modifier, in place of `public` (see Listing 5.15). As a result, the `Password` field is not accessible from inside the `Program` class, for example.

LISTING 5.15: Using the `private` Access Modifier

```
class Employee
{
  public string FirstName;
  public string LastName;
  public string Salary;
  private string Password;
  private bool IsAuthenticated;

  public bool Logon(string password)
  {
      if(Password == password)
      {
          IsAuthenticated = true;
      }
      return IsAuthenticated;
```

```
    }

    public bool GetIsAuthenticated()
    {
        return IsAuthenticated;
    }
    // ...
}
```

```
class Program
{
    static void Main()
    {
        Employee employee = new Employee();

        employee.FirstName = "Inigo";
        employee.LastName = "Montoya";

        // ...

        // Password is private, so it cannot be
        // accessed from outside the class.
        // Console.WriteLine(
        //    ("Password = {0}", employee.Password);
    }
    // ...
}
```

Although this option is not shown in Listing 5.15, it is possible to decorate a method with an access modifier of `private` as well.

If no access modifier is placed on a class member, the declaration defaults to `private`. In other words, members are private by default and programmers need to specify explicitly that a member is to be public.

Properties

The preceding section, "Access Modifiers," demonstrated how you can use the `private` keyword to encapsulate a password, preventing access from outside the class. This type of encapsulation is often too strict, however. For example, sometimes you might need to define fields that external classes can only read, but whose values you can change internally. Alternatively, perhaps you want to allow access to write some data in a class, but you need to be able to validate changes made to the data. In yet another scenario, perhaps you need to construct the data on the fly. Traditionally, languages enabled the features found in these examples by marking fields as private and then providing getter and setter methods for accessing and modifying the data. The code in Listing 5.16 changes both `FirstName` and `LastName` to private fields. Public getter and setter methods for each field allow their values to be accessed and changed.

Listing 5.16: Declaring Getter and Setter Methods

```
class Employee
{

  private string FirstName;
  // FirstName getter
  public string GetFirstName()
  {
      return FirstName;
  }
  // FirstName setter
  public void SetFirstName(string newFirstName)
  {
      if(newFirstName != null && newFirstName != "")
      {
          FirstName = newFirstName;
      }
  }

  private string LastName;
  // LastName getter
  public string GetLastName()
  {
      return LastName;
  }
  // LastName setter
  public void SetLastName(string newLastName)
  {
      if(newLastName != null && newLastName != "")
      {
          LastName = newLastName;
      }
  }
  // ...
}
```

Unfortunately, this change affects the programmability of the `Employee` class. No longer can you use the assignment operator to set data within the class, nor can you access the data without calling a method.

Declaring a Property

Recognizing the frequency of this type of pattern, the C# designers provided explicit syntax for it. This syntax is called a **property** (see Listing 5.17 and Output 5.5).

LISTING 5.17: Defining Properties

```
class Program
{
  static void Main()
  {
      Employee employee = new Employee();

      // Call the FirstName property's setter.
      employee.FirstName = "Inigo";

      // Call the FirstName property's getter.
      System.Console.WriteLine(employee.FirstName);
  }
}
```

```
class Employee
{
  // FirstName property
  public string FirstName
  {
      get
      {
          return _FirstName;
      }
      set
      {
          _FirstName = value;
      }
  }
  private string _FirstName;

  // LastName property
  public string LastName
  {
      get
      {
          return _LastName;
      }
      set
      {
          _LastName = value;
      }
  }
  private string _LastName;
  // ...
}
```

OUTPUT 5.5

```
Inigo
```

The first thing to notice in Listing 5.17 is not the property code itself, but rather the code within the `Program` class. Although you no longer have the fields with the `FirstName` and `LastName` identifiers, you cannot see this by looking at the `Program` class. The API for accessing an employee's first and last names has not changed at all. It is still possible to assign the parts of the name using a simple assignment operator, for example (`employee.FirstName = "Inigo"`).

The key feature is that properties provide an API that looks programmatically like a field. In actuality, no such fields exist. A property declaration looks exactly like a field declaration, but following it are curly braces in which to place the property implementation. Two optional parts make up the property implementation. The `get` part defines the getter portion of the property. It corresponds directly to the `GetFirstName()` and `GetLastName()` functions defined in Listing 5.16. To access the `FirstName` property, you call `employee.FirstName`. Similarly, setters (the `set` portion of the implementation) enable the calling syntax of the field assignment:

```
employee.FirstName = "Inigo";
```

Property definition syntax uses three contextual keywords. You use the `get` and `set` keywords to identify either the retrieval or the assignment portion of the property, respectively. In addition, the setter uses the `value` keyword to refer to the right side of the assignment operation. When `Program.Main()` calls `employee.FirstName = "Inigo"`, therefore, `value` is set to `"Inigo"` inside the setter and can be used to assign `_FirstName`. Listing 5.17's property implementations are the most commonly used. When the getter is called (such as in `Console.WriteLine(employee.FirstName)`), the value from the field (`_FirstName`) is obtained and written to the console.

Begin 3.0

Automatically Implemented Properties

In C# 3.0, property syntax includes a shorthand version. Since a property with a single backing field that is assigned and retrieved by the get and set accessors is so trivial and common (see the implementations of `FirstName` and `LastName`), the C# 3.0 compiler (and higher) allows the declaration of a property without any accessor implementation or backing field declaration. Listing 5.18 demonstrates the syntax with the `Title` and `Manager` properties, and Output 5.6 shows the results.

Listing 5.18: Automatically Implemented Properties

```
class Program
{
  static void Main()
  {
        Employee employee1 =
            new Employee();
        Employee employee2 =
            new Employee();

        // Call the FirstName property's setter.
        employee1.FirstName = "Inigo";

        // Call the FirstName property's getter.
        System.Console.WriteLine(employee1.FirstName);

        // Assign an auto-implemented property
        employee2.Title = "Computer Nerd";
        employee1.Manager = employee2;

        // Print employee1's manager's title.
        System.Console.WriteLine(employee1.Manager.Title);
  }
}
```

```
class Employee
{
  // FirstName property
  public string FirstName
  {
      get
      {
          return _FirstName;
      }
      set
      {
          _FirstName = value;
      }
  }
  private string _FirstName;

  // LastName property
  public string LastName
  {
      get
      {
          return _LastName;
      }
      set
      {
          _LastName = value;
      }
```

3.0

```
    }
    private string _LastName;

    public string Title { get; set; }

    public Employee Manager { get; set; }

    public string Salary { get; set; } = "Not Enough";
    // ...
  }
```

OUTPUT 5.6

```
Inigo
Computer Nerd
```

Auto-implemented properties provide for a simpler way of writing properties in addition to reading them. Furthermore, when it comes time to add something such as validation to the setter, any existing code that calls the property will not have to change, even though the property declaration will have changed to include an implementation.

End 3.0

Throughout the remainder of the book, we will frequently use this C# 3.0 or later syntax without indicating that it is a feature introduced in C# 3.0.

Begin 6.0

One final thing to note about automatically declared properties is that in C# 6.0, it is possible to initialize them as Listing 5.18 does for `Salary`:

```
public string Salary { get; set; } = "Not Enough";
```

Prior to C# 6.0, property initialization was possible only via a method (including the constructor, as we discuss later in the chapter). However, with C# 6.0, you can initialize automatically implemented properties at declaration time using a syntax much like that used for field initialization.

End 6.0

Property and Field Guidelines

Given that it is possible to write explicit setter and getter methods rather than properties, on occasion a question may arise as to whether it is better to use a property or a method. The general guideline is that methods should represent actions and properties should represent data. Properties are intended to provide simple access to simple data with a simple computation. The expectation is that invoking a property will not be significantly more expensive than accessing a field.

With regard to naming, notice that in Listing 5.18 the property name is `FirstName`, and the field name changed from earlier listings to `_FirstName`—that is, PascalCase with an underscore suffix. Other common naming conventions for the private field that backs a property are `_firstName` and `m_FirstName` (a holdover from C++, where the *m* stands for member variable), and on occasion the camelCase convention, just like with local variables.[3] The camelCase convention should be avoided, however. The camelCase used for property names is the same as the naming convention used for local variables and parameters, meaning that overlaps in names become highly probable. Also, to respect the principles of encapsulation, fields should not be declared as public or protected.

Guidelines

DO use properties for simple access to simple data with simple computations.

AVOID throwing exceptions from property getters.

DO preserve the original property value if the property throws an exception.

DO favor automatically implemented properties over properties with simple backing fields when no additional logic is required.

Regardless of which naming pattern you use for private fields, the coding standard for properties is PascalCase. Therefore, properties should use the `LastName` and `FirstName` pattern with names that represent nouns, noun phrases, or adjectives. It is not uncommon, in fact, that the property name is the same as the type name. Consider an `Address` property of type `Address` on a `Person` object, for example.

3. We prefer `_FirstName` because the *m* in front of the name is unnecessary when compared with an underscore (_). Also, by using the same casing as the property, it is possible to have only one string within the Visual Studio code template expansion tools, instead of having one for both the property name and the field name.

Guidelines

CONSIDER using the same casing on a property's backing field as that used in the property, distinguishing the backing field with an "_" prefix. Do not, however, use two underscores; identifiers beginning with two underscores are reserved for the use of the C# compiler itself.

DO name properties using a noun, noun phrase, or adjective.

CONSIDER giving a property the same name as its type.

AVOID naming fields with camelCase.

DO favor prefixing Boolean properties with "Is," "Can," or "Has," when that practice adds value.

DO NOT declare instance fields that are public or protected. (Instead, expose them via a property.)

DO name properties with PascalCase.

DO favor automatically implemented properties over fields.

DO favor automatically implemented properties over using fully expanded ones if there is no additional implementation logic.

Using Properties with Validation

Notice in Listing 5.19 that the `Initialize()` method of `Employee` uses the property rather than the field for assignment as well. Although this is not required, the result is that any validation within the property setter will be invoked both inside and outside the class. Consider, for example, what would happen if you changed the `LastName` property so that it checked `value` for `null` or an empty string, before assigning it to `_LastName`.

LISTING 5.19: Providing Property Validation

```
class Employee
{
  // ...
  public void Initialize(
      string newFirstName, string newLastName)
  {
      // Use property inside the Employee
      // class as well.
      FirstName = newFirstName;
      LastName = newLastName;
  }


  // LastName property
  public string LastName
```

```
    {
        get
        {
            return _LastName;
        }
        set
        {
            // Validate LastName assignment
            if(value == null)
            {
                // Report error
                // In C# 6.0 replace "value" with nameof(value)
                throw new ArgumentNullException("value");
            }
            else
            {
                // Remove any whitespace around
                // the new last name.
                value = value.Trim();
                if(value == "")
                {
                    // Report error
                    // In C# 6.0 replace "value" with nameof(value)
                    throw new ArgumentException(
                        "LastName cannot be blank.", "value");[4]
                }
                else
                    _LastName = value;
            }
        }
    }
    private string _LastName;
    // ...
  }
```

With this new implementation, the code throws an exception if `LastName` is assigned an invalid value, either from another member of the same class or via a direct assignment to `LastName` from inside `Program.Main()`. The ability to intercept an assignment and validate the parameters by providing a field-like API is one of the advantages of properties.

It is a good practice to access a property-backing field only from inside the property implementation. In other words, you should always use the property, rather than calling the field directly. In many cases, this principle holds even from code within the same class as the property. If you follow

4. Apologies to Teller, Cher, Sting, Madonna, Bono, Prince, Liberace, et al.

this practice, when you add code such as validation code, the entire class immediately takes advantage of it.[5]

Although rare, it is possible to assign `value` inside the setter, as Listing 5.19 does. In this case, the call to `value.Trim()` removes any whitespace surrounding the new last name value.

Guidelines

AVOID accessing the backing field of a property outside the property, even from within the containing class.

DO use "value" for the `paramName` argument when calling the `ArgumentException()` or `ArgumentNullException()` constructor ("value" is the implicit name of the parameter on property setters).

Begin 6.0

ADVANCED TOPIC

nameof Operator

If during property validation you determine that the new value assignment is invalid, it is necessary to throw an exception—generally of type `ArgumentException()` or `ArgumentNullException()`. Both of these exceptions take an argument of type `string` called `paramName` that identifies the name of the parameter that is invalid. In Listing 5.19, we pass `"value"` as the argument for this parameter, but C# 6.0 provides an improvement with the `nameof` operator. The `nameof` operator takes an identifier, like the `value` variable, and returns a string representation of that name—in this case, `"value"`.

The advantage of using the `nameof` operator is that if the identifier name changes, then refactoring tools will automatically change the argument to `nameof` as well. If no refactoring tool is used, the code will no longer compile, forcing the developer to change the argument manually.

In the case of a property validator, the "parameter" is always `value` and cannot be changed, so the benefits of leveraging the `nameof` operator are

5. As described later in the chapter, one exception to this occurs when the field is marked as read-only, because then the value can be set only in the constructor. In C# 6.0, you can directly assign the value of a read-only property, completely eliminating the need for the read-only field.

arguably lost. Nonetheless, consider continued use of the `nameof` operator in all cases of the `paramName` argument to remain consistent with the guideline: Always use `nameof` for the `paramName` argument passed into exceptions like `ArgumentNullException` and `ArgumentNullException` that take such a parameter.

End 6.0

Read-Only and Write-Only Properties

By removing either the getter or the setter portion of a property, you can change a property's accessibility. Properties with only a setter are write-only, which is a relatively rare occurrence. Similarly, providing only a getter will cause the property to be read-only; any attempts to assign a value will cause a compile error. To make `Id` read-only, for example, you would code it as shown in Listing 5.20.

Listing 5.20: Defining a Read-Only Property prior to C# 6.0

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();
      employee1.Initialize(42);

      // ERROR:  Property or indexer 'Employee.Id'
      // cannot be assigned to; it is read-only.
      // employee1.Id = "490";
  }
}

class Employee
{
  public void Initialize(int id)
  {
      // Use field because Id property has no setter;
      // it is read-only.
      _Id = id.ToString();
  }

  // ...
  // Id property declaration
  public string Id
  {
      get
      {
          return _Id;
      }
```

```
        // No setter provided.
    }
    private string _Id;

  }
```

Listing 5.20 assigns the field from within the `Employee` constructor rather than the property (`_Id = id`). Assigning via the property causes a compile error, as it does in `Program.Main()`.

Begin 6.0

Starting in C# 6.0, there is also support for read-only **automatically implemented properties** as follows:

```
public bool[,,] Cells { get; } = new bool[2, 3, 3];
```

This is clearly a significant improvement over the pre-C# 6.0 approach, especially given the commonality of read-only properties for something like an array of items or the `Id` in Listing 5.20.

One important note about a read-only automatically implemented property is that, like read-only fields, the compiler requires that it be initialized in the constructor or via an initializer. In the preceding snippet we use an initializer, but the assignment of `Cells` from within the constructor is also permitted.

Given the guideline that fields should not be accessed from outside their wrapping property, those programming in a C# 6.0 world will discover that there is virtually no need to ever use pre-C# 6.0 syntax; instead, the programmer can always use a read-only, automatically implemented property. The only exception might be when the data type of the read-only modified field does not match the data type of the property—for example, if the field was of type `int` and the read-only property was of type `double`.

Guidelines

DO create read-only properties if the property value should not be changed.

DO create read-only automatically implemented properties in C# 6.0 (or later) rather than read-only properties with a backing field if the property value should not be changed

End 6.0

Properties As Virtual Fields

As you have seen, properties behave like virtual fields. In some instances, you do not need a backing field at all. Instead, the property getter returns a calculated value while the setter parses the value and persists it to some other member fields (if it even exists). Consider, for example, the `Name` property implementation shown in Listing 5.21. Output 5.7 shows the results.

LISTING 5.21: Defining Properties

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();

      employee1.Name = "Inigo Montoya";
      System.Console.WriteLine(employee1.Name);

      // ...
  }
}
```

```
class Employee
{
  // ...

  // FirstName property
  public string FirstName
  {
      get
      {
          return _FirstName;
      }
      set
      {
          _FirstName = value;
      }
  }
  private string _FirstName;

  // LastName property
  public string LastName
  {
      get
      {
          return _LastName;
      }
```

```
        set
        {
            _LastName = value;
        }
    }
    private string _LastName;
    // ...

    // Name property
    public string Name
    {
        get
        {
            return $"{ FirstName } { LastName }";
        }
        set
        {
            // Split the assigned value into
            // first and last names.
            string[] names;
            names = value.Split(new char[]{' '});
            if(names.Length == 2)
            {
                FirstName = names[0];
                LastName = names[1];
            }
            else
            {
                // Throw an exception if the full
                // name was not assigned.
               throw new System. ArgumentException (
                    $"Assigned value '{ value }' is invalid", "value");
            }
        }
    }
    public string Initials => $"{ FirstName[0] } { LastName[0] }";
    // ...
  }
```

Output 5.7

```
Inigo Montoya
```

The getter for the `Name` property concatenates the values returned from the `FirstName` and `LastName` properties. In fact, the name value assigned is not actually stored. When the `Name` property is assigned, the value on the right side is parsed into its first and last name parts.

Begin 2.0

Access Modifiers on Getters and Setters

As previously mentioned, it is a good practice not to access fields from outside their properties because doing so circumvents any validation or additional logic that may be inserted. Unfortunately, C# 1.0 did not allow different levels of encapsulation between the getter and setter portions of a property. It was not possible, therefore, to create a public getter and a private setter so that external classes would have read-only access to the property while code within the class could write to the property.

In C# 2.0, support was added for placing an access modifier on either the get or the set portion of the property implementation (not on both), thereby overriding the access modifier specified on the property declaration. Listing 5.22 demonstrates how to do this.

LISTING 5.22: Placing Access Modifiers on the Setter

```
class Program
{
  static void Main()
  {
      Employee employee1 = new Employee();
      employee1.Initialize(42);
      // ERROR: The property or indexer 'Employee.Id'
      // cannot be used in this context because the set
      // accessor is inaccessible
      employee1.Id = "490";
  }
}
```

```
class Employee
{
  public void Initialize(int id)
  {
      // Set Id property
      Id = id.ToString();
  }

  // ...
  // Id property declaration
  public string Id
  {
      get
      {
          return _Id;
      }
      // Providing an access modifier is possible in C# 2.0
      // and higher only
      private set
```

```
        {
            _Id = value;
        }
    }
    private string _Id;

  }
```

By using `private` on the setter, the property appears as read-only to classes other than `Employee`. From within `Employee`, the property appears as read/write, so you can assign the property within the constructor. When specifying an access modifier on the getter or setter, take care that the access modifier is more restrictive than the access modifier on the property as a whole. It is a compile error, for example, to declare the property as `private` and the setter as `public`.

Guidelines

DO apply appropriate accessibility modifiers on implementations of getters and setters on all properties.

DO NOT provide set-only properties or properties with the setter having broader accessibility than the getter.

End 2.0

Properties and Method Calls Not Allowed As `ref` or `out` Parameter Values

C# allows properties to be used identically to fields, except when they are passed as `ref` or `out` parameter values. `ref` and `out` parameter values are internally implemented by passing the memory address to the target method. However, because properties can be virtual fields that have no backing field, or can be read-only or write-only, it is not possible to pass the address for the underlying storage. As a result, you cannot pass properties as `ref` or `out` parameter values. The same is true for method calls. Instead, when code needs to pass a property or method call as a `ref` or `out` parameter value, the code must first copy the value into a variable and then pass the variable. Once the method call has completed, the code must assign the variable back into the property.

ADVANCED TOPIC

Property Internals

Listing 5.23 shows that getters and setters are exposed as `get_FirstName()` and `set_FirstName()` in the CIL.

LISTING 5.23: CIL Code Resulting from Properties

```
// ...

.field private string _FirstName
.method public hidebysig specialname instance string
        get_FirstName() cil managed
{
  // Code size       12 (0xc)
  .maxstack  1
  .locals init (string V_0)
  IL_0000:  nop
  IL_0001:  ldarg.0
  IL_0002:  ldfld      string Employee::_FirstName
  IL_0007:  stloc.0
  IL_0008:  br.s       IL_000a

  IL_000a:  ldloc.0
  IL_000b:  ret
} // end of method Employee::get_FirstName

.method public hidebysig specialname instance void
        set_FirstName(string 'value') cil managed
{
  // Code size       9 (0x9)
  .maxstack  8
  IL_0000:  nop
  IL_0001:  ldarg.0
  IL_0002:  ldarg.1
  IL_0003:  stfld      string Employee::_FirstName
  IL_0008:  ret
} // end of method Employee::set_FirstName

.property instance string FirstName()
{
  .get instance string Employee::get_FirstName()
  .set instance void Employee::set_FirstName(string)
} // end of property Employee::FirstName

// ...
```

Just as important to their appearance as regular methods is the fact that properties are an explicit construct within the CIL, too. As Listing 5.24

shows, the getters and setters are called by CIL properties, which are an explicit construct within the CIL code. Because of this, languages and compilers are not restricted to always interpreting properties based on a naming convention. Instead, CIL properties provide a means for compilers and code editors to provide special syntax.

LISTING 5.24: Properties Are an Explicit Construct in CIL

```
.property instance string FirstName()
{
  .get instance string Program::get_FirstName()
  .set instance void Program::set_FirstName(string)
} // end of property Program::FirstName
```

Notice in Listing 5.23 that the getters and setters that are part of the property include the `specialname` metadata. This modifier is what IDEs, such as Visual Studio, use as a flag to hide the members from IntelliSense.

Begin 3.0

An automatically implemented property is almost identical to one for which you define the backing field explicitly. In place of the manually defined backing field, the C# compiler generates a field with the name `<PropertyName>k_BackingField` in IL. This generated field includes an attribute (see Chapter 17) called `System.Runtime.CompilerServices.CompilerGeneratedAttribute`. Both the getters and the setters are decorated with the same attribute because they, too, are generated—with the same implementation as in Listings 5.23 and 5.24.

End 3.0

Constructors

Now that you have added fields to a class and can store data, you need to consider the validity of that data. As you saw in Listing 5.3, it is possible to instantiate an object using the `new` operator. The result, however, is the ability to create an employee with invalid data. Immediately following the assignment of `employee`, you have an `Employee` object whose name and salary are not initialized. In this particular listing, you assigned the uninitialized fields immediately following the instantiation of an employee, but if you failed to do the initialization, you would not receive a warning from the compiler. As a result, you could end up with an `Employee` object with an invalid name.

Declaring a Constructor

To correct this problem, you need to provide a means of specifying the required data when the object is created. You do this using a constructor as demonstrated in Listing 5.25.

Listing 5.25: Defining a Constructor

```
class Employee
{
  // Employee constructor
  public Employee(string firstName, string lastName)
  {
    FirstName = firstName;
    LastName = lastName;
  }

  public string FirstName{ get; set; }
  public string LastName{ get; set; }
  public string Salary{ get; set; } = "Not Enough";

  // ...
}
```

As shown here, to define a constructor you create a method with no return type, whose method name is identical to the class name.

The constructor is the method that the runtime calls to initialize an instance of the object. In this case, the constructor takes the first name and the last name as parameters, allowing the programmer to specify these names when instantiating the `Employee` object. Listing 5.26 is an example of how to call a constructor.

Listing 5.26: Calling a Constructor

```
class Program
{
  static void Main()
  {
      Employee employee;
      employee = new Employee("Inigo", "Montoya");
      employee.Salary = "Too Little";

      System.Console.WriteLine(
          "{0} {1}: {2}",
          employee.FirstName,
          employee.LastName,
          employee.Salary);
  }
  // ...
}
```

Notice that the `new` operator returns the type of the object being instantiated (even though no return type or return statement was specified explicitly in the constructor's declaration or implementation). In addition, you have removed the initialization code for the first and last names because that initialization takes place within the constructor. In this example, you don't initialize `Salary` within the constructor, so the code assigning the salary still appears.

Developers should take care when using both assignment at declaration time and assignment within constructors. Assignments within the constructor will occur after any assignments are made when a field is declared (such as `string Salary = "Not enough"` in Listing 5.5). Therefore, assignment within a constructor will override any value assigned at declaration time. This subtlety can lead to a misinterpretation of the code by a casual reader who assumes the value after instantiation is the one assigned in the field declaration. Therefore, it is worth considering a coding style that does not mix both declaration assignment and constructor assignment within the same class.

ADVANCED TOPIC

Implementation Details of the new Operator

Internally, the interaction between the `new` operator and the constructor is as follows. The `new` operator retrieves "empty" memory from the memory manager and then calls the specified constructor, passing a reference to the empty memory to the constructor as the implicit `this` parameter. Next, the remainder of the constructor chain executes, passing around the reference between constructors. None of the constructors have a return type; behaviorally they all return `void`. When execution completes on the constructor chain is complete, the `new` operator returns the memory reference, now referring to the memory in its initialized form.

Default Constructors

When you add a constructor explicitly, you can no longer instantiate an `Employee` from within `Main()` without specifying the first and last names. The code shown in Listing 5.27, therefore, will not compile.

Listing 5.27: Default Constructor No Longer Available

```
class Program
{
  static void Main()
  {
      Employee employee;
      // ERROR: No overload because method 'Employee'
      // takes '0' arguments.
      employee = new Employee();

      // ...
  }
}
```

If a class has no explicitly defined constructor, the C# compiler adds one during compilation. This constructor takes no parameters and, therefore, is the **default constructor** by definition. As soon as you add an explicit constructor to a class, the C# compiler no longer provides a default constructor. Therefore, with `Employee(string firstName, string lastName)` defined, the default constructor, `Employee()`, is not added by the compiler. You could manually add such a constructor, but then you would again be allowing construction of an `Employee` without specifying the employee name.

It is not necessary to rely on the default constructor defined by the compiler. It is also possible for programmers to define a default constructor explicitly—perhaps one that initializes some fields to particular values. Defining the default constructor simply involves declaring a constructor that takes no parameters.

Object Initializers

Begin 3.0

Starting with C# 3.0, the C# language team added functionality to initialize an object's accessible fields and properties using an **object initializer.** The object initializer consists of a set of member initializers enclosed in curly braces following the constructor call to create the object. Each member initializer is the assignment of an accessible field or property name with a value (see Listing 5.28).

Listing 5.28: Calling an Object Initializer

```
class Program
{
  static void Main()
  {
```

```
            Employee employee1 = new Employee("Inigo", "Montoya")
                { Title = "Computer Nerd", Salary = "Not enough"};
        // ...
    }
}
```

Notice that the same constructor rules apply even when using an object initializer. In fact, the resultant CIL is exactly the same as it would be if the fields or properties were assigned within separate statements immediately following the constructor call. The order of member initializers in C# provides the sequence for property and field assignment in the statements following the constructor call within CIL.

In general, all properties should be initialized to reasonable default values by the time the constructor exits. Moreover, by using validation logic on the setter, it is possible to restrict the assignment of invalid data to a property. On occasion, the values on one or more properties may cause other properties on the same object to contain invalid values. When this occurs, exceptions from the invalid state should be postponed until the invalid interrelated property values become relevant.

Guidelines

DO provide sensible defaults for all properties, ensuring that defaults do not result in a security hole or significantly inefficient code.
For automatically implemented properties, set the default via the constructor.

3.0

DO allow properties to be set in any order, even if this results in a temporarily invalid object state.

ADVANCED TOPIC

Collection Initializers

Using a similar syntax to that of object initializers, collection initializers were added in C# 3.0. Collection initializers support a similar feature set as object initializers, only with collections. Specifically, a collection initializer allows the assignment of items within the collection at the time of the collection's instantiation. Borrowing on the same syntax used for arrays, the collection initializer initializes each item within the collection as part of collection creation. Initializing a list of `Employees`, for example, involves specifying each item within curly braces following the constructor call, as Listing 5.29 shows.

Listing 5.29: Calling an Object Initializer

```
class Program
{
  static void Main()
  {
      List<Employee> employees = new List<Employee>()
         {
            new Employee("Inigo", "Montoya"),
            new Employee("Kevin", "Bost")
         };
      // ...
  }
}
```

After the assignment of a new collection instance, the compiler-generated code instantiates each object in sequence and adds them to the collection via the `Add()` method.

End 3.0

Advanced Topic

Finalizers

Constructors define what happens during the instantiation process of a class. To define what happens when an object is destroyed, C# provides the finalizer construct. Unlike destructors in C++, finalizers do not run immediately after an object goes out of scope. Rather, the finalizer executes at some unspecified time after an object is determined to be "unreachable." Specifically, the garbage collector identifies objects with finalizers during a garbage collection cycle, and instead of immediately de-allocating those objects, it adds them to a finalization queue. A separate thread runs through each object in the finalization queue and calls the object's finalizer before removing it from the queue and making it available for the garbage collector again. Chapter 9 discusses this process, along with resource cleanup, in depth.

Overloading Constructors

Constructors can be overloaded—you can have more than one constructor as long as the number or types of the parameters vary. For example, as

Listing 5.30 shows, you could provide a constructor that has an employee ID with first and last names, or even just the employee ID.

LISTING 5.30: Overloading a Constructor

```
class Employee
{
  public Employee(string firstName, string lastName)
  {
      FirstName = firstName;
      LastName = lastName;
  }

  public Employee(
      int id, string firstName, string lastName )
  {
      Id = id;
      FirstName = firstName;
      LastName = lastName;
  }

  public Employee(int id)
  {
      Id = id;

      // Look up employee name...
      // ...
  }

  public int Id { get; set; }
  public string FirstName { get; set; }
  public string LastName { get; set; }
  public string Salary { get; set; } = "Not Enough";

  // ...
}
```

This approach enables `Program.Main()` to instantiate an employee from the first and last names either by passing in the employee ID only or by passing both the names and the IDs. You would use the constructor with both the names and the IDs when creating a new employee in the system. You would use the constructor with only the ID to load up the employee from a file or a database.

As is the case with method overloading, multiple constructors are used to support simple scenarios using a small number of parameters and complex scenarios with additional parameters. Consider using optional parameters in favor of overloading so that the default values for “defaulted” properties are visible in the API. For example, a constructor signature of `Person(string firstName, string lastName, int? age = null)` provides signature documentation that if the `Age` of a `Person` is not specified, it will default to `null`.

Guidelines

DO use the same name for constructor parameters (camelCase) and properties (PascalCase) if the constructor parameters are used to simply set the property.

DO provide constructor optional parameters and/or convenience constructor overloads that initialize properties with good defaults.

DO allow properties to be set in any order, even if this results in a temporarily invalid object state.

Constructor Chaining: Calling Another Constructor Using `this`

Notice in Listing 5.30 that the initialization code for the `Employee` object is now duplicated in multiple places and, therefore, has to be maintained in multiple places. The amount of code is small, but there are ways to eliminate the duplication by calling one constructor from another—**constructor chaining**—using **constructor initializers.** Constructor initializers determine which constructor to call before executing the implementation of the current constructor (see Listing 5.31).

LISTING 5.31: Calling One Constructor from Another

```
class Employee
{
  public Employee(string firstName, string lastName)
  {
      FirstName = firstName;
      LastName = lastName;
  }

  public Employee(
      int id, string firstName, string lastName )
      : this(firstName, lastName)
  {
      Id = id;
  }

  public Employee(int id)
```

```
    {
        Id = id;

        // Look up employee name...
        // ...

        // NOTE:  Member constructors cannot be
        // called explicitly inline
        // this(id, firstName, lastName);
    }

    public int Id { get; private set; }
    public string FirstName { get; set; }
    public string LastName { get; set; }
    public string Salary { get; set; } = "Not Enough";

    // ...
  }
```

To call one constructor from another within the same class (for the same object instance), C# uses a colon followed by the `this` keyword, followed by the parameter list on the callee constructor's declaration. In this case, the constructor that takes all three parameters calls the constructor that takes two parameters. Often, this calling pattern is reversed—that is, the constructor with the fewest parameters calls the constructor with the most parameters, passing defaults for the parameters that are not known.

BEGINNER TOPIC

Centralizing Initialization

Notice that in the `Employee(int id)` constructor implementation from Listing 5.31, you cannot call `this(firstName, LastName)` because no such parameters exist on this constructor. To enable such a pattern in which all initialization code happens through one method, you must create a separate method, as shown in Listing 5.32.

Listing 5.32: Providing an Initialization Method

```
  class Employee
  {
    public Employee(string firstName, string lastName)
    {
        int id;
        // Generate an employee ID...
```

```
        // ...
        Initialize(id, firstName, lastName);
    }

    public Employee(int id, string firstName, string lastName )
    {
        Initialize(id, firstName, lastName);
    }

    public Employee(int id)
    {
        string firstName;
        string lastName;
        Id = id;

        // Look up employee data
        // ...

        Initialize(id, firstName, lastName);
    }

    private void Initialize(
        int id, string firstName, string lastName)
    {
        Id = id;
        FirstName = firstName;
        LastName = lastName;
    }
    // ...
}
```

In this case, the method is called `Initialize()` and it takes both the names and the employee IDs. Note that you can continue to call one constructor from another, as shown in Listing 5.31.

ADVANCED TOPIC

Begin 3.0

Anonymous Types

C# 3.0 introduced support for anonymous types. These data types are generated by the compiler "on the fly," rather than through explicit class definitions. Listing 5.33 shows such a declaration.

LISTING 5.33: Implicit Local Variables with Anonymous Types

```
using System;

class Program
```

```
    {
      static void Main()
      {
          var patent1 =
              new
              {
                  Title = "Bifocals",
                  YearOfPublication = "1784"
              };
          var patent2 =
              new
              {
                  Title = "Phonograph",
                  YearOfPublication = "1877"
              };
          var patent3 =
              new
              {
                  patent1.Title,
                  Year = patent1.YearOfPublication
              };

          System.Console.WriteLine("{0} ({1})",
              patent1.Title, patent1.YearOfPublication);
          System.Console.WriteLine("{0} ({1})",
              patent2.Title, patent1.YearOfPublication);

          Console.WriteLine();
          Console.WriteLine(patent1);
          Console.WriteLine(patent2);

          Console.WriteLine();
          Console.WriteLine(patent3);
      }
    }
```

3.0

The corresponding output is shown in Output 5.8.

Output 5.8

```
Bifocals (1784)
Phonograph (1877)

{ Title = Bifocals, YearOfPublication = 1784 }
{ Title = Phonograph, YearOfPublication = 1877 }

{ Title = Bifocals, Year = 1784 }
```

Listing 5.33 demonstrates the assignment of an anonymous type to an implicitly typed (var) local variable. When the compiler encounters the anonymous type syntax, it generates a class with properties corresponding to the named values and data types in the anonymous type declaration. Although there is no available name in C# for the generated type, it is still statically typed. For example, the properties of the type are fully accessible. In Listing 5.33, `patent1.Title` and `patent2.YearOfPublication` are called within the `Console.WriteLine()` statement. Any attempts to call nonexistent members will result in compile-time errors. Even IntelliSense in IDEs such as Visual Studio works with the anonymous type.

In Listing 5.33, member names on the anonymous types are explicitly identified using the assignment of the value to the name (see `Title` and `YearOfPublication` in the `patent1` and `patent2` assignments). However, if the value assigned is a property or field, the name will default to the name of the field or property if not specified explicitly. For example, `patent3` is defined using a property name "Title" rather than an assignment to an implicit name. As Output 5.8 shows, the resultant property name is determined by the compiler to match the property from where the value was retrieved.

Although the compiler allows anonymous type declarations such as the ones shown in Listing 5.33, you should generally avoid these kinds of declarations, and even the associated implicit typing with `var`, unless you are working with lambda and query expressions that associate data from different types or you are horizontally projecting the data so that for a particular type, there is less data overall. Until frequent querying of data held in collections makes explicit type declaration burdensome, it is preferable to explicitly declare types as outlined in this chapter.

End 3.0

Static Members

The `HelloWorld` example in Chapter 1 briefly touched on the keyword `static`. This section defines the `static` keyword more fully.

Let's consider an example. Assume that the employee `Id` value needs to be unique for each employee. One way to accomplish this is to store a counter to track each employee ID. If the value is stored as an instance field, however, every time you instantiate an object, a new `NextId` field will be created such that every instance of the `Employee` object will consume memory for that field. The biggest problem is that each time an `Employee` object is instantiated, the `NextId` value on all of the previously instantiated `Employee` objects needs to be updated with the next ID value. In this case, what you need is a single field that all `Employee` object instances share.

Language Contrast: C++/Visual Basic—Global Variables and Functions

Unlike many of the languages that came before it, C# does not have global variables or global functions. All fields and methods in C# appear within the context of a class. The equivalent of a global field or function within the realm of C# is a static field or function. There is no functional difference between global variables/functions and C# static fields/methods, except that static fields/methods can include access modifiers, such as `private`, that can limit the access and provide better encapsulation.

Static Fields

To define data that is available across multiple instances, you use the `static` keyword, as demonstrated in Listing 5.34.

Listing 5.34: Declaring a Static Field

```
class Employee
{
  public Employee(string firstName, string lastName)
  {
      FirstName = firstName;
      LastName = lastName;
      Id = NextId;
      NextId++;
  }

  // ...

  public static int NextId;
  public int Id { get; set; }
  public string FirstName { get; set; }
  public string LastName { get; set; }
  public string Salary { get; set; } = "Not Enough";

  // ...
}
```

In this example, the `NextId` field declaration includes the `static` modifier and, therefore, is called a **static field.** Unlike `Id`, a single storage location for `NextId` is shared across all instances of `Employee`. Inside the `Employee` constructor, you assign the new `Employee` object's `Id` the value of `NextId` immediately before incrementing the `Id`. When another `Employee` class is created, `NextId` will be incremented and the new `Employee` object's `Id` field will hold a different value.

Just as **instance fields** (nonstatic fields) can be initialized at declaration time, so can static fields, as demonstrated in Listing 5.35.

LISTING 5.35: Assigning a Static Field at Declaration

```
class Employee
{
  // ...
  public static int NextId = 42;
  // ...
}
```

Unlike with instance fields, if no initialization for a static field is provided, the static field will automatically be assigned its default value (`0`, `null`, `false`, and so on)—the equivalent of `default(T)`, where `T` is the name of the type. As a result, it will be possible to access the static field even if it has never been explicitly assigned in the C# code.

Nonstatic fields, or instance fields, provide a new storage location for each object to which they belong. In contrast, static fields don't belong to the instance, but rather to the class itself. As a result, you access a static field from outside a class via the class name. Consider the new `Program` class shown in Listing 5.36 (using the `Employee` class from Listing 5.34).

LISTING 5.36: Accessing a Static Field

```
using System;

class Program
{
  static void Main()
  {
      Employee.NextId = 1000000;

      Employee employee1 = new Employee(
          "Inigo", "Montoya");
      Employee employee2 = new Employee(
          "Princess", "Buttercup");
```

```
        Console.WriteLine(
            "{0} {1} ({2})",
            employee1.FirstName,
            employee1.LastName,
            employee1.Id);
        Console.WriteLine(
            "{0} {1} ({2})",
            employee2.FirstName,
            employee2.LastName,
            employee2.Id);

        Console.WriteLine(
            $"NextId = { Employee.NextId }");
    }

    // ...
}
```

Output 5.9 shows the results of Listing 5.36.

Output 5.9

```
Inigo Montoya (1000000)
Princess Buttercup (1000001)
NextId = 1000002
```

To set and retrieve the initial value of the `NextId` static field, you use the class name, `Employee`, rather than a reference to an instance of the type. The only place you can omit the class name is within the class itself (or a derived class). In other words, the `Employee(...)` constructor did not need to use `Employee.NextId` because the code appeared within the context of the `Employee` class itself and, therefore, the context was already understood. The scope of a variable is the program text in which the variable can be referred to by its unqualified name; the scope of a static field is the text of the class (and any derived classes).

Even though you refer to static fields slightly differently than you refer to instance fields, it is not possible to define a static field and an instance field with the same name in the same class. The possibility of mistakenly referring to the wrong field is high, so the C# designers decided to prevent such code. Overlap in names, therefore, introduces conflict within the declaration space.

BEGINNER TOPIC

Data Can Be Associated with Both a Class and an Object

Both classes and objects can have associated data, just as can the molds and the widgets created from them.

For example, a mold could have data corresponding to the number of widgets it created, the serial number of the next widget, the current color of the plastic injected into the mold, and the number of widgets it produces per hour. Similarly, a widget has its own serial number, its own color, and perhaps the date and time when the widget was created. Although the color of the widget corresponds to the color of the plastic within the mold at the time the widget was created, it obviously does not contain data corresponding to the color of the plastic currently in the mold, or the serial number of the next widget to be produced.

In designing objects, programmers should take care to declare both fields and methods appropriately, as static or instance based. In general, you should declare methods that don't access any instance data as static methods, and methods that access instance data (where the instance is not passed in as a parameter) as instance methods. Static fields store data corresponding to the class, such as defaults for new instances or the number of instances that have been created. Instance fields store data associated with the object.

Static Methods

Just like static fields, you access static methods directly off the class name—for example, as `Console.ReadLine()`. Furthermore, it is not necessary to have an instance to access the method.

Listing 5.37 provides another example of both declaring and calling a static method.

LISTING 5.37: Defining a Static Method on `DirectoryInfo`

```
public static class DirectoryInfoExtension
{
  public static void CopyTo(
      DirectoryInfo sourceDirectory, string target,
      SearchOption option, string searchPattern)
  {
      if (target[target.Length - 1] !=
            Path.DirectorySeparatorChar)
      {
```

```
            target += Path.DirectorySeparatorChar;
        }
        if (!Directory.Exists(target))
        {
            Directory.CreateDirectory(target);
        }

        for (int i = 0; i < searchPattern.Length; i++)
        {
            foreach (string file in
                Directory.GetFiles(
                    sourceDirectory.FullName, searchPattern))
            {
                File.Copy(file,
                    target + Path.GetFileName(file), true);
            }
        }

        //Copy subdirectories (recursively)
        if (option == SearchOption.AllDirectories)
        {
            foreach(string element in
                Directory.GetDirectories(
                    sourceDirectory.FullName))
            {
                Copy(element,
                    target + Path.GetFileName(element),
                    searchPattern);
            }
        }
    }
}
```

```
        // ...
        DirectoryInfo directory = new DirectoryInfo(".\\Source");
        directory.MoveTo(".\\Root");
        DirectoryInfoExtension.CopyTo(
            directory, ".\\Target",
            SearchOption.AllDirectories, "*");
        // ...
```

In Listing 5.37, the `DirectoryInfoExtension.Copy()` method takes a `DirectoryInfo` object and copies the underlying directory structure to a new location.

Because static methods are not referenced through a particular instance, the `this` keyword is invalid inside a static method. In addition, it is not possible to access either an instance field or an instance method directly from within a static method without a reference to the particular instance to which the field or method belongs. (Note that `Main()` is another example of a static method.)

One might have expected this method on the `System.IO.Directory` class or as an instance method on `System.IO.DirectoryInfo`. Since neither exists, Listing 5.37 defines such a method on an entirely new class. In the section “Extension Methods” later in this chapter, we show how to make it appear as an instance method on `DirectoryInfo`.

Static Constructors

In addition to static fields and methods, C# supports **static constructors.** Static constructors are provided as a means to initialize the class itself, rather than the instances of a class. Such constructors are not called explicitly; instead, the runtime calls static constructors automatically upon first access to the class, whether by calling a regular constructor or by accessing a static method or field on the class. Because the static constructor cannot be called explicitly, no parameters are allowed on static constructors.

You use static constructors to initialize the static data within the class to a particular value, primarily when the initial value involves more complexity than a simple assignment at declaration time. Consider Listing 5.38.

LISTING 5.38: Declaring a Static Constructor

```
class Employee
{
  static Employee()
  {
      Random randomGenerator = new Random();
      NextId = randomGenerator.Next(101, 999);
  }

  // ...
  public static int NextId = 42;
  // ...
}
```

Listing 5.38 assigns the initial value of `NextId` to be a random integer between 100 and 1,000. Because the initial value involves a method call, the `NextId` initialization code appears within a static constructor and not as part of the declaration.

If assignment of `NextId` occurs within both the static constructor and the declaration, it is not obvious what the value will be when initialization concludes. The C# compiler generates CIL in which the declaration assignment is moved to be the first statement within the static constructor. Therefore, `NextId` will contain the value returned by `randomGenerator.Next(101, 999)` instead of a value assigned during `NextId`'s declaration. Assignments within the static constructor, therefore, will take precedence over assignments that occur as part of the field declaration, as was the case with instance fields. Note that there is no support for defining a static finalizer.

Be careful not to throw an exception from a static constructor, as this will render the type unusable for the remainder of the application's lifetime.[6]

ADVANCED TOPIC

Favor Static Initialization during Declaration

Static constructors execute before the first access to any member of a class, whether it is a static field, another static member, or an instance constructor. To support this practice, the compiler injects a check into all type static members and constructors to ensure that the static constructor runs first.

Without the static constructor, the compiler initializes all static members to their default values and avoids adding the static constructor check. The result is that static assignment initialization is called before accessing any static fields but not necessarily before all static methods or any instance constructor is invoked. This might provide a performance improvement if initialization of static members is expensive and is not needed before accessing a static field. For this reason, you should consider initializing static fields inline rather than using a static constructor, or initializing them at declaration time.

Guidelines

CONSIDER initializing static fields inline rather than explicitly using static constructors or declaration assigned values.

6. Technically, the application domain's lifetime—the CLR's virtual equivalent of an operating system process.

Static Properties

Begin 2.0

You also can declare properties as static. For example, Listing 5.39 wraps the data for the next ID into a property.

Listing 5.39: Declaring a Static Property

```
class Employee
{
  // ...
  public static int NextId
  {
      get
      {
          return _NextId;
      }
      private set
      {
          _NextId = value;
      }
  }
  public static int _NextId = 42;
  // ...
}
```

It is almost always better to use a static property rather than a public static field, because public static fields are callable from anywhere, whereas a static property offers at least some level of encapsulation.

Begin 6.0

In C# 6.0, the entire `NextId` implementation—including an inaccessible backing field—can be simplified down to an automatically implemented property with an initializer:

```
public static int NextId { get; private set; } = 42;
```

End 6.0

Static Classes

Some classes do not contain any instance fields. Consider, for example, a `Math` class that has functions corresponding to the mathematical operations `Max()` and `Min()`, as shown in Listing 5.40.

Listing 5.40: Declaring a Static Class

```
// Static class introduced in C# 2.0
public static class SimpleMath
{
  // params allows the number of parameters to vary.
  public static int Max(params int[] numbers)
```

```
    {
        // Check that there is at least one item in numbers.
        if(numbers.Length == 0)
        {
            throw new ArgumentException(
                "numbers cannot be empty", "numbers");
        }

        int result;
        result = numbers[0];
        foreach (int number in numbers)
        {
            if(number > result)
            {
                result = number;
            }
        }
        return result;
    }

    // params allows the number of parameters to vary.
    public static int Min(params int[] numbers)
    {
        // Check that there is at least one item in numbers.
        if(numbers.Length == 0)
        {
            throw new ArgumentException(
                "numbers cannot be empty", "numbers");
        }

        int result;
        result = numbers[0];
        foreach (int number in numbers)
        {
            if(number < result)
            {
                result = number;
            }
        }
        return result;
    }
}
```

2.0

```
public class Program
{
    public static void Main(string[] args)
    {
        int[] numbers = new int[args.Length];
        for (int count = 0; count < args.Length; count++)
        {
            numbers[count] = args[count].Length;
        }
```

```
            Console.WriteLine(
                $@"Longest argument length = {
                    SimpleMath.Max(numbers) }");
            Console.WriteLine(
                $@"Shortest argument length = {
                    SimpleMath.Min(numbers) }");
        }
    }
```

This class does not have any instance fields (or methods), so creation of such a class would be pointless. Consequently, the class is decorated with the `static` keyword. The `static` keyword on a class provides two facilities. First, it prevents a programmer from writing code that instantiates the `SimpleMath` class. Second, it prevents the declaration of any instance fields or methods within the class. Because the class cannot be instantiated, instance members would be pointless. The `Program` class in prior listings is another good candidate for a static class because it too contains only static members.

End 2.0

One more distinguishing characteristic of the static class is that the C# compiler automatically marks it as `abstract` and `sealed` within the CIL. This designates the class as **inextensible;** in other words, no class can be derived from this class or even instantiate it.

Begin 6.0

Begin 3.0

In the previous chapter, we saw that the `using static` directive can be used with static classes such as `SimpleMath`. For example, adding a `using static SimpleMath;` declarative at the top of Listing 5.40 would allow you to invoke `Max` without the `SimpleMath` prefix:

```
Console.WriteLine(
    $@"Longest argument length = { Max(numbers) }");
```

End 6.0

Extension Methods

Consider the `System.IO.DirectoryInfo` class, which is used to manipulate filesystem directories. This class supports functionality to list the files and subdirectories (`DirectoryInfo.GetFiles()`) as well as the capability to move the directory (`DirectoryInfo.Move()`). One feature it doesn't support directly is the copy feature. If you needed such a method, you would have to implement it, as shown earlier in Listing 5.37.

The `DirectoryInfoExtension.Copy()` method is a standard static method declaration. However, notice that calling this `Copy()` method is different from calling the `DirectoryInfo.Move()` method. This is unfortunate. Ideally, we want to add a method to `DirectoryInfo` so that, given an instance, we could call `Copy()` as an instance method—`directory.Copy()`.

C# 3.0 simulates the creation of an instance method on a different class via **extension methods.** To do this, we simply change the signature of our static method so that the first parameter—that is, the data type we are extending—is prefixed with the `this` keyword (see Listing 5.41).

LISTING 5.41: Static Copy Method for `DirectoryInfo`

```
public static class DirectoryInfoExtension
{
  public static void CopyTo(
      this DirectoryInfo sourceDirectory, string target,
      SearchOption option, string searchPattern)
  {
      // ...
  }
}
```

```
  // ...
      DirectoryInfo directory = new DirectoryInfo(".\\Source");
      directory.CopyTo(".\\Target",
          SearchOption.AllDirectories, "*");
  // ...
```

With this simple addition to C# 3.0, it is now possible to add "instance methods" to any class, including classes that are not within the same assembly. The resultant CIL code, however, is identical to what the compiler creates when calling the extension method as a normal static method.

3.0

Extension method requirements are as follows.

- The first parameter corresponds to the type that the method extends or on which it operates.
- To designate the extension method, prefix the extended type with the `this` modifier.
- To access the method as an extension method, import the extending type's namespace via a `using` directive (or place the extending class in the same namespace as the calling code).

If the extension method signature matches a signature already found on the extended type (that is, if `CopyTo()` already existed on `DirectoryInfo`), the extension method will never be called except as a normal static method.

Note that specializing a type via inheritance (covered in detail in Chapter 6) is preferable to using an extension method. Extension methods do not provide a clean versioning mechanism, because the addition of a matching signature to the extended type will take precedence over the extension method without warning of the change. The subtlety of this behavior is more pronounced for extended classes whose source code you don't control. Another minor point is that, although development IDEs support IntelliSense for extension methods, simply reading through the calling code does not make it obvious that a method is an extension method.

In general, you should use extension methods sparingly. Do not, for example, define them on type `object`. Chapter 6 discusses how to use extension methods in association with an interface. Without such an association, defining extension methods is rare.

Guidelines

AVOID frivolously defining extension methods, especially on types you don't own.

End 3.0

Encapsulating the Data

In addition to properties and the access modifiers we looked at earlier in the chapter, there are several other specialized ways of encapsulating the data within a class. For instance, there are two more field modifiers. The first is the `const` modifier, which you already encountered when declaring local variables. The second is the capability of fields to be defined as read-only.

const

Just as with `const` values, a `const` field contains a compile-time–determined value that cannot be changed at runtime. Values such as pi make good candidates for constant field declarations. Listing 5.42 shows an example of declaring a `const` field.

Listing 5.42: Declaring a Constant Field

```
class ConvertUnits
{
   public const float CentimetersPerInch = 2.54F;
   public const int CupsPerGallon = 16;
   // ...
}
```

Constant fields are static automatically, since no new field instance is required for each object instance. Declaring a constant field as `static` explicitly will cause a compile error. Also, constant fields are usually declared only for types that have literal values (`string`, `int`, and `double`, for example). Types such as `Program` or `System.Guid` cannot be used for constant fields.

It is important that the types of values used in `public` constant expressions are permanent in time. Values such as pi, Avogadro's number, and the circumference of the Earth are good examples. However, values that could potentially change over time are not. Build numbers, population counts, and exchange rates would be poor choices for constants.

Guidelines

DO use constant fields for values that will never change.

DO NOT use constant fields for values that will change over time.

ADVANCED TOPIC

Public Constants Should Be Permanent Values

Publicly accessible constants should be permanent, because changing the value of a constant will not necessarily take effect in the assemblies that use it. If an assembly references a constant from a different assembly, the value of the constant is compiled directly into the referencing assembly. Therefore, if the value in the referenced assembly is changed but the referencing assembly is not recompiled, the referencing assembly will still use the original value, not the new value. Values that could potentially change in the future should be specified as `readonly` instead.

readonly

Unlike `const`, the `readonly` modifier is available only for fields (not for local variables). It declares that the field value is modifiable only from inside the constructor or via an initializer during declaration. Listing 5.43 demonstrates how to declare a read-only field.

Listing 5.43: Declaring a Field As readonly

```
class Employee
{
  public Employee(int id)
  {
      _Id = id;
  }

  // ...

  public readonly int _Id;
  public int Id
  {
      get { return _Id; }
  }

  // Error: A readonly field cannot be assigned to (except
  // in a constructor or a variable initializer)
  // public void SetId(int id) =>
  //          _Id = id;

  // ...
}
```

Unlike constant fields, `readonly`-decorated fields can vary from one instance to the next. In fact, a read-only field's value can change within the constructor. Furthermore, read-only fields occur as either instance or static fields. Another key distinction is that you can assign the value of a read-only field at execution time rather than just at compile time. Given that read-only fields must be set in the constructor or initializer, such fields are the one case where the compiler requires the fields be accessed from code outside their corresponding property. Besides this one exception, you should avoid accessing a backing field from anywhere other than its wrapping property.

Another important feature of `readonly`-decorated fields over `const` fields is that read-only fields are not limited to types with literal values. It is possible, for example, to declare a `readonly System.Guid` instance field:

```
public static readonly Guid ComIUnknownGuid =
      new Guid("00000000-0000-0000-C000-000000000046");
```

The same, however, is not possible using a constant because of the fact that there is no C# literal representation of a Guid.

Begin 6.0

Given the guideline that fields should not be accessed from outside their wrapping property, those programming in a C# 6.0 world will discover that that there is almost never a need to use the `readonly` modifier. Instead, it is preferable to use a read-only automatically implemented property, as discussed earlier in the chapter.

Consider Listing 5.44 for one more read-only example.

Listing 5.44: Declaring a Read-Only Automatically Implemented Property

```
class TicTacToeBoard
{
   // Set both player's move to all false (blank).
   //    |   |
   // ---+---+---
   //    |   |
   // ---+---+---
   //    |   |
      public bool[,,] Cells { get; } = new bool[2, 3, 3];
   // Error: The property Cells cannot
   // be assigned to because it is read-only
   public void SetCells(bool[,,] value) =>
           Cells = new bool[2, 3, 3];

  // ...
}
```

Whether implemented using C# 6.0 read-only automatically implemented properties or the `readonly` modifier on a field, providing for immutability of the array reference is a useful defensive coding technique. It ensures that the array instance remains the same, while allowing the elements within the array to change. Without the read-only constraint, it would be all too easy to mistakenly assign a new array to the member, thereby discarding the existing array rather than updating individual array elements. In other words, using a read-only approach with an array does not freeze the contents of the array. Rather, it freezes the array instance (and therefore the number of elements in the array) because it is not possible to reassign the value to a new instance. The elements of the array are still writeable.

Guidelines

DO favor use of read-only automatically implemented properties in C# 6.0 (or later) over defining read-only fields.

DO use `public static readonly` modified fields for predefined object instances prior to C# 6.0.

AVOID changing a public `readonly` modified field in pre-C# 6.0 to a read-only automatically implemented property in C# 6.0 (or later) if version API compatibility is required.

End 6.0

Nested Classes

In addition to defining methods and fields within a class, it is possible to define a class within a class. Such classes are called **nested classes.** You use a nested class when the class makes little sense outside the context of its containing class.

Consider a class that handles the command-line options of a program. Such a class is generally unique to each program, so there is no reason to make a `CommandLine` class accessible from outside the class that contains `Main()`. Listing 5.45 demonstrates such a nested class.

LISTING 5.45: Defining a Nested Class

```
// CommandLine is nested within Program
class Program
{
  // Define a nested class for processing the command line.
  private class CommandLine
  {
      public CommandLine(string[] arguments)
      {
          for(int argumentCounter=0;
              argumentCounter<arguments.Length;
              argumentCounter++)
          {
              switch (argumentCounter)
              {
                  case 0:
                      Action = arguments[0].ToLower();
                      break;
                  case 1:
                      Id = arguments[1];
                      break;
```

```
                    case 2:
                        FirstName = arguments[2];
                        break;
                    case 3:
                        LastName = arguments[3];
                        break;
                }
            }
        }
        public string Action;
        public string Id;
        public string FirstName;
        public string LastName;
    }

    static void Main(string[] args)
    {
      CommandLine commandLine = new CommandLine(args);

      switch (commandLine.Action)
      {
          case "new":
              // Create a new employee
              // ...
              break;
          case "update":
              // Update an existing employee's data
              // ...
              break;
          case "delete":
              // Remove an existing employee's file.
              // ...
              break;
          default:
              Console.WriteLine(
                  "Employee.exe " +
           "new|update|delete <id> [firstname] [lastname]");
              break;
      }
    }
  }
```

The nested class in this example is `Program.CommandLine`. As with all class members, no containing class identifier is needed from inside the containing class, so you can simply refer to it as `CommandLine`.

One unique characteristic of nested classes is the ability to specify `private` as an access modifier for the class itself. Because the purpose of this class is to parse the command line and place each argument into a separate field, `Program.CommandLine` is relevant only to the `Program` class in this application. The use of the `private` access modifier defines the intended accessibility of the class and prevents access from outside the class. You can do this only if the class is nested.

The `this` member within a nested class refers to an instance of the nested class, not the containing class. One way for a nested class to access an instance of the containing class is if the containing class instance is explicitly passed, such as via a constructor or method parameter.

Another interesting characteristic of nested classes is that they can access any member on the containing class, including private members. The converse is not true, however: It is not possible for the containing class to access a private member of the nested class.

Nested classes are rare. They should not be defined if they are likely to be referenced outside the containing type. Furthermore, treat `public` nested classes with suspicion; they indicate potentially poor code that is likely to be confusing and hard to discover.

Guidelines

AVOID publicly exposed nested types. The only exception is if the declaration of such a type is unlikely or pertains to an advanced customization scenario.

Language Contrast: Java—Inner Classes

Java includes not only the concept of a nested class, but also the concept of an inner class. Inner classes correspond to objects that are associated with the containing class instance rather than just a syntactic relationship. In C#, you can achieve the same structure by including an instance field of a nested type within the outer class. A factory method or constructor can ensure a reference to the corresponding instance of the outer class is set within the inner class instance as well.

Begin 2.0

Partial Classes

Another language feature added in C# 2.0 is **partial classes.** Partial classes are portions of a class that the compiler can combine to form a complete class. Although you could define two or more partial classes within the same file, the general purpose of a partial class is to allow the splitting of a class definition across multiple files. Primarily this is useful for tools that are generating or modifying code. With partial classes, the tools can work on a file separate from the one the developer is manually coding.

Defining a Partial Class

C# 2.0 (and later) allows declaration of a partial class by prepending a contextual keyword, `partial`, immediately before `class`, as Listing 5.46 shows.

Listing 5.46: Defining a Partial Class

```
// File: Program1.cs
partial class Program
{
}
```

```
// File: Program2.cs
partial class Program
{
}
```

In this case, each portion of `Program` is placed into a separate file, as identified by the comment.

Besides their use with code generators, another common use of partial classes is to place any nested classes into their own files. This is in accordance with the coding convention that places each class definition within its own file. For example, Listing 5.47 places the `Program.CommandLine` class into a file separate from the core `Program` members.

Listing 5.47: Defining a Nested Class in a Separate Partial Class

```
// File: Program.cs
partial class Program
{
  static void Main(string[] args)
  {
    CommandLine commandLine = new CommandLine(args);

    switch (commandLine.Action)
```

```
        {
            // ...
        }
    }
}
```

```
// File: Program+CommandLine.cs
partial class Program
{
  // Define a nested class for processing the command line.
  private class CommandLine
  {
     // ...
  }
}
```

Partial classes do not allow for extending compiled classes, or classes in other assemblies. They are simply a means of splitting a class implementation across multiple files within the same assembly.

End 2.0

Partial Methods

Begin 3.0

Beginning with C# 3.0, the language designers added the concept of partial methods, extending the partial class concept of C# 2.0. Partial methods are allowed only within partial classes, and like partial classes, their primary purpose is to accommodate code generation.

Consider a code generation tool that generates the `Person.Designer.cs` file for the `Person` class based on a `Person` table within a database. This tool examines the table and creates properties for each column in the table. The problem, however, is that frequently the tool cannot generate any validation logic that may be required because this logic is based on business rules that are not embedded into the database table definition. To overcome this difficulty, the developer of the `Person` class needs to add the validation logic. It is undesirable to modify `Person.Designer.cs` directly, because if the file is regenerated (to accommodate an additional column in the database, for example), the changes would be lost. Instead, the structure of the code for `Person` needs to be separated out so that the generated code appears in one file and the custom code (with business rules) is placed into a separate file unaffected by any regeneration. As we saw in the preceding section, partial classes are well suited for the task of splitting a class across multiple files, but they are not always sufficient. In many cases, we also need **partial methods**

Partial methods allow for a declaration of a method without requiring an implementation. However, when the optional implementation is included, it can be located in one of the sister partial class definitions, likely in a separate file. Listing 5.48 shows the partial method declaration and the implementation for the `Person` class.

Listing 5.48: Defining a Nested Class in a Separate Partial Class

3.0

```
// File: Person.Designer.cs
public partial class Person
{
    #region Extensibility Method Definitions
    partial void OnLastNameChanging(string value);
    partial void OnFirstNameChanging(string value);
    #endregion

    // ...
    public System.Guid PersonId
    {
        // ...
    }
    private System.Guid _PersonId;

    // ...
    public string LastName
    {
        get
        {
            return _LastName;
        }
        set
        {
            if ((_LastName != value))
            {
                OnLastNameChanging(value);
                _LastName = value;
            }
        }
    }
    private string _LastName;

    // ...
    public string FirstName
    {
        get
        {
            return _FirstName;
        }
        set
        {
            if ((_FirstName != value))
```

```
                {
                    OnFirstNameChanging(value);
                    _FirstName = value;
                }
            }
        }
        private string _FirstName;

    }
```

```
    // File: Person.cs
    partial class Person
    {
      partial void OnLastNameChanging(string value)
      {
          if (value == null)
          {
              throw new ArgumentNullException("value");
          }
          if(value.Trim().Length == 0)
          {
              throw new ArgumentException(
                  "LastName cannot be empty.",
                  "value");
          }
      }
    }
```

In the listing of `Person.Designer.cs` are declarations for the `OnLastNameChanging()` and `OnFirstNameChanging()` methods. Furthermore, the properties for the last and first names make calls to their corresponding changing methods. Even though the declarations of the changing methods contain no implementation, this code will successfully compile. The key is that the method declarations are prefixed with the contextual keyword `partial` in addition to the class that contains such methods.

3.0

In Listing 5.48, only the `OnLastNameChanging()` method is implemented. In this case, the implementation checks the suggested new `LastName` value and throws an exception if it is not valid. Notice that the signatures for `OnLastNameChanging()` between the two locations match.

Any partial method must return `void`. If the method didn't return `void` and the implementation was not provided, what would the expected return be from a call to a nonimplemented method? To avoid any invalid assumptions about the return, the C# designers decided to prohibit methods with returns other than `void`. Similarly, `out` parameters are not allowed on partial methods. If a return value is required, `ref` parameters may be used.

In summary, partial methods allow generated code to call methods that have not necessarily been implemented. Furthermore, if there is no implementation provided for a partial method, no trace of the partial method appears in the CIL. This helps keep code size small while keeping flexibility high.

End 3.0

SUMMARY

This chapter explained C# constructs for classes and object orientation in C#. Its coverage included a discussion of fields, and a discussion of how to access them on a class instance.

This chapter also discussed the key decision of whether to store data on a per-instance basis or across all instances of a type. Static data is associated with the class, and instance data is stored on each object.

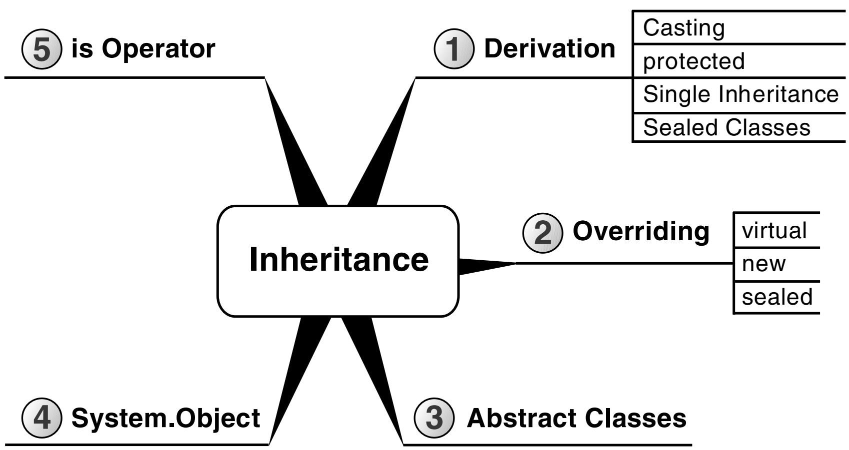
In addition, the chapter explored encapsulation in the context of access modifiers for methods and data. The C# construct of properties was introduced, and you saw how to use it to encapsulate private fields.

The next chapter focuses on how to associate classes with each other via inheritance, and explores the benefits derived from this object-oriented construct.

6

Inheritance

THE PRECEDING CHAPTER DISCUSSED HOW one class can reference other classes via fields and properties. This chapter discusses how to use the inheritance relationship between classes to build class hierarchies that form an "is a" relationship.



BEGINNER TOPIC

Inheritance Definitions

The preceding chapter provided an overview of inheritance. Here's a review of the defined terms:

- *Derive/inherit:* Specialize a base class to include additional members or customization of the base class members.
- *Derived/sub/child type:* The specialized type that inherits the members of the more general type.
- *Base/super/parent type:* The general type whose members a derived type inherits.

Inheritance forms an "is a kind of" relationship. The derived type is always implicitly also of the base type. Just as a hard drive is a kind of storage device, so any other type derived from the storage device type is a kind of storage device. Notice that the converse is not necessarily true: A storage device is not necessarily a hard drive.

NOTE

Inheritance within code is used to define an "is a kind of" relationship between two classes where the derived class is a specialization of the base class.

Derivation

It is common to want to extend a given type to add features, such as behavior and data. The purpose of inheritance is to do exactly that. Given a `Person` class, you create an `Employee` class that additionally contains `EmployeeId` and `Department` properties. The reverse approach may also be applied. Given, for example, a `Contact` class within a personal digital assistant (PDA), you may decide to add calendaring support. Toward this effort, you create an `Appointment` class. However, instead of redefining the methods and properties that are common to both classes, you might choose to **refactor** the `Contact` class. Specifically, you could move the common

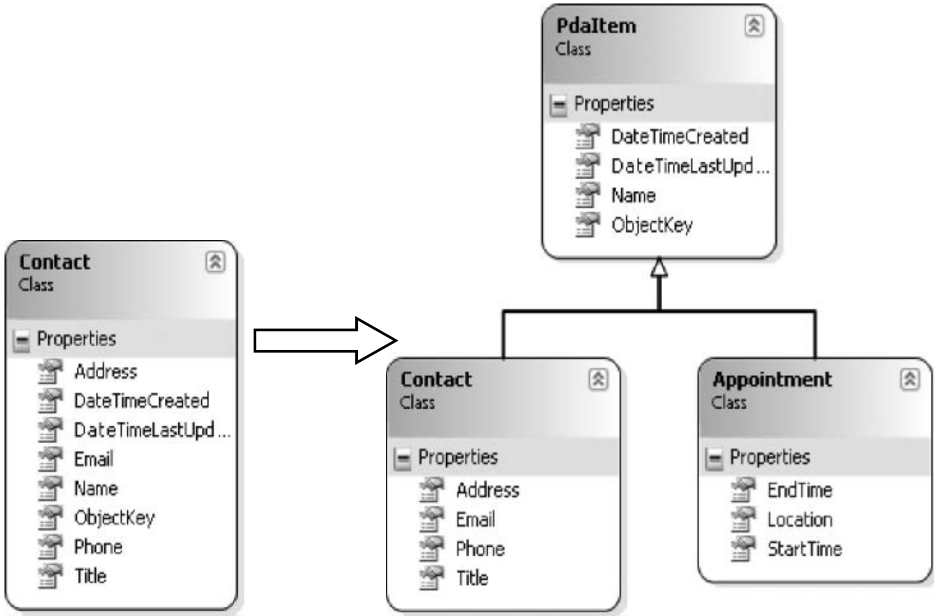


FIGURE 6.1: Refactoring into a Base Class

methods and properties on `Contact` into a base class called `PdaItem` from which both `Contact` and `Appointment` derive, as shown in Figure 6.1.

The common items in this case are `Created`, `LastUpdated`, `Name`, `ObjectKey`, and the like. Through derivation, the methods defined on the base class, `PdaItem`, are accessible from all classes derived from `PdaItem`.

When declaring a derived class, follow the class identifier with a colon and then the base class, as Listing 6.1 demonstrates.

LISTING 6.1: Deriving One Class from Another

```
public class PdaItem
{
  public string Name { get; set; }

  public DateTime LastUpdated { get; set; }
}
```

```
// Define the Contact class as inheriting the PdaItem class
public class Contact : PdaItem
{
  public string Address { get; set; }
  public string Phone { get; set; }
}
```

Listing 6.2 shows how to access the properties defined in `Contact`.

Listing 6.2: Using Inherited Methods

```
public class Program
{
  public static void Main()
  {
      Contact contact = new Contact();
      contact.Name = "Inigo Montoya";

      // ...
  }
}
```

Even though `Contact` does not directly have a property called `Name`, all instances of `Contact` can still access the `Name` property from `PdaItem` and use it as though it was part of `Contact`. Furthermore, any additional classes that derive from `Contact` will also inherit the members of `PdaItem`, or any class from which `PdaItem` was derived. The inheritance chain has no practical limit, and each derived class will have all the members of its base class inheritance chain combined (see Listing 6.3). In other words, although `Customer` doesn't derive from `PdaItem` directly, it still inherits the members of `PdaItem`.

NOTE

Via inheritance, each member of a base class will also appear within the chain of derived classes.

Listing 6.3: Classes Deriving from One Another to Form an Inheritance Chain

```
public class PdaItem : object
{
  // ...
}
```

```
public class Appointment : PdaItem
{
  // ...
}
```

```
public class Contact : PdaItem
{
  // ...
}
```

```
public class Customer : Contact
{
  // ...
}
```

In Listing 6.3, `PdaItem` is shown explicitly to derive from `object`. Although C# allows such syntax, it is unnecessary because all classes that don't have some other derivation will derive from `object`, regardless of whether it is specified.

> **NOTE**
>
> Unless an alternative base class is specified, all classes will derive from `object` by default.

Casting between Base and Derived Types

As Listing 6.4 shows, because derivation forms an "is a" relationship, a derived type value can always be directly assigned to a base type variable.

LISTING 6.4: Implicit Base Type Casting

```
public class Program
{
  public static void Main()
  {
      // Derived types can be implicitly converted to
      // base types
      Contact contact = new Contact();
      PdaItem item = contact;
      // ...

      // Base types must be cast explicitly to derived types
      contact = (Contact)item;
      // ...
  }
}
```

The derived type, `Contact`, is a `PdaItem` and can be assigned directly to a variable of type `PdaItem`. This is known as an **implicit conversion** because no cast operator is required and the conversion will always succeed; that is, it will not throw an exception.

The reverse, however, is not true. A `PdaItem` is not necessarily a `Contact`; it could be an `Appointment` or some other derived type. Therefore, casting from the base type to the derived type requires an **explicit cast,** which could fail at runtime. To perform an explicit cast, you identify the target type within parentheses prior to the original reference, as Listing 6.4 demonstrates.

With the explicit cast, the programmer essentially communicates to the compiler to trust her—she knows what she is doing—and the C# compiler allows the conversion to proceed as long as the target type is derived from the originating type. Although the C# compiler allows an explicit conversion at compile time between potentially compatible types, the CLR will still verify the explicit cast at execution time, throwing an exception if the object instance is not actually of the targeted type.

The C# compiler allows the cast operator even when the type hierarchy allows an implicit cast. For example, the assignment from `contact` to `item` could use a cast operator as follows:

```
item = (PdaItem)contact;
```

or even when no cast is necessary:

```
contact = (Contact)contact;
```

NOTE

A derived object can be implicitly converted to its base class. In contrast, converting from the base class to the derived class requires an explicit cast operator, as the conversion could fail. Although the compiler will allow an explicit cast if it is potentially valid, the runtime will still prevent an invalid cast at execution time by throwing an exception.

BEGINNER TOPIC

Casting within the Inheritance Chain

An implicit conversion to a base class does not instantiate a new instance. Instead, the same instance is simply referred to as the base type, and the capabilities (the accessible members) are those of the base type. It is just like referring to a CD-ROM drive as a "storage device." Since not all storage devices support an eject operation, a CD-ROM drive that is viewed as a storage device cannot be ejected either, and a call to `storageDevice.Eject()` would not compile even though the instantiated object may have been a `CDROM` object that supported the `Eject()` method.

Similarly, casting down from the base class to the derived class simply begins referring to the type more specifically, expanding the available operations. The restriction is that the actual instantiated type must be an instance of the targeted type (or something derived from it).

ADVANCED TOPIC

Defining Custom Conversions

Conversion between types is not limited to types within a single inheritance chain. It is possible to convert between unrelated types as well, such as converting from an `Address` to `string`, and vice versa. The key is the provision of a conversion operator between the two types. C# allows types to include either explicit or implicit conversion operators. If the operation could possibly fail, such as in a cast from `long` to `int`, developers should choose to define an explicit conversion operator. This warns developers performing the conversion to do so only when they are certain the conversion will succeed, or else to be prepared to catch the exception if it doesn't. They should also use an explicit conversion over an implicit conversion when the conversion is lossy. Converting from a `float` to an `int`, for example, truncates the decimal, which a return cast (from `int` back to `float`) would not recover.

Listing 6.5 shows an example of an implicit conversion operator signature.

Listing 6.5: Defining Cast Operators

```
class GPSCoordinates
{
  // ...

  public static implicit operator UTMCoordinates(
      GPSCoordinates coordinates)
  {
      // ...
  }
}
```

In this case, you have an implicit conversion from `GPSCoordinates` to `UTMCoordinates`. A similar conversion could be written to reverse the process. Note that an explicit conversion could also be written by replacing `implicit` with `explicit`.

private Access Modifier

All members of a base class, except for constructors and destructors, are inherited by the derived class. However, just because a member is inherited, that does not mean it is accessible. For example, in Listing 6.6, the `private` field, `_Name`, is not available on `Contact` because private members are accessible only at code locations inside the type that declares them.

Listing 6.6: Private Members Are Inherited But Not Accessible

```
public class PdaItem
{
  private string _Name;
  // ...
}
```

```
public class Contact : PdaItem
{
  // ...
}
```

```
public class Program
{
  public static void Main()
  {
      Contact contact = new Contact();

      // ERROR:  'PdaItem. _Name' is inaccessible
      // due to its protection level
      // contact._Name = "Inigo Montoya";
  }
}
```

As part of respecting the principle of encapsulation, derived classes cannot access members declared as `private`.[1] This forces the base class developer to make an explicit choice as to whether a derived class gains access to a member. In this case, the base class is defining an API in which `_Name`

1. Except for the corner case when the derived class is also a nested class of the base class.

can be changed only via the `Name` property. That way, if validation is added, the derived class will gain the validation benefit automatically because it was unable to access `_Name` directly from the start.

> **NOTE**
>
> Derived classes cannot access members declared as private in a base class.

protected Access Modifier

Encapsulation is finer grained than just `public` or `private`, however. It is possible to define members in base classes that only derived classes can access. As an example, consider the `ObjectKey` property shown in Listing 6.7.

LISTING 6.7: protected Members Are Accessible Only from Derived Classes

```
public class Program
{
  public static void Main()
  {
      Contact contact = new Contact();
      contact.Name = "Inigo Montoya";

      // ERROR:  'PdaItem.ObjectKey' is inaccessible
      // due to its protection level
      // contact.ObjectKey = Guid.NewGuid();
  }
}
```

```
public class PdaItem
{
  protected Guid ObjectKey { get; set; }
  // ...
}
```

```
public class Contact : PdaItem
{
  void Save()
  {
      // Instantiate a FileStream using <ObjectKey>.dat
      // for the filename.
      FileStream stream = System.IO.File.OpenWrite(
          ObjectKey + ".dat");
  }
```

```
    void Load(PdaItem pdaItem)
    {
        // ERROR:  'pdaItem.ObjectKey' is inaccessible
        // due to its protection level
        // pdaItem.ObjectKey = ...;

        Contact contact = pdaItem as Contact;
        if(contact != null)
        {
            contact.ObjectKey = ...;
        }

        // ...
    }
}
```

ObjectKey is defined using the protected access modifier. The result is that it is accessible outside of PdaItem only from classes that derive from PdaItem. Contact derives from PdaItem, so all members of Contact have access to ObjectKey. In contrast, Program does not derive from PdaItem, so using the ObjectKey property within Program results in a compile-time error.

NOTE

Protected members in the base class are accessible only from the base class and other classes within the derivation chain.

A subtlety shown in the Contact.Load() method is worth noting. Developers are often surprised that it is not possible to access the protected ObjectKey of an explicit PdaItem from code within Contact, even though Contact derives from PdaItem. The reason is that a PdaItem could potentially be an Address, and Contact should not be able to access protected members of Address. Therefore, encapsulation prevents Contact from potentially modifying the ObjectKey of an Address. A successful cast to Contact will bypass the restriction as shown. The governing rule is that accessing a protected member from a derived class requires compile-time determination that the protected member is an instance of the derived class (or a class further derived from it).

Extension Methods

Begin 3.0

Extension methods are technically not members of a type and, therefore, are not inherited. Nevertheless, because every derived class may be used as an instance of any of its base classes, an extension method on one type also extends every derived type. If we extend a base class such as `PdaItem`, all the extension methods will also be available in the derived classes. However, as with all extension methods, priority is given to instance methods. If a compatible signature appears anywhere within the inheritance chain, this will take precedence over an extension method.

Requiring extension methods on base types is rare. As with extension methods in general, if the base type's code is available, it is preferable to modify the base type directly. Even in cases where the base type's code is unavailable, programmers should consider whether to add extension methods to an interface that the base type or individual derived types implement. We cover interfaces and how to use them with extension methods in the next chapter.

End 3.0

Single Inheritance

In theory, you can place an unlimited number of classes in an inheritance tree. For example, `Customer` derives from `Contact`, which derives from `PdaItem`, which derives from `object`. However, C# is a **single-inheritance** programming language (as is the CIL language to which C# compiles). This means that a class cannot derive from two classes directly. It is not possible, for example, to have `Contact` derive from both `PdaItem` and `Person`.

Language Contrast: C++—Multiple Inheritance

C#'s single inheritance is one of its major object-oriented differences from C++.

For the rare cases that require a multiple-inheritance class structure, one solution is to use **aggregation;** instead of one class inheriting from another, one class contains an instance of the other. Figure 6.2 shows an example of this class structure. Aggregation occurs when the association relationship defines a core part of the containing object. For multiple inheritance, this involves picking one class as the primary base class (`PdaItem`) and deriving a new class (`Contact`) from that. The second desired base class (`Person`) is added as a field in the derived class (`Contact`). Next, all the nonprivate members on the field (`Person`) are redefined on the derived class (`Contact`), which then delegates the calls out to the field (`Person`). Some code duplication occurs because methods are redeclared; however, this is minimal, since the real method body is implemented only within the aggregated class (`Person`).

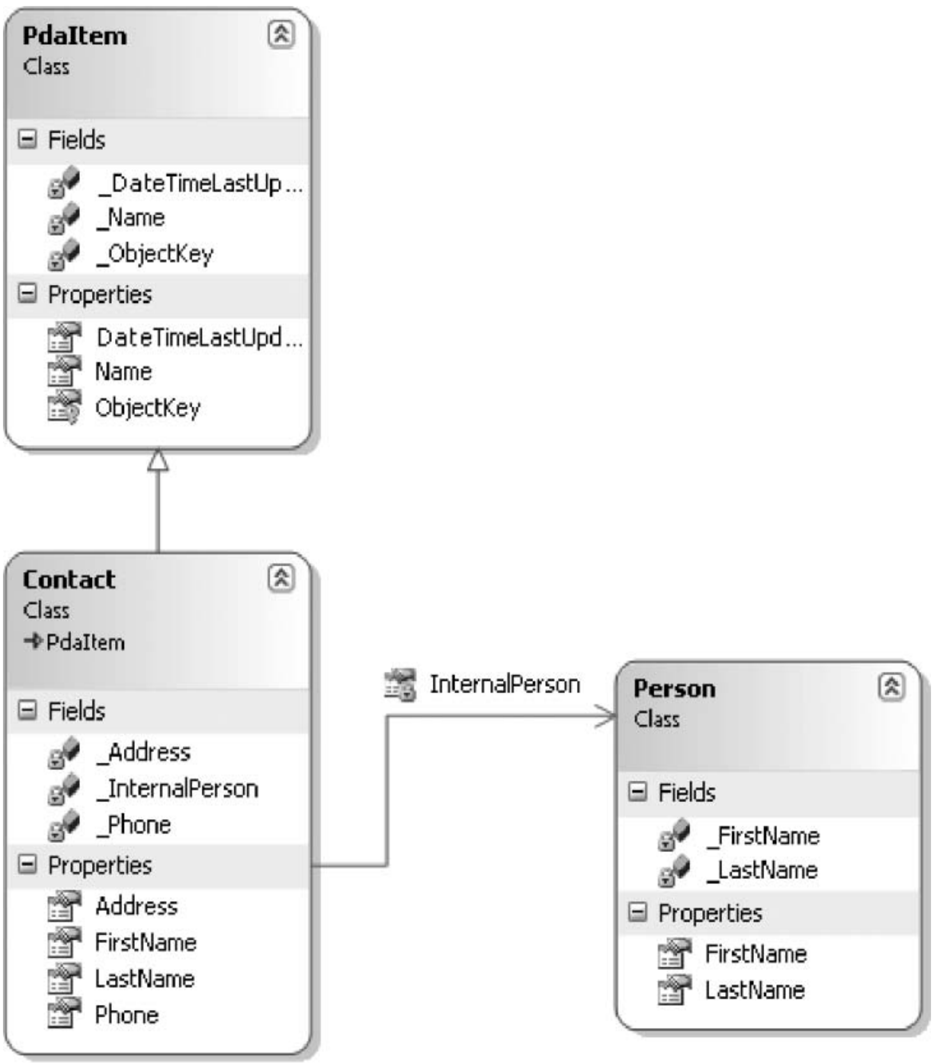


FIGURE 6.2: Simulating Multiple Inheritance Using Aggregation

In Figure 6.2, `Contact` contains a private property called `InternalPerson` that is drawn as an association to the `Person` class. `Contact` also contains the `FirstName` and `LastName` properties but with no corresponding fields. Instead, the `FirstName` and `LastName` properties simply delegate their calls out to `InternalPerson.FirstName` and `InternalPerson.LastName`, respectively. Listing 6.8 shows the resultant code.

LISTING 6.8: Working around Single Inheritance Using Aggregation

```
public class PdaItem
{
  // ...
}

public class Person
{
  // ...
}

public class Contact : PdaItem
{
  private Person InternalPerson { get; set; }

  public string FirstName
  {
      get { return InternalPerson.FirstName; }
      set { InternalPerson.FirstName = value; }
  }

  public string LastName
  {
      get { return InternalPerson.LastName; }
      set { InternalPerson.LastName = value; }
  }

  // ...
}
```

Besides the added complexity of delegation, another drawback is that any methods added to the field class (`Person`) will require manual addition to the derived class (`Contact`); otherwise, `Contact` will not expose the added functionality.

Sealed Classes

To design a class correctly that others can extend via derivation can be a tricky task that requires testing with examples to verify the derivation will work successfully. Listing 6.9 shows how to avoid unexpected derivation scenarios and problems by marking classes as **sealed.**

LISTING 6.9: Preventing Derivation with Sealed Classes

```
public sealed class CommandLineParser
{
  // ...
}
```

```
// ERROR:  Sealed classes cannot be derived from
public sealed class DerivedCommandLineParser :
  CommandLineParser
{
  // ...
}
```

Sealed classes include the `sealed` modifier, and the result is that they cannot be derived from. The `string` type is an example of a type that uses the `sealed` modifier to prevent derivation.

Overriding the Base Class

All members of a base class are inherited in the derived class, except for constructors and destructors. However, sometimes the base class does not have the optimal implementation of a particular member. Consider the `Name` property on `PdaItem`, for example. The implementation is probably acceptable when inherited by the `Appointment` class. For the `Contact` class, however, the `Name` property should return the `FirstName` and `LastName` properties combined. Similarly, when `Name` is assigned, it should be split across `FirstName` and `LastName`. In other words, the base class property declaration is appropriate for the derived class, but the implementation is not always valid. There needs to be a mechanism for **overriding** the base class implementation with a custom implementation in the derived class.

virtual Modifier

C# supports overriding on instance methods and properties, but not on fields or on any static members. It requires an explicit action within both the base class and the derived class. The base class must mark each member for which it allows overriding as `virtual`. If `public` or `protected` members do not include the `virtual` modifier, subclasses will not be able to override those members.

Language Contrast: Java—Virtual Methods by Default

By default, methods in Java are virtual, and they must be explicitly sealed if nonvirtual behavior is preferred. In contrast, C# defaults to nonvirtual.

Listing 6.10 shows an example of property overriding.

LISTING 6.10: Overriding a Property

```
public class PdaItem
{
    public virtual string Name { get; set; }
    // ...
}

public class Contact : PdaItem
{
    public override string Name
    {
        get
        {
            return $"{ FirstName } { LastName }";
        }

        set
        {
            string[] names = value.Split(' ');
            // Error handling not shown.
            FirstName = names[0];
            LastName = names[1];
        }
    }

    public string FirstName { get; set; }
    public string LastName { get; set; }

    // ...
}
```

Not only does `PdaItem` include the `virtual` modifier on the `Name` property, but `Contact`'s `Name` property is also decorated with the keyword `override`. Eliminating `virtual` would result in an error, and omitting `override` would cause a warning to be generated, as you will see shortly. C# requires the overriding methods to use the `override` keyword explicitly. In other words, `virtual` identifies a method or property as available for replacement (overriding) in the derived type.

Language Contrast: Java and C++—Implicit Overriding

Unlike with Java and C++, the `override` keyword is required on the derived class. C# does not allow implicit overriding. To override a method, both the base class and the derived class members must match and have corresponding `virtual` and `override` keywords. Furthermore, when the `override` keyword is specified, the derived implementation is assumed to replace the base class implementation.

Overloading a member causes the runtime to call the most derived implementation (see Listing 6.11).

Listing 6.11: Runtime Calling the Most Derived Implementation of a Virtual Method

```
public class Program
{
  public static void Main()
  {
        Contact contact;
        PdaItem item;

        contact = new Contact();
        item = contact;

        // Set the name via PdaItem variable
        item.Name = "Inigo Montoya";

        // Display that FirstName & LastName
        // properties were set.
        Console.WriteLine(
            $"{ contact.FirstName } { contact.LastName}");
}
```

Output 6.1 shows the results of Listing 6.11.

OUTPUT 6.1

```
Inigo Montoya
```

In Listing 6.11, `item.Name` is called; `item` is declared as a `PdaItem` there. However, the `contact`'s `FirstName` and `LastName` are still set. The rule is that whenever the runtime encounters a virtual method, it calls the most derived and overriding implementation of the virtual member. In this case, the code instantiates a `Contact` and calls `Contact.Name` because `Contact` contains the most derived implementation of `Name`.

In creating a class, programmers should be careful when choosing to allow overriding a method, since they cannot control the derived implementation. Virtual methods should not include critical code because such methods may never be called if the derived class overrides them. Furthermore, converting a method from a virtual method to a nonvirtual method could break derived classes that override the method. You should avoid such a code-breaking change, especially for assemblies intended for use by third parties.

Listing 6.12 includes a virtual `Run()` method. If the `Controller` programmer calls `Run()` with the expectation that the critical `Start()` and `Stop()` methods will be called, he will run into a problem.

LISTING 6.12: Carelessly Relying on a Virtual Method Implementation

```
public class Controller
{
  public void Start()
  {
      // Critical code
  }
  public virtual void Run()
  {
      Start();
      Stop();
  }
  public void Stop()
  {
      // Critical code
  }
}
```

In overriding `Run()`, a developer could perhaps not call the critical `Start()` and `Stop()` methods. To force the `Start()`/`Stop()` expectation, the `Controller` programmer should define the class as shown in Listing 6.13.

LISTING 6.13: Forcing the Desirable Run() Semantics

```
public class Controller
{
    public void Start()
    {
        // Critical code
    }

    private void Run()
    {
        Start();
        InternalRun();
        Stop();
    }

    protected virtual void InternalRun()
    {
        // Default implementation
    }

    public void Stop()
    {
        // Critical code
    }
}
```

With this new listing, on the one hand, the `Controller` programmer prevents users from mistakenly calling `InternalRun()`, because it is protected. On the other hand, declaring `Run()` as `public` ensures that `Start()` and `Stop()` are invoked appropriately. It is still possible for users to modify the default implementation of how the `Controller` executes by overriding the protected `InternalRun()` member from within the derived class.

Virtual methods provide default implementations only—that is, implementations that derived classes could override entirely. However, because of the complexities of inheritance design, it is important to consider (and preferably to implement) a specific scenario that requires the virtual method definition rather than declaring members as `virtual` by default.

Finally, only instance members can be `virtual`. The CLR uses the concrete type, specified at instantiation time, to determine where to dispatch a `virtual` method call, so `static virtual` methods are meaningless and the compiler prohibits them.

Language Contrast: C++—Dispatch Method Calls during Construction

In C++, methods called during construction will not dispatch the virtual method. Instead, during construction, the type is associated with the base type rather than the derived type, and virtual methods call the base implementation. In contrast, C# dispatches virtual method calls to the most derived type. This is consistent with the principle of calling the most derived virtual member, even if the derived constructor has not completely executed. Regardless, in C# the situation should be avoided.

new Modifier

When an overriding method does not use `override`, the compiler issues a warning similar to that shown in Output 6.2 or Output 6.3.

OUTPUT 6.2

```
warning CS0114: '<derived method name>' hides inherited member
'<base method name>'. To make the current member override that
implementation, add the override keyword. Otherwise add the new
keyword.
```

OUTPUT 6.3

```
warning CS0108: The keyword new is required on '<derived property
name>' because it hides inherited member '<base property name>'
```

The obvious solution is to add the `override` modifier (assuming the base member is virtual). However, as the warnings point out, the `new` modifier is also an option. Consider the scenario shown in Table 6.1 on the next page—a specific example of the more general problem known as the **brittle base class** or **fragile base class** problem.

TABLE 6.1: Why the New Modifier?

<table>
<tr><th>Activity</th><th>Code</th></tr>
<tr><td>

Programmer A defines class `Person` that includes properties `FirstName` and `LastName`.

</td><td>

```
public class Person
{
  public string FirstName { get; set; }
  public string LastName { get; set; }
}
```

</td></tr>
<tr><td>

Programmer B derives from `Person` and defines `Contact` with the additional property, `Name`. In addition, he defines the `Program` class whose `Main()` method instantiates `Contact`, assigns `Name`, and then prints out the name.

</td><td>

```
public class Contact : Person
{
  public string Name
  {
      get
      {
          return FirstName + " " + LastName;
      }

      set
      {
          string[] names = value.Split(' ');
          // Error handling not shown.
          FirstName = names[0];
          LastName = names[1];
      }
  }
}
```

</td></tr>
<tr><td>

Later, Programmer A adds the `Name` property, but instead of implementing the getter as `FirstName + " " + LastName`, she implements it as `LastName + ", " + FirstName`. Furthermore, she doesn't define the property as `virtual`, and she uses the property in a `DisplayName()` method.

</td><td>

```
    // ...
public class Person
{
  public string Name
  {
      get
      {
          return LastName + ", " + FirstName;
      }

      set
      {
          string[] names = value.Split(", ");
          // Error handling not shown.
          LastName = names[0];
          FirstName = names[1];
      }
  }
  public static void Display(Person person)
  {
      // Display <LastName>, <FirstName>
      Console.WriteLine( person.Name );
  }
}
```

</td></tr>
</table>

Because Person.Name is not virtual, Programmer A will expect Display() to use the Person implementation, even if a Person-derived data type, Contact, is passed in. However, Programmer B would expect Contact.Name to be used in all cases where the variable data type is a Contact. (Programmer B would have no code where Person.Name was used, since no Person.Name property existed initially.) To allow the addition of Person.Name without breaking either programmer's expected behavior, you cannot assume virtual was intended. Furthermore, because C# requires an override member to explicitly use the override modifier, some other semantic must be assumed, instead of allowing the addition of a member in the base class to cause the derived class to no longer compile.

This semantic is the new modifier, and it hides a redeclared member of the derived class from the base class. Instead of calling the most derived member, a member of the base class calls the most derived member in the inheritance chain prior to the member with the new modifier. If the inheritance chain contains only two classes, a member in the base class will behave as though no method was declared on the derived class (if the derived implementation overrides the base class member). Although the compiler will report the warning shown in either Output 6.2 or Output 6.3, if neither override nor new is specified, new will be assumed, thereby maintaining the desired version safety.

Consider Listing 6.14 as an example. Its output appears in Output 6.4.

LISTING 6.14: override versus new Modifier

```
public class Program
{
  public class BaseClass
  {
      public void DisplayName()
      {
          Console.WriteLine("BaseClass");
      }
  }

    public class DerivedClass : BaseClass
    {
        // Compiler WARNING: DisplayName() hides inherited
        // member. Use the new keyword if hiding was intended.
        public virtual void DisplayName()
        {
            Console.WriteLine("DerivedClass");
        }
```

```
    }

    public class SubDerivedClass : DerivedClass
    {
        public override void DisplayName()
        {
            Console.WriteLine("SubDerivedClass");
        }
    }

    public class SuperSubDerivedClass : SubDerivedClass
    {
        public new void DisplayName()
        {
            Console.WriteLine("SuperSubDerivedClass");
        }
    }

    public static void Main()
    {
        SuperSubDerivedClass superSubDerivedClass
            = new SuperSubDerivedClass();

        SubDerivedClass subDerivedClass = superSubDerivedClass;
        DerivedClass derivedClass = superSubDerivedClass;
        BaseClass baseClass = superSubDerivedClass;

        superSubDerivedClass.DisplayName();
        subDerivedClass.DisplayName();
        derivedClass.DisplayName();
        baseClass.DisplayName();
    }
}
```

OUTPUT 6.4

```
SuperSubDerivedClass
SubDerivedClass
SubDerivedClass
BaseClass
```

These results occur for the following reasons.

- `SuperSubDerivedClass`: `SuperSubDerivedClass.DisplayName()` displays `SuperSubDerivedClass` because there is no derived class and, therefore, no overload.
- `SubDerivedClass`: `SubDerivedClass.DisplayName()` is the most derived member to override a base class's virtual member. `SuperSubDerivedClass.DisplayName()` is hidden because of its `new` modifier.

- `SubDerivedClass`: `DerivedClass.DisplayName()` is virtual and `SubDerivedClass.DisplayName()` is the most derived member to override it. As before, `SuperSubDerivedClass.DisplayName()` is hidden because of the `new` modifier.
- `BaseClass`: `BaseClass.DisplayName()` does not redeclare any base class member and it is not virtual; therefore, it is called directly.

When it comes to the CIL, the `new` modifier has no effect on which statements the compiler generates. However, a "new" method results in the generation of the `newslot` metadata attribute on the method. From the C# perspective, its only effect is to remove the compiler warning that would appear otherwise.

sealed Modifier

Just as you can prevent inheritance using the `sealed` modifier on a class, so virtual members may be `sealed` as well (see Listing 6.15). This approach prevents a subclass from overriding a base class member that was originally declared as `virtual` higher in the inheritance chain. Such a situation arises when a subclass `B` overrides a base class `A`'s member and then needs to prevent any further overriding below subclass `B`.

LISTING 6.15: Sealing Members

```
class A
{
  public virtual void Method()
  {
  }
}
class B : A
{
  public override sealed void Method()
  {
  }
}

class C : B
{
  // ERROR:  Cannot override sealed members
  // public override void Method()
  // {
  // }
}
```

In this example, the use of the `sealed` modifier on class `B`'s `Method()` declaration prevents class `C` from overriding `Method()`.

In general, marking a class as `sealed` is rarely done and should be reserved only for those situations in which there are strong reasons favoring such a restriction. In fact, leaving types unsealed is increasingly desirable, as unit testing has become prominent because of the need to support mock (test double) object creation in place of real implementations. One possible scenario when sealing a class might be warranted is when the cost of sealing individual virtual members outweighs the benefits of leaving the class unsealed. However, a more targeted sealing of individual members—perhaps because there are dependencies in the base implementation for correct behavior—is likely to be preferable.

base Member

In choosing to override a member, developers often want to invoke the member on the base class (see Listing 6.16).

Listing 6.16: Accessing a Base Member

```
using static System.Environment;

public class Address
{
    public string StreetAddress;
    public string City;
    public string State;
    public string Zip;

    public override string ToString()
    {
        return $"{ StreetAddress + NewLine }"
            + $"{ City }, { State }  { Zip }";
    }
}

public class InternationalAddress : Address
{
    public string Country;

    public override string ToString()
    {
        return base.ToString() +
            NewLine + Country;
    }
}
```

In Listing 6.16, `InternationalAddress` inherits from `Address` and implements `ToString()`. To call the parent class's implementation, you use the `base` keyword. The syntax is virtually identical to `this`, including support for using `base` as part of the constructor (discussed shortly).

Parenthetically, in the `Address.ToString()` implementation, you are required to `override` because `ToString()` is also a member of `object`. Any members that are decorated with `override` are automatically designated as virtual, so additional child classes may further specialize the implementation.

> **NOTE**
>
> Any methods decorated with `override` are automatically virtual. A base class method can be overridden only if it is virtual, and the overriding method is therefore virtual as well.

Constructors

When instantiating a derived class, the runtime first invokes the base class's constructor so that the base class initialization is not circumvented. However, if there is no accessible (nonprivate) default constructor on the base class, it is not clear how to construct the base class; in turn, the C# compiler reports an error.

To avoid the error caused by the lack of an accessible default constructor, programmers need to designate explicitly, in the derived class constructor header, which base constructor to run (see Listing 6.17).

LISTING 6.17: Specifying Which Base Constructor to Invoke

```
public class PdaItem
{
  public PdaItem(string name)
  {
      Name = name;
  }

  // ...
}
```

```
public class Contact : PdaItem
{
```

```
    public Contact(string name) :
        base(name)
    {
        Name = name;
    }

    public string Name { get; set; }
    // ...
  }
```

By identifying the base constructor in the code, you let the runtime know which base constructor to invoke before invoking the derived class constructor.

Abstract Classes

Many of the inheritance examples so far have defined a class called `PdaItem` that defines the methods and properties common to `Contact`, `Appointment`, and so on, which are type objects that derive from `PdaItem`. `PdaItem` is not intended to be instantiated itself, however. A `PdaItem` instance has no meaning by itself; it has meaning only when it is used as a base class—to share default method implementations across the set of data types that derive from it. These characteristics are indicative of the need for `PdaItem` to be an **abstract** class rather than a **concrete** class. Abstract classes are designed for derivation only. It is not possible to instantiate an abstract class, except in the context of instantiating a class that derives from it. Classes that are not abstract and can instead be instantiated directly are concrete classes.

BEGINNER TOPIC

Abstract Classes

Abstract classes represent abstract entities. Their **abstract members** define what an object derived from an abstract entity should contain, but they don't include the implementation. Often, much of the functionality within an abstract class is unimplemented. Before a class can successfully derive from an abstract class, however, it needs to provide the implementation for the abstract methods in its abstract base class.

To define an abstract class, C# requires the abstract modifier to the class definition, as shown in Listing 6.18.

LISTING 6.18: Defining an Abstract Class

```
// Define an abstract class
public abstract class PdaItem
{
  public PdaItem(string name)
  {
      Name = name;
  }

  public virtual string Name { get; set; }
}
```

```
public class Program
{
  public static void Main()
  {
      PdaItem item;
      // ERROR:  Cannot create an instance of the abstract class
      // item = new PdaItem("Inigo Montoya");
  }
}
```

Although abstract classes cannot be instantiated, this restriction is a minor characteristic of an abstract class. Their primary significance is achieved when abstract classes include **abstract members.** An abstract member is a method or property that has no implementation. Its purpose is to force all derived classes to provide the implementation.

Consider Listing 6.19 as an example.

LISTING 6.19: Defining Abstract Members

```
// Define an abstract class
public abstract class PdaItem
{
  public PdaItem(string name)
  {
      Name = name;
  }

  public virtual string Name { get; set; }
  public abstract string GetSummary();
}
```

```
using static System.Environment;

public class Contact : PdaItem
{
    public override string Name
```

```
    {
        get
        {
            return $"{ FirstName } { LastName }";
        }

        set
        {
            string[] names = value.Split(' ');
            // Error handling not shown.
            FirstName = names[0];
            LastName = names[1];
        }
    }

    public string FirstName { get; set; }
    public string LastName { get; set; }
    public string Address { get; set; }

  public override string GetSummary()
  {
          return @"FirstName: { FirstName + NewLine }"
          + $"LastName: { LastName + NewLine }"
          + $"Address: { Address + NewLine }";
  }

  // ...
}

public class Appointment : PdaItem
{
  public Appointment(string name) :
    base(name)
  {
    Name = name;
  }

  public DateTime StartDateTime  { get; set; }
  public DateTime EndDateTime  { get; set; }
  public string Location  { get; set; }

  // ...

  public override string GetSummary()
  {
        return $"Subject: { Name + NewLine }"
            + $"Start: { StartDateTime + NewLine }"
            + $"End: { EndDateTime + NewLine }"
            + $"Location: { Location }";
  }
}
```

Listing 6.19 defines the `GetSummary()` member as `abstract`, so it doesn't include any implementation. The code then overrides this member within `Contact` and provides the implementation. Because abstract members are supposed to be overridden, such members are automatically virtual and cannot be declared so explicitly. In addition, abstract members cannot be private because derived classes would not be able to see them.

It is surprisingly difficult to develop a well-designed object hierarchy. For this reason, when programming abstract types, you should be sure to implement at least one (and preferably more) concrete type that derives from the abstract type to validate the design.

NOTE

Abstract members must be overridden, so they are automatically virtual and cannot be declared so explicitly.

Language Contrast: C++—Pure Virtual Functions

C++ allows for the definition of abstract functions using the cryptic notation `=0`. These functions are called pure virtual functions in C++. In contrast with C#, however, C++ does not require the class itself to have any special declaration. Unlike C#'s `abstract` class modifier, C++ has no class declaration change when the class includes pure virtual functions.

If you provide no `GetSummary()` implementation in `Contact`, the compiler will report an error.

NOTE

By declaring an abstract member, the abstract class programmer states that to form an "is a" relationship between a concrete class and an abstract base class (that is, a `PdaItem`), it is necessary to implement the abstract members, the members for which the abstract class could not provide an appropriate default implementation.

BEGINNER TOPIC

Polymorphism

When the implementation for the same member signature varies between two or more classes, the scenario demonstrates a key object-oriented principle: **polymorphism.** "Poly" means "many" and "morph" means "form," so polymorphism refers to the fact that there are multiple implementations of the same signature. Also, because the same signature cannot be used multiple times within a single class, each implementation of the member signature occurs on a different class.

The idea behind polymorphism is that the object itself knows best how to perform a particular operation. Moreover, by enforcing common ways to invoke those operations, polymorphism is a technique that encourages code reuse when taking advantage of the commonalities. Given multiple types of documents, each document type class knows best how to perform a `Print()` method for its corresponding document type. Therefore, instead of defining a single print method that includes a `switch` statement with the special logic to print each document type, with polymorphism you call the `Print()` method corresponding to the specific type of document you wish to print. For example, calling `Print()` on a word processing document class behaves according to word processing specifics, whereas calling the same method on a graphics document class will result in print behavior specific to the graphic. Given the document types, however, all you have to do to print a document is to call `Print()`, regardless of the type.

Moving the custom print implementation out of a `switch` statement offers a number of maintenance advantages. First, the implementation appears in the context of each document type's class rather than in a location far removed; this is in keeping with encapsulation. Second, adding a new document type doesn't require a change to the `switch` statement. Instead, all that is necessary is for the new document type class to implement the `Print()` signature.

Abstract members are intended to be a way to enable polymorphism. The base class specifies the signature of the method and the derived class provides the implementation (see Listing 6.20).

LISTING 6.20: Using Polymorphism to List the `PdaItems`

```
public class Program
{
```

```
    public static void Main()
    {
        PdaItem[] pda = new PdaItem[3];

        Contact contact = new Contact("Sherlock Holmes");
        contact.Address = "221B Baker Street, London, England";
        pda[0] = contact;

        Appointment appointment =
           new Appointment("Soccer tournament");
        appointment.StartDateTime = new DateTime(2008, 7, 18);
        appointment.EndDateTime = new DateTime(2008, 7, 19);
        appointment.Location = "Estádio da Machava";
        pda[1] = appointment;

        contact = new Contact("Hercule Poirot");
        contact.Address =
            "Apt 56B, Whitehaven Mansions, Sandhurst Sq, London";
        pda[2] = contact;

        List(pda);
    }

    public static void List(PdaItem[] items)
    {
        // Implemented using polymorphism. The derived
        // type knows the specifics of implementing
        // GetSummary().
        foreach (PdaItem item in items)
        {
            Console.WriteLine("________");
            Console.WriteLine(item.GetSummary());
        }
    }
}
```

The results of Listing 6.20 appear in Output 6.5.

OUTPUT 6.5

```
________
FirstName: Sherlock
LastName: Holmes
Address: 221B Baker Street, London, England
________
Subject: Soccer tournament
Start: 7/18/2008 12:00:00 AM
End: 7/19/2008 12:00:00 AM
Location: Estádio da Machava
________
FirstName: Hercule
LastName: Poirot
Address: Apt 56B, Whitehaven Mansions, Sandhurst Sq, London
```

In this way, you can call the method on the base class but the implementation is specific to the derived class. Output 6.5 shows that the `List()` method from Listing 6.20 is able to successfully display both `Contacts` and `Addresses`, and display them in a way custom to each. The invocation of the abstract `GetSummary()` method actually invokes the overriding method specific to the instance.

All Classes Derive from `System.Object`

Given any class, whether a custom class or one built into the system, the methods shown in Table 6.2 will be defined.

TABLE 6.2: Members of `System.Object`

Method Name	Description
`public virtual bool Equals(object o)`	Returns `true` if the object supplied as a parameter is equal in *value,* not necessarily in reference, to the instance.
`public virtual int GetHashCode()`	Returns an integer corresponding to an evenly spread hash code. This is useful for collections such as `HashTable` collections.
`public Type GetType()`	Returns an object of type `System.Type` corresponding to the type of the object instance.
`public static bool ReferenceEquals( object a, object b)`	Returns `true` if the two supplied parameters refer to the same object.
`public virtual string ToString()`	Returns a string representation of the object instance.
`public virtual void Finalize()`	An alias for the destructor; informs the object to prepare for termination. C# prevents you from calling this method directly.
`protected object MemberwiseClone()`	Clones the object in question by performing a shallow copy; references are copied, but not the data within a referenced type.

All of the methods listed in Table 6.2 appear on all objects through inheritance; all classes derive (either directly or via an inheritance chain) from object. Even literals include these methods, enabling somewhat peculiar-looking code such as this:

```
Console.WriteLine( 42.ToString() );
```

Even class definitions that don't have any explicit derivation from `object`, derive from `object` anyway. The two declarations for `PdaItem` in Listing 6.21, therefore, result in identical CIL.

LISTING 6.21: `System.Object` Derivation Implied When No Derivation Is Specified Explicitly

```
public class PdaItem
{
  // ...
}
```

```
public class PdaItem : object
{
  // ...
}
```

When the `object`'s default implementation isn't sufficient, programmers can override one or more of the three virtual methods. Chapter 9 describes the details involved in doing so.

Verifying the Underlying Type with the `is` Operator

Because C# allows casting down the inheritance chain, it is sometimes desirable to determine what the underlying type is before attempting a conversion. Also, checking the type may be necessary for type-specific actions where polymorphism was not implemented. To determine the underlying type, C# provides the `is` operator (see Listing 6.22).

LISTING 6.22: `is` Operator Determining the Underlying Type

```
public static void Save(object data)
{
    if (data is string)
    {
        data = Encrypt((string) data);
    }

    // ...
}
```

Listing 6.22 encrypts the data if the underlying type is a `string`. This is significantly different from encrypting any data type that casts successfully to a `string` since many types support casting to a `string`, and yet their underlying type is not a `string`.

Although this capability is important, you should consider issues related to polymorphism prior to using the `is` operator. Polymorphism supports the expansion of a behavior to other data types without requiring any modification of the implementation that defines the behavior. For example, deriving from a common base type and then using that type as the parameter to the `Save()` method avoids the need to check for `string` explicitly and enables other data types to support encryption during the save operation by deriving from the same base type.

Conversion Using the as Operator

The advantage of the `is` operator is that it enables verification that a data item is of a particular type. The `as` operator goes one step further: It attempts a conversion to a particular data type and assigns `null` if the source type is not inherently (within the inheritance chain) of the target type. This strategy is significant because it avoids the exception that could result from casting. Listing 6.23 demonstrates use of the `as` operator.

LISTING 6.23: Data Conversion Using the as Operator

```
object Print(IDocument document)
{
  if(thing != null)
  {
      // Print document...
  }
  else
  {
  }
}

static void Main()
{
  object data;

  // ...

  Print(data as Document);
}
```

By using the `as` operator, you are able to avoid additional try/catch handling code if the conversion is invalid, because the `as` operator provides a way to attempt a cast without throwing an exception if the cast fails.

One advantage of the `is` operator over the `as` operator is that the latter cannot successfully determine the underlying type. The `as` operator may implicitly cast up or down an inheritance chain, as well as across to types supporting the cast operator. Unlike the `as` operator, the `is` operator can determine the underlying type.

SUMMARY

This chapter discussed how to specialize a class by deriving from it and adding additional methods and properties. This coverage included a discussion of the `private` and `protected` access modifiers that control the level of encapsulation.

The chapter also investigated the details of overriding the base class implementation and, alternatively, hiding it using the `new` modifier. To control overriding, C# provides the `virtual` modifier, which identifies to the deriving class developer which members she intends for derivation. To prevent any derivation, the `sealed` modifier may be used on the class. Similarly, placing the `sealed` modifier on a member prevents further overriding from subclasses.

This chapter ended with a brief discussion of how all types derive from `object`. Chapter 9 discusses this derivation further, with a look at how `object` includes three virtual methods with specific rules and guidelines that govern overloading. Before you get there, however, you need to consider another programming paradigm that builds on object-oriented programming: interfaces. This is the subject of Chapter 7.

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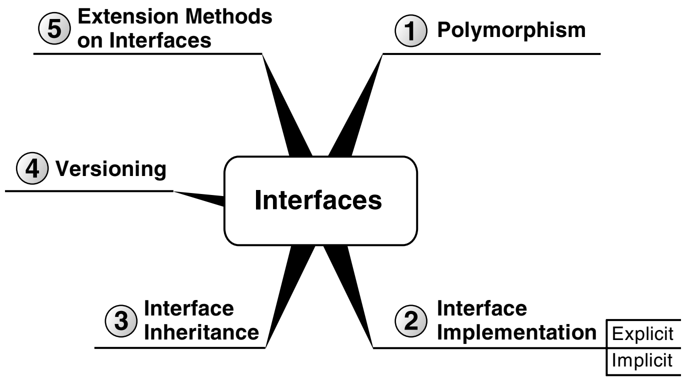
7

Interfaces

POLYMORPHISM IS AVAILABLE NOT ONLY via inheritance (as discussed in the preceding chapter), but also via interfaces. Unlike abstract classes, interfaces cannot include any implementation. Like abstract classes, however, interfaces define a set of members that callers can rely on being implemented.

By implementing an interface, a type defines its capabilities. The interface implementation relationship is a "can do" relationship: The type can do what the interface requires an implementing type to do. The interface defines the contract between the types that implement the interface and the code that uses the interface. Types that implement interfaces must declare methods with the same signatures as the methods declared by the implemented interfaces. This chapter discusses implementing and using interfaces.



Introducing Interfaces

BEGINNER TOPIC

Why Interfaces?

Interfaces are useful because—unlike abstract classes—they enable the complete separation of implementation details from services provided. For a real-world example, consider the "interface" that is an electrical wall socket. How the electrical power gets to the socket is an implementation detail: It might be generated by chemical, nuclear, or solar energy; the generator might be in the next room or far away; and so on. The socket provides a "contract": It agrees to supply a particular voltage at a specific frequency, and in return it requires that the appliance using that interface provide a compatible plug. The appliance need not care anything about the implementation details that get power to the socket; all it needs to worry about is that it provides a compatible plug.

Consider the following example: A huge number of file compression formats are available (`.zip`, `.7-zip`, `.cab`, `.lha`, `.tar`, `.tar.gz`, `.tar.bz2`, `.bh`, `.rar`, `.arj`, `.arc`, `.ace`, `.zoo`, `.gz`, `.bzip2`, `.xxe`, `.mime`, `.uue`, and `.yenc`, just to name a few). If you created classes for each compression format, you could end up with different method signatures for each compression implementation and no ability to apply a standard calling convention across them. The desired method could be declared as abstract in the base class. However, deriving from a common base class uses up a class's one and only opportunity for inheritance. It is unlikely that there is any code common to various compression implementations that can be put in the base class, thereby ruling out the potential benefits of having a base class implementation. The key point is that base classes let you share implementation along with the member signatures, whereas interfaces allow you to share the member signatures without the implementation.

Instead of sharing a common base class, each compression class needs to implement a common interface. Interfaces define the contract that a class supports to interact with the other classes that expect the interface. If all the classes implemented the `IFileCompression` interface and its `Compress()` and `Uncompress()` methods, the code for calling the algorithm on any particular compression class would simply involve a conversion to the `IFileCompression` interface and a call to the members. The result is polymorphism because each compression class has the same method signature but individual implementations of that signature.

The `IFileCompression` interface shown in Listing 7.1 is an example of an interface implementation. By convention—a convention so strong it is universal—the interface name is PascalCase with a capital "I" prefix.

Listing 7.1: Defining an Interface

```
interface IFileCompression
{
  void Compress(string targetFileName, string[] fileList);
  void Uncompress(
      string compressedFileName, string expandDirectoryName);
}
```

`IFileCompression` defines the methods a type must implement to be used in the same manner as other compression-related classes. The power of interfaces is that they grant the ability to callers to switch among implementations without modifying the calling code.

One key characteristic of an interface is that it has no implementation and no data. Method declarations in an interface have a single semicolon in place of curly braces after the header. Fields (data) cannot appear in an interface declaration. When an interface requires the derived class to have certain data, it declares a property rather than a field. Since the property does not contain any implementation as part of the interface declaration, it doesn't reference a backing field.

The declared members of an interface describe the members that must be accessible on an implementing type. The purpose of nonpublic members is to make those members inaccessible to other code. Therefore, C# does not allow access modifiers on interface members; instead, it automatically defines them as public.

Guidelines

DO use Pascal casing for interface names, with an "I" prefix.

Polymorphism through Interfaces

Consider another example, as shown in Listing 7.2: `IListable` defines the members that a class needs to support for the `ConsoleListControl` class to display it. As such, any class that implements `IListable` can use the

ConsoleListControl to display itself. The IListable interface requires a read-only property, ColumnValues.

LISTING 7.2: Implementing and Using Interfaces

```
interface IListable
{
  // Return the value of each column in the row.
  string[] ColumnValues
  {
      get;
  }
}
```

```
public abstract class PdaItem
{
  public PdaItem(string name)
  {
      Name = name;
  }

  public virtual string Name{get;set;}
}
```

```
class Contact : PdaItem, IListable
{
    public Contact(string firstName, string lastName,
        string address, string phone) : base(null)
    {
        FirstName = firstName;
        LastName = lastName;
        Address = address;
        Phone = phone;
    }

    public string FirstName { get; set; }
    public string LastName { get; set; }
    public string Address { get; set; }
    public string Phone { get; set; }

  public string[] ColumnValues
  {
      get
      {
          return new string[]
          {
                FirstName,
                LastName,
                Phone,
                Address
          };
```

```
      }
  }

  public static string[] Headers
  {
      get
      {
          return new string[] {
              "First Name", "Last Name    ",
              "Phone       ",
              "Address                       " };
      }
  }

  // ...
}
```

```
class Publication : IListable
{
  public Publication(string title, string author, int year)
  {
      Title = title;
      Author = author;
      Year = year;
  }

  public string Title { get; set; }
  public string Author { get; set; }
  public int Year { get; set; }

  public string[] ColumnValues
  {
      get
      {
          return new string[]
          {
              Title,
              Author,
              Year.ToString()
          };
      }
  }

  public static string[] Headers
  {
      get
      {
          return new string[] {
              "Title                                 ",
              "Author              ",
              "Year" };
      }
```

```
    }

    // ...
  }
```

```
  class Program
  {
    public static void Main()
    {
        Contact[] contacts = new Contact[6];
        contacts[0] = new Contact(
            "Dick", "Traci",
            "123 Main St., Spokane, WA  99037",
            "123-123-1234");
        contacts[1] = new Contact(
            "Andrew", "Littman",
            "1417 Palmary St., Dallas, TX 55555",
            "555-123-4567");
        contacts[2] = new Contact(
            "Mary", "Hartfelt",
            "1520 Thunder Way, Elizabethton, PA 44444",
            "444-123-4567");
        contacts[3] = new Contact(
            "John", "Lindherst",
            "1 Aerial Way Dr., Monteray, NH 88888",
            "222-987-6543");
        contacts[4] = new Contact(
            "Pat", "Wilson",
            "565 Irving Dr., Parksdale, FL 22222",
            "123-456-7890");
        contacts[5] = new Contact(
            "Jane", "Doe",
            "123 Main St., Aurora, IL 66666",
            "333-345-6789");

        // Classes are cast implicitly to
        // their supported interfaces.
        ConsoleListControl.List(Contact.Headers, contacts);

        Console.WriteLine();

        Publication[] publications = new Publication[3] {
            new Publication("Celebration of Discipline",
                "Richard Foster", 1978),
            new Publication("Orthodoxy",
                "G.K. Chesterton", 1908),
            new Publication(
                "The Hitchhiker's Guide to the Galaxy",
                "Douglas Adams", 1979)
            };
        ConsoleListControl.List(
            Publication.Headers, publications);
```

```
    }
  }
```

```
  class ConsoleListControl
  {
      public static void List(string[] headers, IListable[] items)
      {
          int[] columnWidths = DisplayHeaders(headers);

          for (int count = 0; count < items.Length; count++)
          {
              string[] values = items[count].ColumnValues;
              DisplayItemRow(columnWidths, values);
          }
      }

      /// <summary>Displays the column headers</summary>
      /// <returns>Returns an array of column widths</returns>
      private static int[] DisplayHeaders(string[] headers)
      {
          // ...
      }

      private static void DisplayItemRow(
          int[] columnWidths, string[] values)
      {
          // ...
      }
  }
```

The results of Listing 7.2 appear in Output 7.1.

OUTPUT 7.1

```
First Name  Last Name     Phone         Address
Dick        Traci         123-123-1234  123 Main St., Spokane, WA  99037
Andrew      Littman       555-123-4567  1417 Palmary St., Dallas, TX 55555
Mary        Hartfelt      444-123-4567  1520 Thunder Way, Elizabethton, PA 44444
John        Lindherst     222-987-6543  1 Aerial Way Dr., Monteray, NH 88888
Pat         Wilson        123-456-7890  565 Irving Dr., Parksdale, FL 22222
Jane        Doe           333-345-6789  123 Main St., Aurora, IL 66666

Title                                 Author              Year
Celebration of Discipline             Richard Foster      1978
Orthodoxy                             G.K. Chesterton     1908
The Hitchhiker's Guide to the Galaxy  Douglas Adams       1979
```

In Listing 7.2, the `ConsoleListControl` can display seemingly unrelated classes (`Contact` and `Publication`). Any class can be displayed provided that it implements the required interface. As a result, the `ConsoleListControl.List()` method relies on polymorphism to appropriately display whichever set of objects it is passed. Each class has its own implementation of `ColumnValues`, and converting a class to `IListable` still allows the particular class's implementation to be invoked.

Interface Implementation

Declaring a class to implement an interface is similar to deriving from a base class: The implemented interfaces appear in a comma-separated list along with the base class. The base class specifier (if there is one) must come first, but otherwise order is not significant. Classes can implement multiple interfaces, but may derive directly from only one base class. An example appears in Listing 7.3.

Listing 7.3: Implementing an Interface

```
public class Contact : PdaItem, IListable, IComparable
{
  // ...

  #region IComparable Members
  /// <summary>
  ///
  /// </summary>
  /// <param name="obj"></param>
  /// <returns>
  /// Less than zero:      This instance is less than obj.
  /// Zero                 This instance is equal to obj.
  /// Greater than zero    This instance is greater than obj.
  /// </returns>
  public int CompareTo(object obj)
  {
      int result;
      Contact contact = obj as Contact;

      if (obj == null)
      {
          // This instance is greater than obj.
          result = 1;
      }
      else if (obj.GetType() != typeof(Contact))
      {
          // Use C# 6.0 nameof operator in message to
          // ensure consistency in the Type name.
          throw new ArgumentException(
              $"The parameter is not a of type { nameof(Contact) }",
```

```
                nameof(obj));
        }
        else if (Contact.ReferenceEquals(this, obj))
        {
            result = 0;
        }
        else
        {
            result = LastName.CompareTo(contact.LastName);
            if (result == 0)
            {
                result = FirstName.CompareTo(contact.FirstName);
            }
        }
        return result;
    }
    #endregion

    #region IListable Members
    string[] IListable.ColumnValues
    {
        get
        {
            return new string[]
            {
                FirstName,
                LastName,
                Phone,
                Address
            };
        }
    }
    #endregion
}
```

Once a class declares that it implements an interface, all members of the interface must be implemented. An abstract class is permitted to supply an abstract implementation of an interface member. A nonabstract implementation may throw a `NotImplementedException` type exception in the method body, but somehow an implementation of the member must be supplied.

One important characteristic of interfaces is that they can never be instantiated; you cannot use `new` to create an interface, so interfaces do not have constructors or finalizers. Interface instances are available only by instantiating a type that implements the interface. Furthermore, interfaces cannot include static members. One key interface purpose is polymorphism, and polymorphism without an instance of the implementing type has little value.

Each interface member behaves like an abstract method, forcing the derived class to implement the member. Therefore, it is not possible to use the abstract modifier on interface members explicitly.

When implementing an interface member in a type, there are two ways to do so: **explicitly** or **implicitly.** So far we've seen only implicit implementations, where the type member that implements the interface member is a public member of the implementing type.

Explicit Member Implementation

Explicitly implemented methods are available only by calling them through the interface itself; this is typically achieved by casting an object to the interface. For example, to call `IListable.ColumnValues` in Listing 7.4, you must first cast the contact to `IListable` because of `ColumnValues`' explicit implementation.

Listing 7.4: Calling Explicit Interface Member Implementations

```
string[] values;
Contact contact1, contact2;

// ...

// ERROR:  Unable to call ColumnValues() directly
//         on a contact.
// values = contact1.ColumnValues;

// First cast to IListable.
values = ((IListable)contact2).ColumnValues;
// ...
```

The cast and the call to `ColumnValues` occur within the same statement in this case. Alternatively, you could assign `contact2` to an `IListable` variable before calling `ColumnValues`.

To declare an explicit interface member implementation, prefix the member name with the interface name (see Listing 7.5).

Listing 7.5: Explicit Interface Implementation

```
public class Contact : PdaItem, IListable, IComparable
{
  // ...

  public int CompareTo(object obj)
  {
```

```
        // ...
    }

    #region IListable Members
    string[] IListable.ColumnValues
    {
        get
        {
            return new string[]
            {
                FirstName,
                LastName,
                Phone,
                Address
            };
        }
    }
    #endregion
}
```

Listing 7.5 implements `ColumnValues` explicitly by prefixing the property name with `IListable`. Furthermore, since explicit interface implementations are directly associated with the interface, there is no need to modify them with `virtual`, `override`, or `public`. In fact, these modifiers are not allowed. The method is not treated as a public member of the class, so marking it as `public` would be misleading.

Implicit Member Implementation

Notice that `CompareTo()` in Listing 7.5 does not include the `IComparable` prefix; it is implemented implicitly. With implicit member implementation, it is necessary only for the member to be public and for the member's signature to match the interface member's signature. Interface member implementation does not require use of the `override` keyword or any indication that this member is tied to the interface. Furthermore, since the member is declared just like any other class member, code that calls implicitly implemented members can do so directly, just as it would any other class member:

```
result = contact1.CompareTo(contact2);
```

In other words, implicit member implementation does not require a cast because the member is not hidden from direct invocation on the implementing class.

Many of the modifiers disallowed on an explicit member implementation are required or are optional on an implicit implementation. For example, implicit member implementations must be `public`. Furthermore, `virtual` is optional depending on whether derived classes may override the implementation. Eliminating `virtual` will cause the member to behave as though it is `sealed`.

Explicit versus Implicit Interface Implementation

The key difference between implicit and explicit member interface implementation lies not in the syntax of the method declaration, but rather in the ability to access the method by name through an instance of the type rather than via the interface.

When building a class hierarchy, it's desirable to model real-world "is a" relationships—a giraffe is a mammal, for example. These are "semantic" relationships. Interfaces are often used to model "mechanism" relationships. A `PdaItem` "is not a" "comparable," but it might well be `IComparable`. This interface has nothing to do with the semantic model; it's a detail of the implementation mechanism. Explicit interface implementation is a technique for enabling the separation of mechanism concerns from model concerns. Forcing the caller to convert the object to an interface such as `IComparable` before treating the object as "comparable" explicitly separates out in the code when you are talking to the model and when you are dealing with its implementation mechanisms.

In general, it is preferable to limit the public surface area of a class to be "all model" with as little extraneous mechanism as possible. (Unfortunately, some mechanisms are unavoidable in .NET. You cannot get a giraffe's hash code or convert a giraffe to a string, for example. However, you can get a `Giraffe`'s hash code [`GetHashCode()`] and convert it to a `string` [`ToString()`]. By using `object` as a common base class, .NET mixes model code with mechanism code, even if only to a limited extent.)

Here are several guidelines that will help you choose between an explicit implementation and an implicit implementation.

- Is the member a core part of the class functionality?

  Consider the `ColumnValues` property implementation on the `Contact` class. This member is not an integral part of a `Contact` type but rather a peripheral member probably accessed only by the `ConsoleListControl` class. As such, it doesn't make sense for the member to be immediately visible on a `Contact` object, cluttering up what could potentially already be a large list of members.

Alternatively, consider the `IFileCompression.Compress()` member. Including an implicit `Compress()` implementation on a `ZipCompression` class is a perfectly reasonable choice: `Compress()` is a core part of the `ZipCompression` class's behavior, so it should be directly accessible from the `ZipCompression` class.

- Is the interface member name appropriate as a class member?

  Consider an `ITrace` interface with a member called `Dump()` that writes out a class's data to a trace log. Implementing `Dump()` implicitly on a `Person` or `Truck` class would result in confusion as to which operation the method performs. Instead, it is preferable to implement the member explicitly so that only from a data type of `ITrace`, where the meaning is clearer, can the `Dump()` method be called. Consider using an explicit implementation if a member's purpose is unclear on the implementing class.

- Is there already a class member with the same signature?

  Explicit interface member implementation does not add a named element to the type's declaration space. Therefore, if there is already a potentially conflicting member of a type, a second one can be provided with the same name or signature as long as it is an explicit interface member.

Much of the decision making regarding implicit versus explicit interface member implementation comes down to intuition. However, these questions provide suggestions about which issues to consider when making your choice. Since changing an implementation from implicit to explicit results in a version-breaking change, it is better to err on the side of defining interfaces explicitly, allowing them to be changed to implicit implementations later on. Furthermore, since the decision between implicit and explicit does not have to be consistent across all interface members, defining some methods as explicit and others as implicit is fully supported.

Guidelines

AVOID implementing interface members explicitly without a good reason. However, if you're unsure, favor explicit implementation.

Converting between the Implementing Class and Its Interfaces

Just as with a derived type and a base class, a conversion from an implementing type to its implemented interface is an implicit conversion. No cast operator is required because an instance of the implementing type will always provide all the members in the interface; therefore, the object can always be converted successfully to the interface type.

Although the conversion will always be successful from the implementing type to the implemented interface, many different types could implement a particular interface. As a consequence, you can never be certain that a "downward" cast from an interface to one of its implementing types will be successful. Therefore, converting from an interface to one of its implementing types requires an explicit cast.

Interface Inheritance

Interfaces can derive from each other, resulting in an interface that inherits all the members in its base interfaces. As shown in Listing 7.6, the interfaces directly derived from `IReadableSettingsProvider` are the explicit base interfaces.

Listing 7.6: Deriving One Interface from Another

```
interface IReadableSettingsProvider
{
    string GetSetting(string name, string defaultValue);
}
```

```
interface ISettingsProvider : IReadableSettingsProvider
{
    void SetSetting(string name, string value);
}
```

```
class FileSettingsProvider : ISettingsProvider
{
    #region ISettingsProvider Members
    public void SetSetting(string name, string value)
    {
        // ...
    }
    #endregion
```

```
        #region IReadableSettingsProvider Members
        public string GetSetting(string name, string defaultValue)
        {
            // ...
        }
        #endregion
    }
```

In this case, ISettingsProvider is derived from IReadableSettingsProvider and, therefore, inherits its members. If IReadableSettingsProvider also had an explicit base interface, ISettingsProvider would inherit those members as well, and the full set of interfaces in the derivation hierarchy would simply be the accumulation of base interfaces.

Note that if GetSetting() is implemented explicitly, it must be done using IReadableSettingsProvider. The declaration with ISettingsProvider in Listing 7.7 will not compile.

LISTING 7.7: Explicit Member Declaration without the Containing Interface (Failure)

```
    // ERROR:  GetSetting() not available on ISettingsProvider
    string ISettingsProvider.GetSetting(
      string name, string defaultValue)
    {
      // ...
    }
```

The results of Listing 7.7 appear in Output 7.2.

OUTPUT 7.2

```
'ISettingsProvider.GetSetting' in explicit interface declaration
is not a member of interface.
```

This output appears in addition to an error indicating that IReadableSettingsProvider.GetSetting() is not implemented. The fully qualified interface member name used for explicit interface member implementation must reference the interface name in which it was originally declared.

Even though a class implements an interface (ISettingsProvider) that is derived from a base interface (IReadableSettingsProvider), the class can still declare an implementation of both interfaces overtly, as Listing 7.8 demonstrates.

LISTING 7.8: Using a Base Interface in the Class Declaration

```
class FileSettingsProvider : ISettingsProvider,
     IReadableSettingsProvider
{
    #region ISettingsProvider Members
    public void SetSetting(string name, string value)
    {
        // ...
    }
    #endregion

    #region IReadableSettingsProvider Members
    public string GetSetting(string name, string defaultValue)
    {
        // ...
    }
    #endregion
}
```

In this listing, there is no change to the interface's implementations on the class. Although the additional interface implementation declaration on the class header is superfluous, it provides for better readability.

The decision to provide multiple interfaces rather than just one combined interface depends largely on what the interface designer wants to require of the implementing class. By providing an `IReadableSettingsProvider` interface, the designer communicates that implementers are required only to implement a settings provider that retrieves settings. They do not have to be able to write to those settings. This reduces the implementation burden by not imposing the complexities of writing settings as well.

In contrast, implementing `ISettingsProvider` assumes that there is never a reason to have a class that can write settings without reading them. The inheritance relationship between `ISettingsProvider` and `IReadableSettingsProvider`, therefore, forces the combined total of both interfaces on the `ISettingsProvider` class.

One final but important note: Although inheritance is the correct term, conceptually it is more accurate to say that an interface represents a contract; and one contract is allowed to specify that the provisions of another contract must also be followed. So, the code `ISettingsProvider : IReadableSettingsProvider` conceptually states that the `ISettingsProvider` contract requires also respecting the `IReadableSettingsProvider` contract rather than that the `ISettingsProvider` "is a kind of" `IReadableSettingsProvider`. That being said, the remainder of the chapter will continue using the inheritance relationship terminology in accordance with the standard C# terminology.

Multiple Interface Inheritance

Just as classes can implement multiple interfaces, so interfaces can inherit from multiple interfaces. The syntax used for this purpose is consistent with class derivation and implementation, as shown in Listing 7.9.

LISTING 7.9: Multiple Interface Inheritance

```
interface IReadableSettingsProvider
{
  string GetSetting(string name, string defaultValue);
}
```

```
interface IWriteableSettingsProvider
{
  void SetSetting(string name, string value);
}
```

```
interface ISettingsProvider : IReadableSettingsProvider,
    IWriteableSettingsProvider
{
}
```

It is unusual to have an interface with no members, but if implementing both interfaces together is predominant, it is a reasonable choice for this case. The difference between Listing 7.9 and Listing 7.6 is that it is now possible to implement `IWriteableSettingsProvider` without supplying any read capability. Listing 7.6's `FileSettingsProvider` is unaffected, but if it used explicit member implementation, specifying the interface to which a member belongs changes slightly.

Extension Methods on Interfaces

Begin 3.0

Perhaps one of the most important features of extension methods is the fact that they work with interfaces in addition to classes. The syntax used is identical to that used for extension methods for classes. The extended type (the first parameter and the parameter prefixed with `this`) is the interface that we extend. Listing 7.10 shows an extension method for `IListable()`. It is declared on `Listable`.

Listing 7.10: Interface Extension Methods

```
class Program
{
  public static void Main()
  {
      Contact[] contacts = new Contact[6];
      contacts[0] = new Contact(
          "Dick", "Traci",
          "123 Main St., Spokane, WA  99037",
          "123-123-1234");
       // ...

      // Classes are implicitly converted to
      // their supported interfaces.
      contacts.List(Contact.Headers);

      Console.WriteLine();

      Publication[] publications = new Publication[3] {
          new Publication("Celebration of Discipline",
              "Richard Foster", 1978),
          new Publication("Orthodoxy",
              "G.K. Chesterton", 1908),
          new Publication(
              "The Hitchhiker's Guide to the Galaxy",
              "Douglas Adams", 1979)
          };
      publications.List(Publication.Headers);
  }
}
```

3.0

```
static class Listable
{
  public static void List(
      this IListable[] items, string[] headers)
  {
      int[] columnWidths = DisplayHeaders(headers);

      for (int itemCount = 0; itemCount < items.Length; itemCount++)
      {
          string[] values = items[itemCount].ColumnValues;

          DisplayItemRow(columnWidths, values);
      }
  }
  // ...
}
```

In this example, the extension method is not on for an `IListable` parameter (although it could have been), but rather for an `IListable[]` parameter. This demonstrates that C# allows extension methods not only on an instance of a particular type, but also on a collection of those objects. Support for extension methods is the foundation on which LINQ is implemented. `IEnumerable` is the fundamental interface that all collections implement. By defining extension methods for `IEnumerable`, LINQ support was added to all collections. This radically changed programming with collections; we will explore this topic in detail in Chapter 14.

End 3.0

Implementing Multiple Inheritance via Interfaces

As Listing 7.3 demonstrated, a single class can implement any number of interfaces in addition to deriving from a single class. This feature provides a possible workaround for the lack of multiple inheritance support in C# classes. The process uses aggregation as described in the preceding chapter, but you can vary the structure slightly by adding an interface to the mix, as shown in Listing 7.11.

LISTING 7.11: Working around Single Inheritance Using Aggregation with Interfaces

```
public class PdaItem
{
  // ...
}
```

```
interface IPerson
{
    string FirstName
    {
        get;
        set;
    }

    string LastName
    {
        get;
        set;
    }
}
```

```
public class Person : IPerson
{
  // ...
}
```

```
public class Contact : PdaItem, IPerson
{
  private Person Person
  {
      get { return _Person; }
      set { _Person = value; }
  }
  private Person _Person;

  public string FirstName
  {
      get { return _Person.FirstName; }
      set { _Person.FirstName = value; }
  }

  public string LastName
  {
      get { return _Person.LastName; }
      set { _Person.LastName = value; }
  }

  // ...
}
```

`IPerson` ensures that the signatures between the `Person` members and the same members duplicated onto `Contact` are consistent. The implementation is still not synonymous with multiple inheritance, however, because new members added to `Person` will not be added to `Contact`.

One possible improvement that works if the implemented members are methods (not properties) is to define interface extension methods for the additional functionality "derived" from the second base class. An extension method on `IPerson` could provide a method called `VerifyCredentials()`, for example, and all classes that implement `IPerson`—even an `IPerson` interface that had no members but just extension methods—would have a default implementation of `VerifyCredentials()`. What makes this approach viable is the fact that polymorphism is still available, as is overriding. Overriding is supported because any instance implementation of a method will take priority over an extension method with the equivalent static signature.

Guidelines

CONSIDER defining interfaces to achieve a similar effect to that of multiple inheritance.

BEGINNER TOPIC

Interface Diagramming

Interfaces in a UML-like[1] figure take two possible forms. First, you can show the interface as though it is an inheritance relationship similar to a class inheritance, as demonstrated in Figure 7.1 between `IPerson` and `IContact`. Alternatively, you can show the interface using a small circle, often referred to as a lollipop, exemplified by `IPerson` and `IContact` in Figure 7.1.

In Figure 7.1, `Contact` derives from `PdaItem` and implements `IContact`. In addition, it aggregates the `Person` class, which implements `IPerson`. Although the Visual Studio Class Designer does not support this practice, interfaces are sometimes shown as using a derivation-type arrow to a class. For example, `Person` could have an arrow to `IPerson` instead of a lollipop.

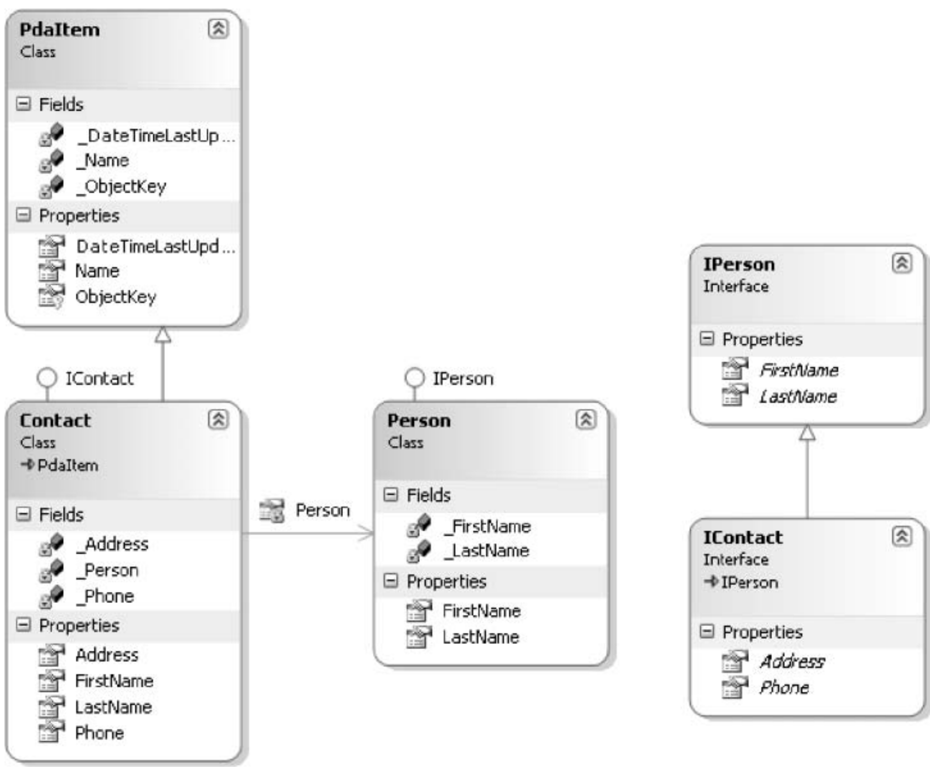


FIGURE 7.1: Working around Single Inheritances with Aggregation and Interfaces

1. Unified Modeling Language (UML), a standard specification for modeling object design using graphical notation.

Versioning

When creating a new version of a component or application that other developers have programmed against, you should not change interfaces. Because interfaces define a contract between the implementing class and the class using the interface, changing the interface is equivalent to changing the contract, which will possibly break any code written against the interface.

Changing or removing a particular interface member signature is obviously a code-breaking change, as any call to that member will no longer compile without modification. The same is true when you change public or protected member signatures on a class. However, unlike with classes, adding members to an interface could also prevent code from compiling without additional changes. The problem is that any class implementing the interface must do so entirely, and implementations for all members must be provided. With new interface members, the compiler will require that developers add new interface members to the class implementing the interface.

Guidelines

DO NOT add members to an interface that has already shipped.

The creation of `IDistributedSettingsProvider` in Listing 7.12 serves as a good example of extending an interface in a version-compatible way. Imagine that at first, only the `ISettingsProvider` interface is defined (as it was in Listing 7.6). In the next version, however, it is determined that per-machine settings are required. To enable this constraint, the `IDistributedSettingsProvider` interface is created, and it derives from `ISettingsProvider`.

Listing 7.12: Deriving One Interface from Another

```
interface IDistributedSettingsProvider : ISettingsProvider
{
  /// <summary>
  /// Get the settings for a particular machine.
  /// </summary>
  /// <param name="machineName">
  /// The machine name the setting is related to.</param>
  /// <param name="name">The name of the setting.</param>
```

```
    /// <param name="defaultValue">
    /// The value returned if the setting is not found.</param>
    /// <returns>The specified setting.</returns>
    string GetSetting(
        string machineName, string name, string defaultValue);

    /// <summary>
    /// Set the settings for a particular machine.
    /// </summary>
    /// <param name="machineName">
    /// The machine name the setting is related to.</param>
    /// <param name="name">The name of the setting.</param>
    /// <param name="value">The value to be persisted.</param>
    /// <returns>The specified setting.</returns>
    void SetSetting(
        string machineName, string name, string value);
}
```

The important issue is that programmers with classes that implement `ISettingsProvider` can choose to upgrade the implementation to include `IDistributedSettingsProvider`, or they can ignore it.

If instead of creating a new interface, the machine-related methods are added to `ISettingsProvider`, classes implementing this interface will no longer successfully compile with the new interface definition. Instead, a version-breaking change will occur.

Changing interfaces during the development phase is obviously acceptable, although perhaps laborious if implemented extensively. However, once an interface is released, it should not be changed. Instead, a second interface should be created, possibly deriving from the original interface.

(Listing 7.12 includes XML comments describing the interface members, as discussed further in Chapter 9.)

Interfaces Compared with Classes

Interfaces introduce another category of data types. (They are one of the few categories of types that don't extend `System.Object`.[2]) Unlike classes, however, interfaces can never be instantiated. An interface instance is accessible only via a reference to an object that implements the interface. It is not possible to use the `new` operator with an interface; therefore, interfaces

2. The others being pointer types and type parameter types. However, every interface type is convertible to `System.Object`, and it is permissible to call the methods of `System.Object` on any instance of an interface, so perhaps this is a hairsplitting distinction.

cannot contain any constructors or finalizers. Furthermore, static members are not allowed on interfaces.

Interfaces are closer to abstract classes, sharing such features as the lack of instantiation capability. Table 7.1 lists additional comparisons.

Given that abstract classes and interfaces have their own sets of advantages and disadvantages, you must make a cost–benefit decision based on the comparisons in Table 7.1 and the guidelines that follow to make the right choice.

Guidelines

DO generally favor classes over interfaces. Use abstract classes to decouple contracts (what the type does) from implementation details (how the type does it.)

CONSIDER defining an interface if you need to support its functionality on types that already inherit from some other type.

TABLE 7.1: Comparing Abstract Classes and Interfaces

Abstract Classes	Interfaces
Cannot be instantiated directly, only by instantiating a derived class.	Cannot be instantiated directly, only by instantiating an implementing type.
Derived classes either must be abstract themselves or must implement all abstract members.	Implementing types must implement all interface members.
Can add additional nonabstract members that all derived classes can inherit without breaking cross-version compatibility.	Adding additional members to interfaces breaks the version compatibility.
Can declare both properties and fields.	Can declare properties but not fields.
Members may be instance, virtual, abstract, or static and may provide implementations for nonabstract members that can be used by derived classes.	All members are automatically treated as though they were abstract, so they cannot include any implementation.
A derived class may derive from only a single base class.	An implementing type may arbitrarily implement many interfaces.

Interfaces Compared with Attributes

Interfaces with no members at all, inherited or otherwise, are sometimes used to represent information about a type. For example, you might create a marker `IObsolete` interface to indicate that a particular type has been replaced by another type. This is generally considered to be an abuse of the interface mechanism; interfaces should be used to represent which functions a type can perform, not to indicate facts about particular types. Instead of marker interfaces, use attributes for this purpose. See Chapter 17 for more details.

Guidelines

AVOID using "marker" interfaces with no members; use attributes instead.

SUMMARY

Interfaces are a key element of object-oriented programming in C#. They provide functionality similar to abstract classes but without using up the single-inheritance option. They also support implementation of multiple interfaces.

In C#, the implementation of interfaces can be either explicit or implicit, depending on whether the implementing class is to expose an interface member directly or only via a conversion to the interface. Furthermore, the granularity of whether the implementation is explicit or implicit is at the member level: One member may be implicitly implemented, while another member of the same interface is explicitly implemented.

The next chapter looks at value types and discusses the importance of defining custom value types. At the same time, the chapter points out the subtle problems that such types can introduce.

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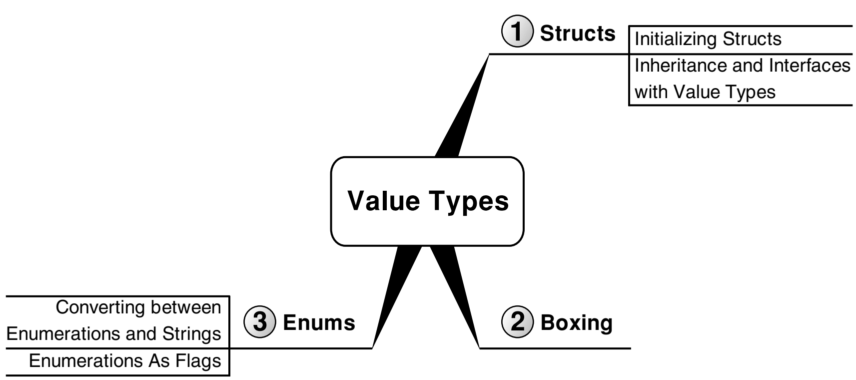
8

Value Types

YOU HAVE USED VALUE TYPES throughout this book; for example, `int` is a value type. This chapter discusses not only using value types, but also defining custom value types. There are two categories of custom value types: structs and enums. This chapter discusses how structs enable programmers to define new value types that behave very similarly to most of the predefined types discussed in Chapter 2. The key is that any newly defined value types have their own custom data and methods. The chapter also discusses how to use enums to define sets of constant values.



BEGINNER TOPIC

Categories of Types

All types discussed so far have fallen into one of two categories: reference types and value types. The differences between the types in each category stem from differences in copying strategies, which in turn result in each type being stored differently in memory. As a review, this Beginner Topic reintroduces the value type/reference type discussion for those readers who are unfamiliar with these issues.

Value Types

Variables of **value types** directly contain their values, as shown in Figure 8.1. The variable name is associated directly with the storage location in memory where the value is stored. Because of this, when a second variable is assigned the value of an original variable, a copy of the original variable's value is made to the storage location associated with the second variable. Two variables never refer to the same storage location (unless one or both are `out` or `ref` parameters, which are, by definition, aliases for another variable). Changing the value of the original variable will not affect the value in the second variable, because each variable is associated with a different storage location. Consequently, changing the value of one value type variable cannot affect the value of any other value type variable.

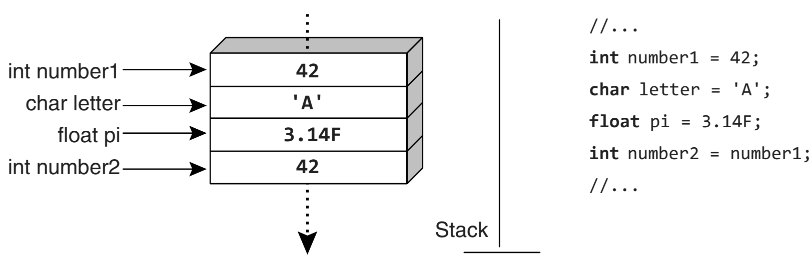


FIGURE 8.1: Value Types Contain the Data Directly

A value type variable is like a piece of paper that has a number written on it. If you want to change the number, you can erase it and replace it with a different number. If you have a second piece of paper, you can copy the number from the first piece of paper, but the two pieces of paper are then independent; erasing and replacing the number on one of them does not change the other.

Similarly, passing an instance of a value type to a method such as `Console.WriteLine()` will also result in a memory copy from the storage location associated with the argument to the storage location associated with the parameter, and any changes to the parameter variable inside the method will not affect the original value within the caller. Since value types require a memory copy, they generally should be defined to consume a small amount of memory (typically 16 bytes or less).

Guidelines

DO NOT create value types that consume more than 16 bytes of memory.

Values of value types are often short-lived; in many situations, a value is needed only for a portion of an expression or for the activation of a method. In these cases, variables and temporary values of value types can often be stored on the **temporary storage pool,** called "the stack." (This is actually a misnomer: There is no requirement that the temporary pool allocates its storage off the stack. In fact, as an implementation detail, it frequently chooses to allocate storage out of available registers instead.)

The temporary pool is less costly to clean up than the garbage-collected heap; however, value types tend to be copied more than reference types, and that copying can impose a performance cost of its own. Do not fall into the trap of believing that "value types are faster because they can be allocated on the stack."

Reference Types

In contrast, the value of a reference type variable is a reference to an instance of an object (see Figure 8.2). Variables of reference type store the reference (typically implemented as the memory address) where the data for the object instance is located, instead of storing the data directly, as a variable of value type does. Therefore, to access the data, the runtime will read the reference out of the variable and then dereference it to reach the location in memory that actually contains the data for the instance.

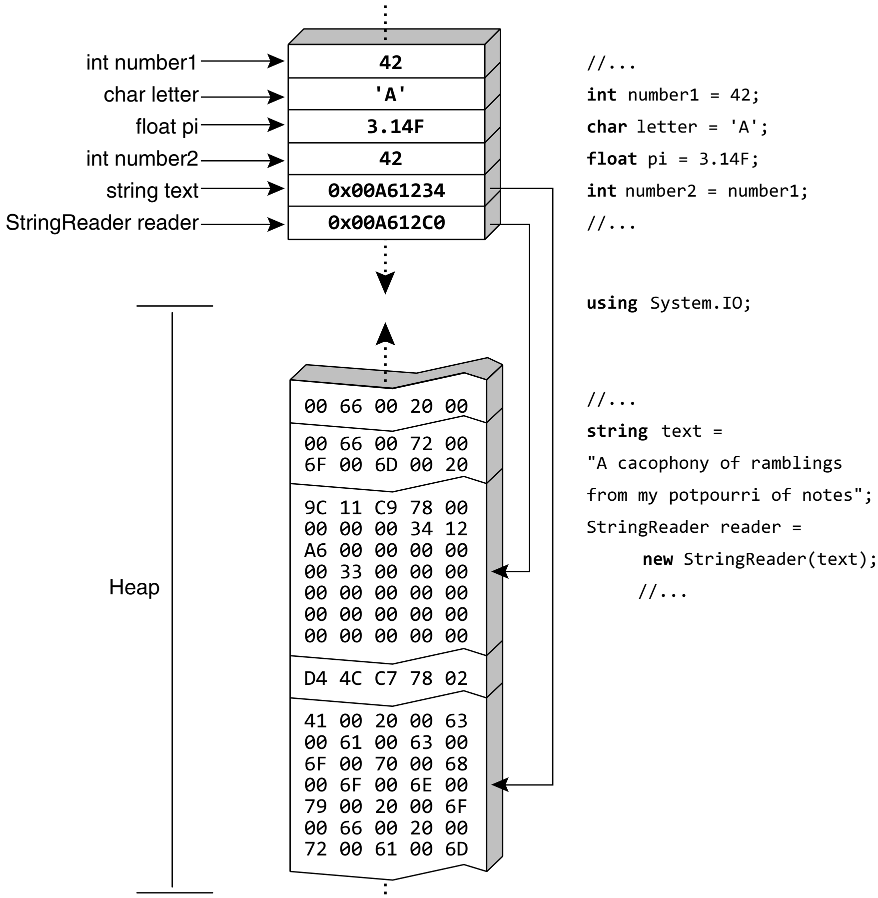


FIGURE 8.2: Reference Types Point to the Heap

A reference type variable, therefore, has two storage locations associated with it: the storage location directly associated with the variable, and the storage location referred to by the reference that is the value stored in the variable.

A reference type variable is, again, like a piece of paper that always has something written on it. Imagine a piece of paper that has a house address written on it—for example, “123 Sesame Street, New York City.” The piece of paper is a variable; the address is a reference to a building. Neither the paper nor the address written on it is the building, and the location of the paper need not have anything whatsoever to do with the location of the building to which its contents refer. If you make a copy of that reference on another piece of paper, the contents of both pieces of paper refer to the same building. If you then paint that building green, the building referred to by both pieces of paper can be observed to be green, because the references refer to the same thing.

The storage location directly associated with the variable (or temporary value) is treated no differently than the storage location associated with a value type variable: If the variable is known to be short-lived, it is allocated on the short-term storage pool. The value of a reference type variable is always either a reference to a storage location in the garbage-collected heap or null.

Compared to a variable of value type, which stores the data of the instance directly, accessing the data associated with a reference involves an extra "hop": First the reference must be dereferenced to find the storage location of the actual data, and then the data can be read or written. Copying a reference type value copies only the reference, which is small. (A reference is guaranteed to be no larger than the "bit size" of the processor; a 32-bit machine has 4-byte references, a 64-bit machine has 8-byte references, and so on.) Copying the value of a value type copies all the data, which could be large. Therefore, in some circumstances, reference types are more efficient to copy. This is why the guideline for value types is to ensure that they are never more than 16 bytes or thereabouts; if a value type is more than four times as expensive to copy as a reference, it probably should simply be a reference type.

Since reference types copy only a reference to the data, two different variables can refer to the same data. In such a case, changing the data through one variable will be observed to change the data for the other variable as well. This happens both for assignments and for method calls.

To continue our previous analogy, if you pass the address of a building to a method, you make a copy of the paper containing the reference and hand the copy to the method. The method cannot change the contents of the original paper to refer to a different building. If the method paints the referred-to building, however, when the method returns, the caller can observe that the building to which the caller is still referring is now a different color.

Structs

All of the C# "built-in" types, such as `bool` and `decimal`, are value types, with the exception of `string` and `object`, which are reference types. Numerous additional value types are provided within the framework. It is also possible for developers to define their own value types.

To define a custom value type, you use a similar syntax as you would use to define class and interface types. The key difference in the syntax is that value types use the keyword `struct`, as shown in Listing 8.1. Here we have a value type that describes a high-precision angle in terms of its degrees, minutes, and seconds. (A "minute" is one-sixtieth of a degree, and a second is one-sixtieth of a minute. This system is used in navigation because it has the nice property that an arc of one minute over the surface of the ocean at the equator is exactly one nautical mile.)

Begin 6.0

Listing 8.1: Declaring a struct

```
// Use keyword struct to declare a value type.
struct Angle
{
  public Angle(int degrees, int minutes, int seconds)
  {
      Degrees = degrees;
      Minutes = minutes;
      Seconds = seconds;
  }

  // Using C# 6.0 read-only, automatically implememted properties.
  public int Degrees { get; }
  public int Minutes { get; }
  public int Seconds { get; }

  public Angle Move(int degrees, int minutes, int seconds)
  {
      return new Angle(
          Degrees + degrees,
          Minutes + minutes,
          Seconds + seconds);
  }
}
```

```
// Declaring a class--a reference type
// (declaring it as a struct would create a value type
// larger than 16 bytes.)
class Coordinate
{
  public Angle Longitude { get; set; }

  public Angle Latitude { get; set; }
}
```

This listing defines `Angle` as a value type that stores the degrees, minutes, and seconds of an angle, either longitude or latitude. The resultant C# type is a **struct**.

Note that the `Angle` struct in Listing 8.1 is immutable because all properties are declared using C# 6.0's read-only, automatically implemented property capability. To create a read-only property without C# 6.0, programmers will need to declare a property with only a getter that accesses its data from a `readonly` modified field (see Listing 8.3). C# 6.0 provides a noticeable code reduction when it comes to defining immutable types.

NOTE

Although nothing in the language requires it, a good guideline is for value types to be immutable: Once you have instantiated a value type, you should not be able to modify the same instance. In scenarios where modification is desirable, you should create a new instance. Listing 8.1 supplies a `Move()` method that doesn't modify the instance of `Angle`, but instead returns an entirely new instance.

There are two good reasons for this guideline. First, value types should represent values. One does not think of adding two integers together as mutating either of them; rather, the two addends are immutable and a third value is produced as the result.

Second, because value types are copied by value, not by reference, it is very easy to get confused and incorrectly believe that a mutation to one value type variable can be observed to cause a mutation in another, as it would with a reference type.

Guidelines

DO create value types that are immutable.

Initializing Structs

In addition to properties and fields, structs may contain methods and constructors. However, user-defined default (parameterless) constructors were not allowed until C# 6.0. When no default constructor is provided, the C# compiler automatically generates a default constructor that initializes all fields to their default values. The default value is null for a field of reference type data, a zero value for a field of numeric type, false for a field of Boolean type, and so on.

To ensure that a local value type variable can be fully initialized by a constructor, every constructor in a struct must initialize all fields (and read-only, automatically implemented properties) within the struct. (In C# 6.0, initialization via a read-only, automatically implemented property is sufficient because the backing field is unknown and its initialization would not be possible.) Failure to initialize all data within the struct causes a compile-time error. To complicate matters slightly, C# disallows field initializers in a struct. Listing 8.2, for example, will not compile if the line `_Degrees = 42` was uncommented.

6.0

LISTING 8.2: Initializing a `struct` Field within a Declaration, Resulting in an Error

```
struct Angle
{
  // ...
  // ERROR:  Fields cannot be initialized at declaration time
  // int _Degrees = 42;
  // ...
}
```

If not explicitly instantiated via the `new` operator's call to the constructor, all data contained within the struct is implicitly initialized to that data's default value. However, all data within a value type must be explicitly initialized to avoid a compiler error. This raises a question: When might a value type be implicitly initialized but not explicitly instantiated? This situation occurs when instantiating a reference type that contains an unassigned field of value type as well as when instantiating an array of value types without an array initializer.

To fulfill the initialization requirement on a struct, all explicitly declared fields must be initialized. Such initialization must be done directly. For example, in Listing 8.3, the constructor that initializes the property (if uncommented out) rather than the field produces a compile error.

LISTING 8.3: Accessing Properties before Initializing All Fields

```
struct Angle
               {
// ERROR:  The 'this' object cannot be used before
//         all of its fields are assigned to
// public Angle(int degrees, int minutes, int seconds)
// {
//     Degrees = degrees;
//     Minutes = minutes;
```

```
    //      Seconds = seconds;
    // }

    public Angle(int degrees, int minutes, int seconds)
    {
        _Degrees = degrees;
        _Minutes = minutes;
        _Seconds = seconds;
    }

    public int Degrees { get { return _Degrees; } }
    readonly private int _Degrees;

    public int Minutes { get { return _Minutes; } }
    readonly private int _Minutes;

    public int Seconds { get { return _Seconds; } }
    readonly private int _Seconds;

    // ...
     }
```

6.0

It is not legal to access `this` until the compiler knows that all fields have been initialized; the use of `Degrees` is implicitly `this.Degrees`. To resolve this issue, you need to initialize the fields directly, as demonstrated in the constructor of Listing 8.3 that is not commented out.

Because of the struct's field initialization requirement, the succinctness of C# 6.0's read-only, automatically implemented property support, and the guideline to avoid accessing fields from outside of their wrapping property, you should favor read-only, automatically implemented properties over fields within structs starting with C# 6.0.

Guidelines

DO ensure that the default value of a struct is valid; it is always possible to obtain the default "all zero" value of a struct.

ADVANCED TOPIC

Using new with Value Types

Invoking the `new` operator with a reference type causes the runtime to create a new instance of the object on the garbage-collected heap, initialize all of its fields to their default values, and call the constructor, passing a reference to the instance as `this`. The result is the reference to the instance, which can then be copied to its final destination. In contrast, invoking the `new` operator with a value type causes the runtime to create a new instance of the object on the temporary storage pool, initialize all of its fields to their default values, and call the constructor (passing the temporary storage location as a `ref` variable as `this`), resulting in the value being stored in the temporary storage location, which can then be copied to its final destination.

6.0

Unlike classes, structs do not support finalizers. Structs are copied by value; they do not have "referential identity" as reference types do. Therefore, it is hard to know when it would be safe to execute the finalizer and free an unmanaged resource owned by the struct. The garbage collector knows when there are no "live" references to an instance of reference type and can choose to run the finalizer for an instance of reference type at any time after there are no more live references. Nevertheless, no part of the runtime tracks how many copies of a given value type exist at any moment.

Language Contrast: C++—struct Defines Type with Public Members

In C++, the difference between a type declared with `struct` and one declared with `class` is whether the default accessibility is public or private. The contrast is far greater in C#, where the difference is whether instances of the type are copied by value or by reference.

Using the default Operator

As described earlier, if no default constructor is provided (which is possible only starting with C# 6.0), all value types have an automatically defined default constructor that initializes the storage of a value type to its default state. Therefore, it is always legal to use the `new` operator to create a value type instance. As an alternative syntax, you can use the `default` operator to produce the default value for a struct. In Listing 8.4, we add a second constructor to the `Angle` struct that uses the `default` operator on `int` as an argument to the previously declared three-argument constructor.

LISTING 8.4: Using the `default` Operator to Obtain the Default Value of a Type

```
// Use keyword struct to declare a value type.
struct Angle
{
  public Angle(int degrees, int minutes)
      : this( degrees, minutes, default(int) )
  {
  }

  // ...
}
```

The expressions `default(int)` and `new int()` both produce the same value. In contrast, that is not necessarily the case for custom-defined value types if the constructor is a C# 6.0 custom default constructor. In C# 6.0, a default constructor initializes its data to nondefault values. The result is that an invocation of the default constructor—which requires the `new` operator—would not produce the same value that `default(T)` produces. Like reference types, custom default constructors are invoked only explicitly via the `new` operator. However, unlike reference types, whose default value is null, implicit initialization of value types results in a zeroed-out memory block equivalent to the result of the `default` operator. Hence, `default(T)` is not necessarily equivalent to `new T()` when a value type has a default constructor. Furthermore, accessing the implicitly initialized value type is a valid operation; accessing the default value of a reference type, in contrast, would produce a `NullReferenceException`. For this reason, you should take care to explicitly initialize value types with custom default constructors if the `default(T)` value is not a valid state for the type.

> **NOTE**
>
> Default constructors on value types are invoked only by explicit uses of the `new` operator.

End 6.0

Inheritance and Interfaces with Value Types

All value types are implicitly sealed. In addition, all non-enum value types derive from `System.ValueType`. As a consequence, the inheritance chain for structs is always from `object` to `System.ValueType` to the struct.

Value types can implement interfaces, too. Many of those built into the framework implement interfaces such as `IComparable` and `IFormattable`.

`System.ValueType` brings with it the behavior of value types, but it does not include any additional members. The `System.ValueType` customizations focus on overriding all of `object`'s virtual members. The rules for overriding base class methods in a struct are almost the same as those for classes (see Chapter 9). However, one difference is that with value types, the default implementation for `GetHashCode()` is to forward the call to the first non-null field within the struct. Also, `Equals()` makes significant use of reflection. Therefore, if a value type is used frequently inside collections, especially dictionary-type collections that use hash codes, the value type should include overrides for both `Equals()` and `GetHashCode()` to ensure good performance. See Chapter 9 for more details.

Guidelines

DO overload the equality operators (`Equals()`, `==`, and `!=`) on value types, if equality is meaningful. (Also consider implementing the `IEquatable<T>` interface.)

Boxing

We know that variables of value type directly contain their data, whereas variables of reference type contain a reference to another storage location. But what happens when a value type is converted to one of its implemented interfaces or to its root base class, `object`? The result of the conversion has to be a reference to a storage location that contains something that looks like an instance of a reference type, but the variable contains a value of value type. Such a conversion, which is known as **boxing,** has special behavior. Converting a variable of value type that directly refers its data to a reference type that refers to a location on the garbage-collected heap involves several steps.

1. Memory is allocated on the heap that will contain the value type's data and the other overhead necessary to make the object look like every other instance of a managed object of reference type (namely, a `SyncBlockIndex` and method table pointer).

2. The value of the value type is copied from its current storage location into the newly allocated location on the heap.
3. The result of the conversion is a reference to the new storage location on the heap.

The reverse operation is **unboxing.** The unboxing conversion checks whether the type of the boxed value is compatible with the type to which the value is being unboxed, and then results in a copy of the value stored in the heap location.

Boxing and unboxing are important to consider because boxing has some performance and behavioral implications. Besides learning how to recognize these conversions within C# code, a developer can count the box/unbox instructions in a particular snippet of code by looking through the CIL. Each operation has specific instructions, as shown in Table 8.1.

TABLE 8.1: Boxing Code in CIL

C# Code	CIL Code
`static void Main()`	`.method private hidebysig static void Main() cil managed`
`{`	`{`
	`.entrypoint`
	`// Code size 21 (0x15)`
	`.maxstack 1`
`int number;`	`.locals init ([0] int32 number,`
`object thing;`	`[1] object thing)`
	`IL_0000: nop`
`number = 42;`	`IL_0001: ldc.i4.s 42`
	`IL_0003: stloc.0`
`// Boxing`	`IL_0004: ldloc.0`
`thing = number;`	`IL_0005: box [mscorlib]System.Int32`
	`IL_000a: stloc.1`
`// Unboxing`	`IL_000b: ldloc.1`
`number = (int)thing;`	`IL_000c: unbox.any [mscorlib]System.Int32`
	`IL_0011: stloc.0`
	`IL_0012: br.s IL_0014`
`return;`	`IL_0014: ret`
`}`	`} // end of method Program::Main`

When boxing and unboxing occur infrequently, their implications for performance are irrelevant. However, boxing can occur in some unexpected situations, and frequent occurrences can have a significant impact on performance. Consider Listing 8.5 and Output 8.1. The `ArrayList` type maintains a list of references to objects, so adding an integer or floating-point number to the list will box the value so that a reference can be obtained.

LISTING 8.5: Subtle Box and Unbox Instructions

```
class DisplayFibonacci
{
  static void Main()
  {

      int totalCount;
      System.Collections.ArrayList list =
          new System.Collections.ArrayList();

      Console.Write("Enter a number between 2 and 1000:");
      totalCount = int.Parse(Console.ReadLine());

      // Execution-time error:
      // list.Add(0);  // Cast to double or 'D' suffix required.
                       // Whether cast or using 'D' suffix,
                       // CIL is identical.
      list.Add((double)0);
      list.Add((double)1);
      for (int count = 2; count < totalCount; count++)
      {
          list.Add(
              ((double)list[count - 1] +
              (double)list[count - 2]) );
      }

      foreach (double count in list)
      {
          Console.Write("{0}, ", count);
      }
  }
}
```

OUTPUT 8.1

```
Enter a number between 2 and 1000:42
0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597,
2584, 4181, 6765, 10946, 17711, 28657, 46368, 75025, 121393, 196418,
317811, 514229, 832040, 1346269, 2178309, 3524578, 5702887, 9227465,
14930352, 24157817, 39088169, 63245986, 102334155, 165580141,
```

The code shown in Listing 8.5, when compiled, produces five box and three unbox instructions in the resultant CIL.

1. The first two box instructions occur in the initial calls to `list.Add()`. The signature for the `ArrayList` method is `int Add(object value)`. As such, any value type passed to this method is boxed.
2. Next are two unbox instructions in the call to `Add()` within the `for` loop. The return from an `ArrayList`'s index operator is always `object` because that is what `ArrayList` contains. To add the two values, you need to cast them back to `double`s. This cast from a reference to an object to a value type is implemented as an unbox call.
3. Now you take the result of the addition and place it into the `ArrayList` instance, which again results in a box operation. Note that the first two unbox instructions and this box instruction occur within a loop.
4. In the `foreach` loop, you iterate through each item in `ArrayList` and assign the items to `count`. As you saw earlier, the items within `ArrayList` are references to `object`s, so assigning them to a `double` is, in effect, unboxing each of them.
5. The signature for `Console.WriteLine()`, which is called within the `foreach` loop, is `void Console.Write(string format, object arg)`. As a result, each call to it boxes the `double` to `object`.

Every boxing operation involves both an allocation and a copy; every unboxing operation involves a type check and a copy. Doing the equivalent work using the unboxed type would eliminate the allocation and type check. Obviously, you can easily improve this code's performance by eliminating many of the boxing operations. Using an `object` rather than `double` in the last `foreach` loop is one such improvement. Another would be to change the `ArrayList` data type to a generic collection (see Chapter 11). The point being made here is that boxing can be rather subtle, so developers need to pay special attention and notice situations where it could potentially occur repeatedly and affect performance.

Another unfortunate boxing-related problem also occurs at runtime: If you wanted to change the initial two `Add()` calls so that they did not use a cast (or a double literal), you would have to insert integers into the array list. Since `int`s will implicitly be converted to `double`s, this would appear to be an innocuous modification. However, the casts to `double` from within the `for` loop, and again in the assignment to `count` in the `foreach` loop, would fail. The problem is that immediately following the unbox operation is an attempt to perform a memory copy of the value of the boxed `int` into a `double`. You cannot do this without first casting to an `int`, because the code will throw an `InvalidCastException` at execution time. Listing 8.6 shows a similar error commented out and followed by the correct cast.

Listing 8.6: Unboxing Must Be to the Underlying Type

```
// ...
int number;
object thing;
double bigNumber;

number = 42;
thing = number;
// ERROR: InvalidCastException
// bigNumber = (double)thing;
bigNumber = (double)(int)thing;
// ...
```

ADVANCED TOPIC

Value Types in the lock Statement

C# supports a `lock` statement for synchronizing code. The statement compiles down to `System.Threading.Monitor`'s `Enter()` and `Exit()` methods. These two methods must be called in pairs. `Enter()` records the unique reference argument passed so that when `Exit()` is called with the same reference, the lock can be released. The trouble with using value types is the boxing. Therefore, each time `Enter()` or `Exit()` is called, a new value is created on the heap. Comparing the reference of one copy to the reference of a different copy will always return `false`, so you cannot hook up `Enter()` with the corresponding `Exit()`. Therefore, value types in the `lock()` statement are not allowed.

Listing 8.7 points out a few more runtime boxing idiosyncrasies and Output 8.2 shows the results.

Listing 8.7: Subtle Boxing Idiosyncrasies

```
interface IAngle
{
    void MoveTo(int degrees, int minutes, int seconds);
}
```

```
struct Angle : IAngle
{
  // ...

  // NOTE:  This makes Angle mutable, against the general
  //        guideline
  public void MoveTo(int degrees, int minutes, int seconds)
  {
          _Degrees = degrees;
          _Minutes = minutes;
          _Seconds = seconds;
  }
}
```

```
class Program
{
  static void Main()
  {
      // ...

      Angle angle = new Angle(25, 58, 23);
      object objectAngle = angle;  // Box
      Console.Write( ((Angle)objectAngle).Degrees);

      // Unbox, modify unboxed value, and discard value
      ((Angle)objectAngle).MoveTo(26, 58, 23);
      Console.Write(", " +  ((Angle)objectAngle).Degrees);

      // Box, modify boxed value, and discard reference to box
      ((IAngle)angle).MoveTo(26, 58, 23);
      Console.Write(", " + ((Angle)angle).Degrees);

      // Modify boxed value directly
      ((IAngle)objectAngle).MoveTo(26, 58, 23);
      Console.WriteLine(", " + ((Angle)objectAngle).Degrees);

      // ...
  }
}
```

Output 8.2

```
25, 25, 25, 26
```

Listing 8.7 uses the `Angle` struct and `IAngle` interface. Note also that the `IAngle.MoveTo()` interface changes `Angle` to be mutable. This change brings out some of the idiosyncrasies of mutable value types and, in so doing, demonstrates the importance of the guideline to make structs immutable.

In the first two lines of Listing 8.6, you initialize `angle` and then box it into a variable called `objectAngle`. Next, you call `move` to change `Hours` to `26`. However, as the output demonstrates, no change actually occurs the first time. The problem is that to call `MoveTo()`, the compiler unboxes `objectAngle` and (by definition) makes a copy of the value. Value types are copied by value—that is why they are called value types. Although the resultant value is successfully modified at execution time, this copy of the value is discarded and no change occurs on the heap location referenced by `objectAngle`.

Recall our analogy that suggested variables of value type are like pieces of paper with the value written on them. When you box a value, you make a photocopy of the paper and put the copy in a box. When you unbox the value, you make a photocopy of the paper in the box. Making an edit to this second copy does not change the copy that is in the box.

In the next example, labeled with the comment "box, modify boxed value, and discard reference to box," a similar problem occurs in reverse. Instead of calling `MoveTo()` directly, the value is cast to `IAngle`. The conversion to an interface type boxes the value, so the runtime copies the data in `angle` to the heap and provides a reference to that box. Next, the method call modifies the value in the referenced box. The value stored in variable `angle` remains unmodified.

In the last case, the cast to `IAngle` is a reference conversion, not a boxing conversion. The value has already been boxed by the conversion to `object` in this case, so no copy of the value occurs on this conversion. The call to `MoveTo()` updates the `_Hours` value stored in the box, and the code behaves as desired.

As you can see from this example, mutable value types are quite confusing because it is often unclear when you are mutating a copy of the value, rather than the storage location you actually intend to change. By avoiding mutable value types in the first place, you can eliminate this sort of confusion.

Guidelines

AVOID mutable value types.

ADVANCED TOPIC

How Boxing Can Be Avoided during Method Calls

Anytime a method is called with a receiver of value type, the receiver (represented by `this` in the body of the method) must be a variable, not a value, because the method might be trying to mutate the receiver. Clearly, it must be mutating the receiver's storage location, rather than mutating a copy of the receiver's value and then discarding it. The second and fourth cases in Listing 8.7 illustrate how this fact affects the performance of a method invocation on a boxed value type.

In the second case, the unboxing conversion logically produces the boxed value, not a reference to the storage location on the heap that contains the boxed copy. Which storage location, then, is passed as the `this` to the mutating method call? It cannot be the storage location from the box on the heap, because the unboxing conversion produces a copy of that value, not a reference to that storage location.

When this situation arises—a variable of value type is required but only a value is available—one of two things happens: Either the C# compiler generates code that makes a new, temporary storage location and copies the value from the box into the new location, resulting in the temporary storage location becoming the needed variable, or the compiler produces an error and disallows the operation. In this case, the former strategy is used. The new temporary storage location is then the receiver of the call; after it is mutated, the temporary storage location is discarded.

This process—performing a type check of the boxed value, unboxing to produce the storage location of the boxed value, allocating a temporary variable, copying the value from the box to the temporary variable, and then calling the method with the location of the temporary storage—happens every time you use the unbox-and-then-call pattern, regardless of whether the method actually mutates the variable. Clearly, if it does not mutate the variable, some of this work could be avoided. Because the C# compiler does not know whether any particular method you call will try to mutate the receiver, it must err on the side of caution.

These expenses are all eliminated when calling an interface method on a boxed value type. In such a case, the expectation is that the receiver will be the storage location in the box; if the interface method mutates the storage location, it is the boxed location that should be mutated. Therefore, the expense of performing a type check, allocating new temporary storage, and making a copy is avoided. Instead, the runtime simply uses the storage location in the box as the receiver of the call to the struct's method.

In Listing 8.8, we call the two-argument version of `ToString()` that is found on the `IFormattable` interface, which is implemented by the `int` value type. In this example, the receiver of the call is a boxed value type, but it is not unboxed to make the call to the interface method.

Listing 8.8: Avoiding Unboxing and Copying

```
int number;
object thing;
number = 42;
// Boxing
thing = number;
// No unboxing conversion.
string text = ((IFormattable)thing).ToString(
    "X", null);
Console.WriteLine(text);
```

You might now wonder: Suppose that we had instead called the virtual `ToString()` method declared by `object` with an instance of a value type as the receiver. What happens then? Is the instance boxed, unboxed, or what? A number of different scenarios are possible depending on the details:

- If the receiver is unboxed and the struct overrides `ToString()`, the overridden method is called directly. There is no need for a virtual call because the method cannot be overridden further by a more derived class; all value types are automatically sealed.
- If the receiver is unboxed and the struct does not override `ToString()`, the base class implementation must be called, and it expects a reference to an object as its receiver. Therefore, the receiver is boxed.
- If the receiver is boxed and the struct overrides `ToString()`, the storage location in the box is passed to the overriding method without unboxing it.
- If the receiver is boxed and the struct does not override `ToString()`, the reference to the box is passed to the base class's implementation of the method, which is expecting a reference.

Enums

Compare the two code snippets shown in Listing 8.9.

LISTING 8.9: Comparing an Integer Switch to an Enum Switch

```
int connectionState;
// ...
switch (connectionState)
{
    case 0:
        // ...
        break;
    case 1:
        // ...
        break;
    case 2:
        // ...
        break;
    case 3:
        // ...
        break;
}
```

```
ConnectionState connectionState;
// ...
switch (connectionState)
{
    case ConnectionState.Connected:
        // ...
        break;
    case ConnectionState.Connecting:
        // ...
        break;
    case ConnectionState.Disconnected:
        // ...
        break;
    case ConnectionState.Disconnecting:
        // ...
        break;
}
```

Obviously, the difference in terms of readability is tremendous—in the second snippet, the cases are self-documenting. However, the performance at runtime is identical. To achieve this outcome, the second snippet uses **enum values** in each case.

An enum is a value type that the developer can declare. The key characteristic of an enum is that it declares at compile time a set of possible constant values that can be referred to by name, thereby making the code easier to read. The syntax for a typical enum declaration is show in Listing 8.10.

LISTING 8.10: Defining an Enum

```
enum ConnectionState
{
  Disconnected,
  Connecting,
  Connected,
  Disconnecting
}
```

> **NOTE**
>
> An enum can be used as a more readable replacement for Boolean values as well. For example, a method call such as `SetState(true)` is less readable than `SetState(DeviceState.On)`.

You use an enum value by prefixing it with the enum name. To use the `Connected` value, for example, you would use the syntax `ConnectionState.Connected`. Do not make the enum type name a part of the value's name so as to avoid the redundancy of something such as `ConnectionState.ConnectionStateConnected`. By convention, the enum name itself should be singular (unless the enums are bit flags, as discussed shortly). That is, the nomenclature should be `ConnectionState`, not `ConnectionStates`.

Enum values are actually implemented as nothing more than integer constants. By default, the first enum value is given the value `0`, and each subsequent entry increases by 1. However, you can assign explicit values to enums, as shown in Listing 8.11.

LISTING 8.11: Defining an Enum Type

```
enum ConnectionState : short
{
  Disconnected,
  Connecting = 10,
  Connected,
  Joined = Connected,
  Disconnecting
}
```

In this code, Disconnected has a default value of 0 and Connecting has been explicitly assigned 10; consequently, Connected will be assigned 11. Joined is assigned 11, the value assigned to Connected. (In this case, you do not need to prefix Connected with the enum name, since it appears within its scope.) Disconnecting is 12.

An enum always has an underlying type, which may be any integral type other than char. In fact, the enum type's performance is identical to that of the underlying type. By default, the underlying value type is int, but you can specify a different type using inheritance type syntax. Instead of int, for example, Listing 8.11 uses a short. For consistency, the syntax for enums emulates the syntax of inheritance, but this doesn't actually make an inheritance relationship. The base class for all enums is System.Enum, which in turn is derived from System.ValueType. Furthermore, these classes are sealed; you can't derive from an existing enum type to add additional members.

Guidelines

CONSIDER using the default 32-bit integer type as the underlying type of an enum. Use a smaller type only if you must do so for interoperability or performance reasons; use a larger type only if you are creating a flags enum (see the discussion later in this chapter) with more than 32 flags.

An enum is really nothing more than a set of names thinly layered on top of the underlying type; there is no mechanism that restricts the value of a variable of enumerated type to just the values named in the declaration. For example, because it is possible to cast the integer 42 to short, it is also possible to cast the integer 42 to the ConnectionState type, even though there is no corresponding ConnectionState enum value. If the value can be converted to the underlying type, the conversion to the enum type will also be successful.

The advantage of this odd feature is that enums can have new values added in later API releases, without breaking earlier versions. Additionally, the enum values provide names for the known values while still allowing unknown values to be assigned at runtime. The burden is that developers must code defensively for the possibility of unnamed values. It would be unwise, for example, to replace case ConnectionState.Disconnecting with default and expect that the only possible value for the default case was `ConnectionState.Disconnecting`. Instead, you should handle the `Disconnecting` case explicitly and the `default` case should report an error or behave innocuously. As indicated earlier, however, conversion between the enum and the underlying type, and vice versa, requires an explicit cast; it is not an implicit conversion. For example, code cannot call `ReportState(10)` if the method's signature is `void ReportState(ConnectionState state)`. The only exception occurs when passing `0`, because there is an implicit conversion from `0` to any enum.

Although you can add more values to an enum in a later version of your code, you should do so with care. Inserting an enum value in the middle of an enum will bump the values of all later enums (adding `Flooded` or `Locked` before `Connected` will change the `Connected` value, for example). This will affect the versions of all code that is recompiled against the new version. However, any code compiled against the old version will continue to use the old values, making the intended values entirely different. Besides inserting an enum value at the end of the list, one way to avoid changing enum values is to assign values explicitly.

Guidelines

CONSIDER adding new members to existing enums, but keep in mind the compatibility risk.

AVOID creating enums that represent an "incomplete" set of values, such as product version numbers.

AVOID creating "reserved for future use" values in an enum.

AVOID enums that contain a single value.

DO provide a value of `0` (none) for simple enums, knowing that `0` will be the default value when no explicit initialization is provided.

Enums are slightly different from other value types because they derive from `System.Enum` before deriving from `System.ValueType`.

Type Compatibility between Enums

C# also does not support a direct cast between arrays of two different enums. However, the CLR does, provided that both enums share the same underlying type. To work around this restriction of C#, the trick is to cast first to `System.Array`, as shown at the end of Listing 8.12.

LISTING 8.12: Casting between Arrays of Enums

```
enum ConnectionState1
{
  Disconnected,
  Connecting,
  Connected,
  Disconnecting
}
```

```
enum ConnectionState2
{
  Disconnected,
  Connecting,
  Connected,
  Disconnecting
}
```

```
class Program
{
  static void Main()
  {
      ConnectionState1[] states =
          (ConnectionState1[])(Array)new ConnectionState2[42];
  }
}
```

This example exploits the fact that the CLR's notion of assignment compatibility is more lenient than C#'s concept. (The same trick is possible for other illegal conversions, such as `int[]` to `uint[]`.) However, use this approach cautiously because there is no C# specification requiring that this behavior work across different CLR implementations.

Converting between Enums and Strings

One of the conveniences associated with enums is that the `ToString()` method, which is called by methods such as `System.Console.WriteLine()`, writes out the enum value identifier:

```
System.Diagnostics.Trace.WriteLine(
    $"The connection is currently { ConnectionState.Disconnecting }");
```

The preceding code will write the text in Output 8.3 to the trace buffer.

OUTPUT 8.3

```
The connection is currently Disconnecting.
```

Conversion from a string to an enum is a little more difficult to achieve, because it involves a static method on the `System.Enum` base class. Listing 8.13 provides an example of how to do it without generics (see Chapter 11), and Output 8.4 shows the results.

LISTING 8.13: Converting a String to an Enum Using `Enum.Parse()`

```
ThreadPriorityLevel priority = (ThreadPriorityLevel)Enum.Parse(
  typeof(ThreadPriorityLevel), "Idle");
Console.WriteLine(priority);
```

OUTPUT 8.4

```
Idle
```

In this code, the first parameter to `Enum.Parse()` is the type, which you specify using the keyword `typeof()`. This example depicts a compile-time way of identifying the type, like a literal for the type value (see Chapter 17).

Until .NET Framework 4, there was no `TryParse()` method, so code written to target prior versions needs to include appropriate exception handling if there is a chance the string will not correspond to an enum value identifier. .NET Framework 4's `TryParse<T>()` method uses generics, but the type parameters can be inferred, resulting in the to-enum conversion behavior shown in Listing 8.14.

LISTING 8.14: Converting a String to an Enum Using `Enum.TryParse<T>()`

```
System.Diagnostics.ThreadPriorityLevel priority;
if(Enum.TryParse("Idle", out priority))
{
  Console.WriteLine(priority);
}
```

This technique eliminates the need to use exception handling if the string might not convert successfully. Instead, code can check the Boolean result returned from the call to `TryParse<T>()`.

Regardless of whether the code uses the "Parse" or "TryParse" approach, the key caution about converting from a string to an enum is that such a cast is not localizable. Therefore, developers should use this type of cast only for messages that are not exposed to users (assuming localization is a requirement).

Guidelines

AVOID direct enum/string conversions where the string must be localized into the user's language.

Enums As Flags

Many times, developers not only want enum values to be unique, but also want to be able to represent a combination of values. For example, consider `System.IO.FileAttributes`. This enum, shown in Listing 8.15, indicates various attributes on a file: read-only, hidden, archive, and so on. Unlike with the `ConnectionState` attribute, where each enum value was mutually exclusive, the `FileAttributes` enum values can and are intended for combination: A file can be both read-only and hidden. To support this behavior, each enum value is a unique bit.

LISTING 8.15: Using Enums As Flags

```
[Flags] public enum FileAttributes
{
  ReadOnly =          1<<0,      // 000000000000000001
  Hidden =            1<<1,      // 000000000000000010
  System =            1<<2,      // 000000000000000100
  Directory =         1<<4,      // 000000000000010000
  Archive =           1<<5,      // 000000000000100000
  Device =            1<<6,      // 000000000001000000
  Normal =            1<<7,      // 000000000010000000
  Temporary =         1<<8,      // 000000000100000000
  SparseFile =        1<<9,      // 000000001000000000
  ReparsePoint =      1<<10,     // 000000010000000000
  Compressed =        1<<11,     // 000000100000000000
  Offline =           1<<12,     // 000001000000000000
  NotContentIndexed = 1<<13,     // 000010000000000000
  Encrypted =         1<<14,     // 000100000000000000
  IntegrityStream =   1<<15,     // 001000000000000000
  NoScrubData  =         1<<17,     // 100000000000000000
}
```

NOTE

Note that the name of a bit flags enum is usually pluralized, indicating that a value of the type represents a set of flags.

To join enum values, you use a bitwise OR operator. To test for the existence of a particular bit you use the bitwise AND operator. Both cases are illustrated in Listing 8.16.

LISTING 8.16: Using Bitwise OR and AND with Flag Enums

```
using System;
using System.IO;

public class Program
{
 public static void Main()
 {
      // ...

      string fileName = @"enumtest.txt";

      System.IO.FileInfo file =
          new System.IO.FileInfo(fileName);

      file.Attributes = FileAttributes.Hidden |
          FileAttributes.ReadOnly;

      Console.WriteLine("{0} | {1} = {2}",
          FileAttributes.Hidden, FileAttributes.ReadOnly,
          (int)file.Attributes);

      if ( (file.Attributes & FileAttributes.Hidden) !=
          FileAttributes.Hidden)
      {
          throw new Exception("File is not hidden.");
      }

      if (( file.Attributes & FileAttributes.ReadOnly) !=
          FileAttributes.ReadOnly)
      {
          throw new Exception("File is not read-only.");
      }

      // ...
}
```

The results of Listing 8.16 appear in Output 8.5.

OUTPUT 8.5

```
Hidden | ReadOnly = 3
```

Using the bitwise OR operator allows you to set the file to both read-only and hidden. In addition, you can check for specific settings using the bitwise AND operator.

Each value within the enum does not need to correspond to only one flag. It is perfectly reasonable to define additional flags that correspond to frequent combinations of values. Listing 8.17 shows an example.

LISTING 8.17: Defining Enum Values for Frequent Combinations

```
[Flags] enum DistributedChannel
{
  None = 0,
  Transacted = 1,
  Queued = 2,
  Encrypted = 4,
  Persisted = 16,
  FaultTolerant =
      Transacted | Queued | Persisted
}
```

It is a good practice to have a zero `None` member in a flags enum because the initial default value of a field of enum type or an element of an array of enum type is `0`. Avoid enum values corresponding to items such as `Maximum` as the last enum, because `Maximum` could be interpreted as a valid enum value. To check whether a value is included within an enum, use the `System.Enum.IsDefined()` method.

Guidelines

DO use the `FlagsAttribute` to mark enums that contain flags.

DO provide a `None` value equal to `0` for all flag enums.

AVOID creating flag enums where the zero value has a meaning other than “no flags are set.”

CONSIDER providing special values for commonly used combinations of flags.

DO NOT include “sentinel” values (such as a value called `Maximum`); such values can be confusing to the user.

DO use powers of 2 to ensure that all flag combinations are represented uniquely.

ADVANCED TOPIC

FlagsAttribute

If you decide to use bit flag enums, the declaration of the enum should be marked with `FlagsAttribute`. In such a case, the attribute appears in square brackets (see Chapter 17) just prior to the enum declaration, as shown in Listing 8.18.

LISTING 8.18: Using FlagsAttribute

```
// FileAttributes defined in System.IO.

[Flags]  // Decorating an enum with FlagsAttribute.
public enum FileAttributes
{
  ReadOnly =          1<<0,      // 000000000000001
  Hidden =            1<<1,      // 000000000000010
  // ...
}
```

```
using System;
using System.Diagnostics;
using System.IO;

class Program
{
  public static void Main()
  {
      string fileName = @"enumtest.txt";
      FileInfo file = new FileInfo(fileName);
      file.Open(FileMode.Create).Close();

      FileAttributes startingAttributes =
          file.Attributes;

      file.Attributes = FileAttributes.Hidden |
          FileAttributes.ReadOnly;

      Console.WriteLine("\"{0}\" outputs as \"{1}\"",
          file.Attributes.ToString().Replace(",", " |"),
          file.Attributes);

      FileAttributes attributes =
          (FileAttributes) Enum.Parse(typeof(FileAttributes),
          file.Attributes.ToString());

      Console.WriteLine(attributes);

      File.SetAttributes(fileName,
          startingAttributes);
```

```
        file.Delete();
    }
  }
```

The results of Listing 8.18 appear in Output 8.6.

OUTPUT 8.6

```
"ReadOnly | Hidden" outputs as "ReadOnly, Hidden"
ReadOnly, Hidden
```

The attribute documents that the enum values can be combined. Furthermore, it changes the behavior of the `ToString()` and `Parse()` methods. For example, calling `ToString()` on an enum that is decorated with `FlagsAttribute` writes out the strings for each enum flag that is set. In Listing 8.18, `file.Attributes.ToString()` returns `ReadOnly, Hidden` rather than the `3` it would have returned without the `FileAttributes` flag. If two enum values are the same, the `ToString()` call would return the first value. As mentioned earlier, however, you should use caution when relying on this behavior because it is not localizable.

Parsing a value from a string to the enum also works. Each enum value identifier is separated from the others by a comma.

Note that `FlagsAttribute` does not automatically assign unique flag values or check that they have unique values. Doing this wouldn't make sense, given that duplicates and combinations are often desirable. Instead, you must assign the values of each enum item explicitly.

SUMMARY

This chapter began with a discussion of how to define custom value types. Because it is easy to write confusing or buggy code when mutating value types, and because value types are typically used to model immutable values, it is a good idea to make value types immutable. We also described how value types are "boxed" when they must be treated polymorphically as reference types.

The idiosyncrasies introduced by boxing are subtle, and the vast majority of them lead to problematic issues at execution time rather than at compile time. Although it is important to know about these quirks so as to try to avoid them, in many ways paying too much attention to the potential pitfalls overshadows the usefulness and performance advantages of value types. Programmers should not be overly concerned about using value types. Value types permeate virtually every chapter of this book, yet the idiosyncrasies associated with them come into play infrequently. We have staged the code surrounding each issue to demonstrate the concern, but in reality these types of patterns rarely occur. The key to avoiding most of them is to follow the guideline of not creating mutable value types and following this constraint explains why you don't encounter them within the built-in value types.

Perhaps the only issue to occur with some frequency is repetitive boxing operations within loops. However, generics greatly reduce boxing, and even without them, performance is rarely affected enough to warrant their avoidance until a particular algorithm with boxing is identified as a bottleneck.

Furthermore, custom-built structs are relatively rare. They obviously play an important role within C# development, but the number of custom-built structs declared by typical developers is usually tiny compared to the number of custom-built classes. Heavy use of custom-built structs is most common in code targeted at interoperating with unmanaged code.

Guidelines

DO NOT define a struct unless it logically represents a single value, consumes 16 bytes or less of storage, is immutable, and is infrequently boxed.

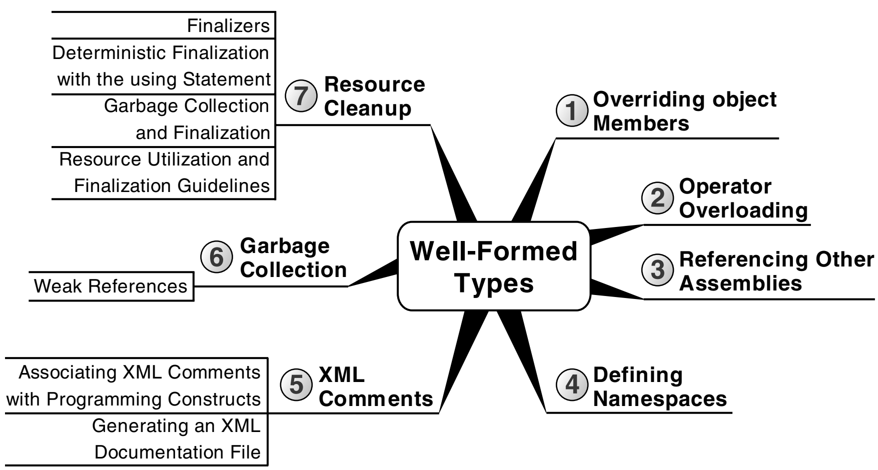
This chapter also introduced enums. Enumerated types are a standard construct available in many programming languages. They help improve both API usability and code readability.

The next chapter presents more guidelines for creating well-formed types—both value types and reference types. It begins by looking at overriding the virtual members of objects and defining operator-overloading methods. These two topics apply to both structs and classes, but they are somewhat more important when completing a struct definition and making it well formed.

9

Well-Formed Types

THE PREVIOUS CHAPTERS COVERED MOST of the constructs for defining classes and structs. However, several details remain to round out the type definition with fit-and-finish-type functionality. This chapter explains how to put the final touches on a type declaration.



Overriding `object` Members

Chapter 6 discussed how all classes and structs derive from `object`. In addition, it reviewed each method available on `object` and discussed how some of them are virtual. This section discusses the details concerning overriding the virtual methods.

Overriding ToString()

By default, calling `ToString()` on any object will return the fully qualified name of the class. Calling `ToString()` on a `System.IO.FileStream` object will return the string `System.IO.FileStream`, for example. For some classes, however, `ToString()` can be more meaningful. On `string`, for example, `ToString()` returns the string value itself. Similarly, returning a `Contact`'s name would make more sense. Listing 9.1 overrides `ToString()` to return a string representation of `Coordinate`.

LISTING 9.1: Overriding ToString()

```
public struct Coordinate
{
  public Coordinate(Longitude longitude, Latitude latitude)
  {
      Longitude = longitude;
      Latitude = latitude;
  }

  public Longitude Longitude { get; }
  public Latitude Latitude { get; }

  public override string ToString()
  {
      return $"{ Longitude } { Latitude }";
  }

  // ...
}
```

Write methods such as `Console.WriteLine()` and `System.Diagnostics.Trace.Write()` call an object's `ToString()` method, so overloading the method often outputs more meaningful information than the default implementation. Given this point, you should consider overloading the `ToString()` method whenever relevant diagnostic information can be provided from the output—specifically, when the target audience is developers, since the default `object.ToString()` output is a type name and is not end-user friendly. `ToString()` is useful for debugging from within a developer IDE or writing to a log file. For this reason, you should keep the strings relatively short (one screen length) so that they are not cut off. However, the lack of localization and other advanced formatting features makes this approach less suitable for general end-user text display.

> ### Guidelines
>
> **DO** override `ToString()` whenever useful developer-oriented diagnostic strings can be returned.
>
> **DO** try to keep the string returned from `ToString()` short.
>
> **DO NOT** return an empty string or null from `ToString()`.
>
> **AVOID** throwing exceptions or making observable side effects (changing the object state) from `ToString()`.
>
> **DO** provide an overloaded `ToString(string format)` or implement `IFormattable` if the return value is culture-sensitive or requires formatting (for example, `DateTime`).
>
> **CONSIDER** returning a unique string from `ToString()` so as to identify the object instance.

Overriding GetHashCode()

Overriding `GetHashCode()` is more complex than overriding `ToString()`. Even so, you should override `GetHashCode()` when you are overriding `Equals()`, and there is a compiler warning to indicate this step is recommended if you don't. Overriding `GetHashCode()` is also a good practice when you are using it as a key into a hash table collection (`System.Collections.Hashtable` and `System.Collections.Generic.Dictionary`, for example).

The purpose of the hash code is to *efficiently balance a hash table* by generating a number that corresponds to the value of an object. Here are some implementation principles for a good `GetHashCode()` implementation:

- *Required:* Equal objects must have equal hash codes (if `a.Equals(b)`, then `a.GetHashCode() == b.GetHashCode()`).
- *Required:* `GetHashCode()`'s returns over the life of a particular object should be constant (the same value), even if the object's data changes. In many cases, you should cache the method return to enforce this constraint.
- *Required:* `GetHashCode()` should not throw any exceptions; `GetHashCode()` must always successfully return a value.

- *Performance:* Hash codes should be unique whenever possible. However, since hash codes return only an `int`, there has to be an overlap in hash codes for objects that have potentially more values than an `int` can hold, which is virtually all types. (An obvious example is `long`, since there are more possible `long` values than an `int` could uniquely identify.)
- *Performance:* The possible hash code values should be distributed evenly over the range of an `int`. For example, creating a hash that doesn't consider the fact that distribution of a string in Latin-based languages primarily centers on the initial 128 ASCII characters would result in a very uneven distribution of string values and would not be a strong `GetHashCode()` algorithm.
- *Performance:* `GetHashCode()` should be optimized for performance. `GetHashCode()` is generally used in `Equals()` implementations to short-circuit a full equals comparison if the hash codes are different. As a result, it is frequently called when the type is used as a key type in dictionary collections.
- *Performance:* Small differences between two objects should result in large differences between hash code values—ideally, a 1-bit difference in the object should result in approximately 16 bits of the hash code changing, on average. This helps ensure that the hash table remains balanced no matter how it is "bucketing" the hash values.
- *Security:* It should be difficult for an attacker to craft an object that has a particular hash code. The attack is to flood a hash table with large amounts of data that all hash to the same value. The hash table implementation can become inefficient, resulting in a possible denial-of-service attack.

These guidelines and rules are, of course, contradictory: It is very difficult to come up with a hash algorithm that is fast and meets all of these guidelines. As with any design problem, you'll need to use a combination of good judgment and realistic performance measurements to come up with a good solution.

Consider the `GetHashCode()` implementation for the `Coordinate` type shown in Listing 9.2.

LISTING 9.2: Implementing **GetHashCode()**

```
public struct Coordinate
{
  public Coordinate(Longitude longitude, Latitude latitude)
  {
      Longitude = longitude;
      Latitude = latitude;
  }

  public Longitude Longitude { get; }
  public Latitude Latitude { get; }

  public override int GetHashCode()
  {
      int hashCode = Longitude.GetHashCode();
      // As long as the hash codes are not equal
      if(Longitude.GetHashCode() != Latitude.GetHashCode())
      {
          hashCode ^= Latitude.GetHashCode();  // eXclusive OR
      }
      return hashCode;
  }

  // ...
}
```

Generally, the key is to use the XOR operator over the hash codes from the relevant types, and to make sure the XOR operands are not likely to be close or equal—or else the result will be all zeroes. (In those cases where the operands are close or equal, consider using bit shifts and adds instead.) The alternative operands, AND and OR, have similar restrictions, but those restrictions come into play more frequently. Applying AND multiple times tends toward all 0 bits, and applying OR tends toward all 1 bits.

For finer-grained control, split larger-than-`int` types using the shift operator. For example, `GetHashCode()` for a `long` called `value` is implemented as follows:

```
int GetHashCode() { return ((int)value ^ (int)(value >> 32)) };
```

Also, if the base class is not `object`, `base.GetHashCode()` should be included in the XOR assignment.

Finally, `Coordinate` does not cache the value of the hash code. Since each field in the hash code calculation is `readonly`, the value can't change. However, implementations should cache the hash code if calculated values could change or if a cached value could offer a significant performance advantage.

Overriding Equals()

Overriding `Equals()` without overriding `GetHashCode()` results in a warning such as that shown in Output 9.1.

OUTPUT 9.1

```
warning CS0659: '<Class Name>' overrides Object.Equals(object o) but
does not override Object.GetHashCode()
```

Generally, developers expect overriding `Equals()` to be trivial, but it includes a surprising number of subtleties that require careful thought and testing.

Object Identity versus Equal Object Values

Two references are identical if both refer to the same instance. `object` (and, by inheritance, all derived types) includes a static method called `ReferenceEquals()` that explicitly checks for this object identity (see Figure 9.1).

However, reference equality is not the only type of equality. Two object instances can also be called equal if the values of some or all of their members are equal. Consider the comparison of two `ProductSerialNumbers` shown in Listing 9.3.

LISTING 9.3: Overriding the Equality Operator

```
public sealed class ProductSerialNumber
{
  // ...
}
```

```
class Program
{
static void Main()
  {
      ProductSerialNumber serialNumber1 =
          new ProductSerialNumber("PV", 1000, 09187234);
     ProductSerialNumber serialNumber2 = serialNumber1;
      ProductSerialNumber serialNumber3 =
         new ProductSerialNumber("PV", 1000, 09187234);

     // These serial numbers ARE the same object identity.
      if(!ProductSerialNumber.ReferenceEquals(serialNumber1,
          serialNumber2))
```

```
        {
            throw new Exception(
                "serialNumber1 does NOT " +
                "reference equal serialNumber2");
        }
        // And, therefore, they are equal.
        else if(!serialNumber1.Equals(serialNumber2))
        {
            throw new Exception(
                "serialNumber1 does NOT equal serialNumber2");
        }
       else
       {
            Console.WriteLine(
                "serialNumber1 reference equals serialNumber2");
            Console.WriteLine(
                "serialNumber1 equals serialNumber2");
        }


        // These serial numbers are NOT the same object identity.
        if (ProductSerialNumber.ReferenceEquals(serialNumber1,
                serialNumber3))
        {
            throw new Exception(
                "serialNumber1 DOES reference " +
                "equal serialNumber3");
        }
        // But they are equal (assuming Equals is overloaded).
        else if(!serialNumber1.Equals(serialNumber3) ||
            serialNumber1 != serialNumber3)
        {
            throw new Exception(
                "serialNumber1 does NOT equal serialNumber3");
        }

        Console.WriteLine( "serialNumber1 equals serialNumber3" );
    }
  }
```

The results of Listing 9.3 appear in Output 9.2.

Output 9.2

```
serialNumber1 reference equals serialNumber2
serialNumber1 equals serialNumber3
```

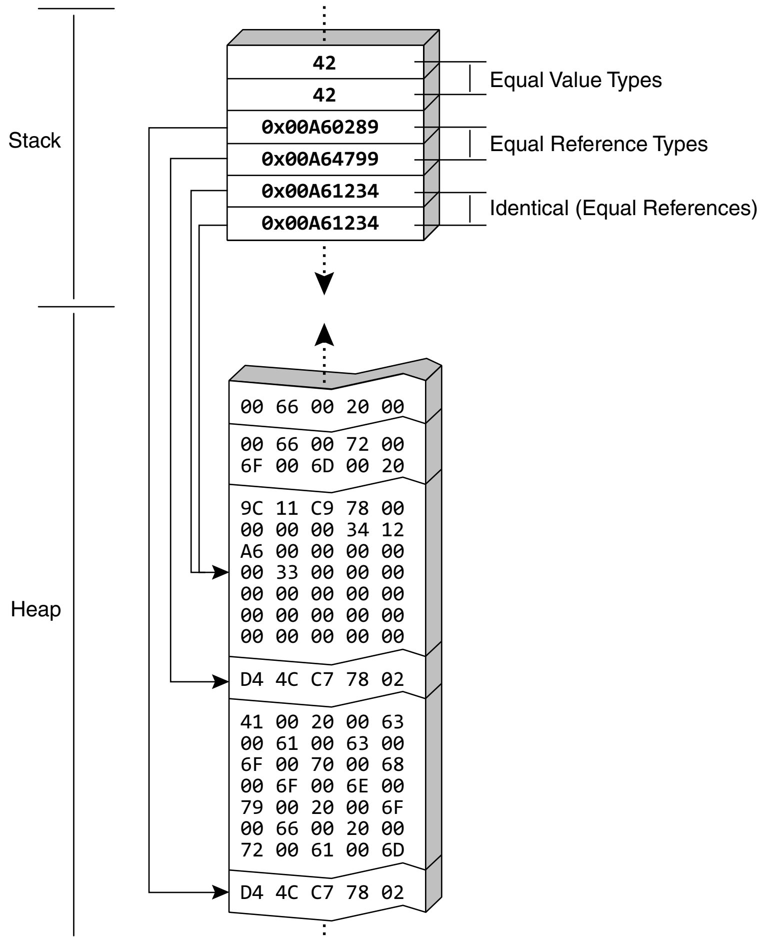


FIGURE 9.1: Identity

As the last assertion demonstrates with `ReferenceEquals()`, `serialNumber1` and `serialNumber3` are not the same reference. However, the code constructs them with the same values and both are logically associated with the same physical product. If one instance was created from data in the database and another was created from manually entered data, you would expect that the instances would be equal and, therefore, that the product would not be duplicated (reentered) in the database. Two identical references are obviously equal; however, two different objects could be equal but not reference equal. Such objects will not have identical object identities, but they may have key data that identifies them as being equal objects.

Only reference types can be reference equal, thereby supporting the concept of identity. Calling `ReferenceEquals()` on value types will always return `false` because value types are boxed when they are converted to `object` for the call. Even when the same variable is passed in both (value type) parameters to `ReferenceEquals()`, the result will still be `false` because the values are boxed independently. Listing 9.4 demonstrates this behavior because each argument is put into a "different box" in this example, they are never reference equal.

> **NOTE**
>
> Calling `ReferenceEquals()` on value types will always return `false`.

LISTING 9.4: Value Types Never Reference Equal Themselves

```
public struct Coordinate
{
  public Coordinate(Longitude longitude, Latitude latitude)
  {
      Longitude = longitude;
      Latitude = latitude;
  }

  public Longitude Longitude { get; }
  public Latitude Latitude { get; }
  // ...
}
```

```
class Program
{
  public void Main()
  {
      //...

      Coordinate coordinate1 =
          new Coordinate( new Longitude(48, 52),
                          new Latitude(-2, -20));

      // Value types will never be reference equal.
      if ( Coordinate.ReferenceEquals(coordinate1,
          coordinate1) )
      {
          throw new Exception(
              "coordinate1 reference equals coordinate1");
      }
```

```
            Console.WriteLine(
                "coordinate1 does NOT reference equal itself" );
        }
    }
```

In contrast to the definition of `Coordinate` as a reference type in Chapter 8, the definition going forward is that of a value type (`struct`) because the combination of `Longitude` and `Latitude` data is logically thought of as a value and its size is less than 16 bytes. (In Chapter 8, `Coordinate` aggregated `Angle` rather than `Longitude` and `Latitude`.) A contributing factor to declaring `Coordinate` as a value type is that it is a (complex) numeric value that has particular operations on it. In contrast, a reference type such as `Employee` is not a value that you manipulate numerically, but rather refers to an object in real life.

Implementing `Equals()`

To determine whether two objects are equal (that is, if they have the same identifying data), you use an object's `Equals()` method. The implementation of this virtual method on `object` uses `ReferenceEquals()` to evaluate equality. Since this implementation is often inadequate, it is sometimes necessary to override `Equals()` with a more appropriate implementation.

> **NOTE**
>
> The implementation of `object.Equals()`, the default implementation on all objects before overloading, relies on `ReferenceEquals()` alone.

For objects to *equal* one another, the expectation is that the identifying data within them will be equal. For `ProductSerialNumbers`, for example, the `ProductSeries`, `Model`, and `Id` must be the same; however, for an `Employee` object, perhaps comparing `EmployeeIds` would be sufficient for equality. To correct the `object.Equals()` implementation, it is necessary to override it. Value types, for example, override the `Equals()` implementation to instead use the fields that the type includes.

The steps for overriding `Equals()` are as follows:

1. Check for `null`.

2. Check for reference equality if the type is a reference type.
3. Check for equivalent types.
4. Invoke a typed helper method that can treat the operand as the compared type rather than an object (see the `Equals(Coordinate obj)` method in Listing 9.5).
5. Possibly check for equivalent hash codes to short-circuit an extensive, field-by-field comparison. (Two objects that are equal cannot have different hash codes.)
6. Check `base.Equals()` if the base class overrides `Equals()`.
7. Compare each identifying field for equality.
8. Override `GetHashCode()`.
9. Override the `==` and `!=` operators (see the next section).

Listing 9.5 shows a sample `Equals()` implementation.

Listing 9.5: Overriding Equals()

```
public struct Longitude
{
  // ...
}
```

```
public struct Latitude
{
  // ...
}
```

```
public struct Coordinate
{
  public Coordinate(Longitude longitude, Latitude latitude)
  {
      Longitude = longitude;
      Latitude = latitude;
  }

  public Longitude Longitude { get; }
  public Latitude Latitude { get; }

  public override bool Equals(object obj)
  {
      // STEP 1: Check for null.
      if (obj == null)
      {
          return false;
      }
```

```
        // STEP 3: Equivalent data types.
        // Can be avoided if type is sealed.
        if (this.GetType() != obj.GetType())
        {
            return false;
        }
        return Equals((Coordinate)obj);
    }
    public bool Equals(Coordinate obj)
    {
        // STEP 1: Check for null if a reference type
        // (e.g., a reference type).
        // if (obj == null)
        // {
        //     return false;
        // }

        // STEP 2: Check for ReferenceEquals if this
        // is a reference type.
        // if ( ReferenceEquals(this, obj))
        // {
        //   return true;
        // }

        // STEP 4: Possibly check for equivalent hash codes.
        // if (this.GetHashCode() != obj.GetHashCode())
        // {
        //    return false;
        // }

        // STEP 5: Check base.Equals if base overrides Equals().
        // System.Diagnostics.Debug.Assert(
        //     base.GetType() != typeof(object) );
        // if ( !base.Equals(obj) )
        // {
        //    return false;
        // }

        // STEP 6: Compare identifying fields for equality
        // using an overload of Equals on Longitude.
        return ( (Longitude.Equals(obj.Longitude)) &&
            (Latitude.Equals(obj.Latitude)) );
    }

    // STEP 7: Override GetHashCode.
    public override int GetHashCode()
    {
        int hashCode = Longitude.GetHashCode();
        hashCode ^= Latitude.GetHashCode(); // Xor (eXclusive OR)
        return hashCode;
    }

  }
```

In this implementation, the first two checks are relatively obvious. However, it is interesting to point out that step 3 can be avoided if the type is sealed.

Steps 4–6 occur in an overload of `Equals()` that takes the `Coordinate` data type specifically. This way, a comparison of two `Coordinates` will avoid `Equals(object obj)` and its `GetType()` check altogether.

Since `GetHashCode()` is not cached and is no more efficient than step 5, the `GetHashCode()` comparison is commented out. Similarly, `base.Equals()` is not used since the base class is not overriding `Equals()`. (The assertion checks that `base` is not of type `object`, but does not verify whether the base class overrides `Equals()`, which is required to appropriately call `base.Equals()`.) Regardless, because `GetHashCode()` does not necessarily return a unique value (it simply identifies when operands are different), on its own it does not conclusively identify equal objects.

Like `GetHashCode()`, `Equals()` should never throw any exceptions. It is valid to compare any object with any other object, and doing so should never result in an exception.

Guidelines

DO implement `GetHashCode()`, `Equals()`, the `==` operator, and the `!=` operator together—not one of these without the other three.

DO use the same algorithm when implementing `Equals()`, `==`, and `!=`.

AVOID throwing exceptions from implementations of `GetHashCode()`, `Equals()`, `==`, and `!=`.

AVOID overloading equality operators on mutable reference types or if the implementation would be significantly slower.

DO implement all the equality-related methods when implementing `IComparable`.

Operator Overloading

The preceding section looked at overriding `Equals()` and provided the guideline that the class should also implement `==` and `!=`. Implementing any operator is called *operator overloading*. This section describes how to perform such overloading, not only for `==` and `!=`, but also for other supported operators.

For example, `string` provides a + operator that concatenates two strings. This is perhaps not surprising, because `string` is a predefined type, so it could possibly have special compiler support. However, C# provides for adding + operator support to a class or struct. In fact, all operators are supported except `x.y`, `f(x)`, `new`, `typeof`, `default`, `checked`, `unchecked`, `delegate`, `is`, `as`, `=`, and `=>`. One particularly noteworthy operator that cannot be implemented is the assignment operator; there is no way to change the behavior of the = operator.

Before going through the exercise of implementing an operator overload, consider the fact that such operators are not discoverable through IntelliSense. Unless the intent is for a type to act like a primitive type (a numeric type, for example), you should avoid overloading an operator.

Comparison Operators (==, !=, <, >, <=, >=)

Once `Equals()` is overridden, there is a possible inconsistency. That is, two objects could return `true` for `Equals()` but `false` for the == operator because == performs a reference equality check by default. To correct this flaw, it is important to overload the equals (==) and not equals (!=) operators as well.

For the most part, the implementation for these operators can delegate the logic to `Equals()`, or vice versa. However, for reference types, some initial null checks are required first (see Listing 9.6).

Listing 9.6: Implementing the == and != Operators

```
public sealed class ProductSerialNumber
{
  // ...

  public static bool operator ==(
      ProductSerialNumber leftHandSide,
      ProductSerialNumber rightHandSide)
  {

      // Check if leftHandSide is null.
      // (operator== would be recursive)
      if(ReferenceEquals(leftHandSide, null))
      {
          // Return true if rightHandSide is also null
          // and false otherwise.
          return ReferenceEquals(rightHandSide, null);
      }
```

```
        return (leftHandSide.Equals(rightHandSide));
    }

    public static bool operator !=(
        ProductSerialNumber leftHandSide,
        ProductSerialNumber rightHandSide)
    {
        return !(leftHandSide == rightHandSide);
    }
}
```

Note that in this example, we use `ProductSerialNumber` rather than `Coordinate` to demonstrate the logic for a reference type, which has the added complexity of a null value.

Be sure to avoid the null checks with an equality operator (`leftHandSide == null`). Doing so would recursively call back into the method, resulting in a loop that continues until the stack overflows. To avoid this problem, you can call `ReferenceEquals()` to check for null.

> **NOTE**
>
> AVOID using the equality comparison operator (==) from within the implementation of the == operator overload.

Binary Operators (+, -, *, /, %, &, |, ^, <<, >>)

You can add an `Arc` to a `Coordinate`. However, the code so far provides no support for the addition operator. Instead, you need to define such a method, as Listing 9.7 demonstrates.

Listing 9.7: Adding an Operator

```
struct Arc
{
    public Arc(
        Longitude longitudeDifference,
        Latitude latitudeDifference)
    {
        LongitudeDifference = longitudeDifference;
        LatitudeDifference = latitudeDifference;
    }

    public Longitude LongitudeDifference { get; }
```

```
    public Latitude LatitudeDifference { get; }
  }
```

```
  struct Coordinate
  {
    // ...
    public static Coordinate operator +(
        Coordinate source, Arc arc)
    {
        Coordinate result = new Coordinate(
            new Longitude(
                source.Longitude + arc.LongitudeDifference),
            new Latitude(
                source.Latitude + arc.LatitudeDifference));
        return result;
    }
  }
```

The `+`, `-`, `*`, `/`, `%`, `&`, `|`, `^`, `<<`, and `>>` operators are implemented as binary static methods where at least one parameter is of the containing type. The method name is the operator prefixed by the word *operator* as a keyword. As shown in Listing 9.8, given the definition of the `-` and `+` binary operators, you can add and subtract an `Arc` to and from the coordinate. Note that `Longitude` and `Latitude` will also require implementations of the `+` operator because they are called by `source.Longitude + arc.LongitudeDifference` and `source.Latitude + arc.LatitudeDifference`.

LISTING 9.8: Calling the – and + Binary Operators

```
public class Program
{
  public static void Main()
  {
      Coordinate coordinate1,coordinate2;
      coordinate1 = new Coordinate(
          new Longitude(48, 52), new Latitude(-2, -20));
      Arc arc = new Arc(new Longitude(3), new Latitude(1));

      coordinate2 = coordinate1 + arc;
      Console.WriteLine(coordinate2);

      coordinate2 = coordinate2 - arc;
      Console.WriteLine(coordinate2);

      coordinate2 += arc;
      Console.WriteLine(coordinate2);
  }
}
```

The results of Listing 9.8 appear in Output 9.3.

OUTPUT 9.3

```
51° 52' 0 E  -1° -20' 0 N
48° 52' 0 E  -2° -20' 0 N
51° 52' 0 E  -1° -20' 0 N
```

For `Coordinate`, you implement the `-` and `+` operators to return coordinate locations after adding/subtracting `Arc`. This allows you to string multiple operators and operands together, as in `result = ((coordinate1 + arc1) + arc2) + arc3`. Moreover, by supporting the same operators (+/-) on `Arc` (see Listing 9.9), you could eliminate the parenthesis. This approach works because the result of the first operand (`arc1 + arc2`) is another `Arc`, which you can then add to the next operand of type `Arc` or `Coordinate`.

In contrast, consider what would happen if you provided a `-` operator that had two `Coordinates` as parameters and returned a `double` corresponding to the distance between the two `coordinates`. Adding a `double` to a `Coordinate` is undefined, so you could not string together operators and operands. Caution is in order when defining operators that return a different type, because doing so is counterintuitive.

Combining Assignment with Binary Operators (+=, -=, *=, /=, %=, &=, …)

As previously mentioned, there is no support for overloading the assignment operator. However, assignment operators in combination with binary operators (`+=`, `-=`, `*=`, `/=`, `%=`, `&=`, `|=`, `^=`, `<<=`, and `>>=`) are effectively overloaded when overloading the binary operator. Given the definition of a binary operator without the assignment, C# automatically allows for assignment in combination with the operator. Using the definition of `Coordinate` in Listing 9.7, therefore, you can have code such as

```
coordinate += arc;
```

which is equivalent to the following:

```
coordinate = coordinate + arc;
```

Conditional Logical Operators (&&, ||)

Like assignment operators, conditional logical operators cannot be overloaded explicitly. However, because the logical operators `&` and `|` can be overloaded, and the conditional operators comprise the logical operators, effectively it is possible to overload conditional operators. `x && y` is processed as `x & y`, where `y` must evaluate to `true`. Similarly, `x || y` is processed as `x | y` only if `x` is `false`. To enable support for evaluating a type to `true` or `false`—in an `if` statement, for example—it is necessary to override the `true`/`false` unary operators.

Unary Operators (+, -, !, ~, ++, --, true, false)

Overloading unary operators is very similar to overloading binary operators, except that they take only one parameter, also of the containing type. Listing 9.9 overloads the + and – operators for `Longitude` and `Latitude` and then uses these operators when overloading the same operators in `Arc`.

Listing 9.9: Overloading the – and + Unary Operators

```
public struct Latitude
{
  // ...
  public static Latitude operator -(Latitude latitude)
  {
      return new Latitude(-latitude.DecimalDegrees);
  }
  public static Latitude operator +(Latitude latitude)
  {
      return latitude;
  }
}
```

```
public struct Longitude
{
  // ...
  public static Longitude operator -(Longitude longitude)
  {
      return new Longitude(-longitude.DecimalDegrees);
  }
  public static Longitude operator +(Longitude longitude)
  {
      return longitude;
  }
}
```

```
public struct Arc
```

```
{
  // ...
  public static Arc operator -(Arc arc)
  {
      // Uses unary – operator defined on
      // Longitude and Latitude
      return new Arc(-arc.LongitudeDifference,
          -arc.LatitudeDifference);
  }
  public static Arc operator +(Arc arc)
  {
      return arc;
  }
}
```

Just as with numeric types, the + operator in this listing doesn't have any effect and is provided for symmetry.

Overloading `true` and `false` is subject to the additional requirement that both must be overloaded—not just one of the two. The signatures are the same as with other operator overloads; however, the return must be a `bool`, as demonstrated in Listing 9.10.

LISTING 9.10: Overloading the `true` and `false` Operators

```
public static bool operator false(IsValid item)
{
    // ...
}
public static bool operator true(IsValid item)
{
    // ...
}
```

You can use types with overloaded `true` and `false` operators in `if`, `do`, `while`, and `for` controlling expressions.

Conversion Operators

Currently, there is no support in `Longitude`, `Latitude`, and `Coordinate` for casting to an alternative type. For example, there is no way to cast a `double` into a `Longitude` or `Latitude` instance. Similarly, there is no support for assigning a `Coordinate` using a `string`. Fortunately, C# provides for the definition of methods specifically intended to handle the converting of one type to another. Furthermore, the method declaration allows for specifying whether the conversion is implicit or explicit.

ADVANCED TOPIC

Cast Operator (`()`)

Implementing the explicit and implicit conversion operators is not technically overloading the cast operator (`()`). However, this action is effectively what takes place, so *defining a cast operator* is common terminology for implementing explicit or implicit conversion.

Defining a conversion operator is similar in style to defining any other operator, except that the "operator" is the resultant type of the conversion. Additionally, the `operator` keyword follows a keyword that indicates whether the conversion is implicit or explicit (see Listing 9.11).

LISTING 9.11: Providing an Implicit Conversion between `Latitude` and `double`

```
public struct Latitude
{
  // ...

  public Latitude(double decimalDegrees)
  {
      DecimalDegrees = Normalize(decimalDegrees);
  }

  public double DecimalDegrees { get; }

  // ...

  public static implicit operator double(Latitude latitude)
  {
      return latitude.DecimalDegrees;
  }
  public static implicit operator Latitude(double degrees)
  {
      return new Latitude(degrees);
  }

  // ...
}
```

With these conversion operators, you now can convert `double`s implicitly to and from `Latitude` objects. Assuming similar conversions exist for `Longitude`, you can simplify the creation of a `Coordinate` object by specifying the decimal degrees portion of each coordinate portion (for example, `coordinate = new Coordinate(43, 172);`).

NOTE

When implementing a conversion operator, either the return or the parameter must be of the enclosing type—in support of encapsulation. C# does not allow you to specify conversions outside the scope of the converted type.

Guidelines for Conversion Operators

The difference between defining an implicit and an explicit conversion operator centers on preventing an unintentional implicit conversion that results in undesirable behavior. You should be aware of two possible consequences of using the explicit conversion operator. First, conversion operators that throw exceptions should always be explicit. For example, it is highly likely that a string will not conform to the format that a conversion from `string` to `Coordinate` requires. Given the chance of a failed conversion, you should define the particular conversion operator as explicit, thereby requiring that you be intentional about the conversion and ensure that the format is correct or, alternatively, that you provide code to handle the possible exception. Frequently, the pattern for conversion is that one direction (`string` to `Coordinate`) is explicit and the reverse (`Coordinate` to `string`) is implicit.

A second consideration is the fact that some conversions will be lossy. Converting from a `float` (`4.2`) to an `int` is entirely valid, assuming an awareness of the fact that the decimal portion of the `float` will be lost. Any conversions that will lose data and will not successfully convert back to the original type should be defined as explicit. If an explicit cast is unexpectedly lossy or invalid, consider throwing a `System.InvalidCastException`.

Guidelines

DO NOT provide an implicit conversion operator if the conversion is lossy.

DO NOT throw exceptions from implicit conversions.

Referencing Other Assemblies

Instead of placing all code into one monolithic binary file, C# and the underlying CLI platform allow you to spread code across multiple assemblies. This approach enables you to reuse assemblies across multiple executables.

BEGINNER TOPIC

Class Libraries

The `HelloWorld.exe` program is one of the most trivial programs you can write. Real-world programs are more complex, and as complexity increases, it helps to organize the complexity by breaking programs into multiple parts. To do this, developers move portions of a program into separate compiled units called **class libraries** or, simply, **libraries.** Programs then reference and rely on class libraries to provide parts of their functionality. The power of this concept is that two programs can rely on the same class library, thereby sharing the functionality of that class library across both programs and reducing the total amount of code needed.

In other words, it is possible to write features once, place them into a class library, and allow multiple programs to include those features by referencing the same class library. Later in the development cycle, when developers fix a bug or add functionality to the class library, all the programs will have access to the increased functionality, just because they continue to reference the now improved class library.

To reuse the code within a different assembly, it is necessary to reference the assembly when running the C# compiler. Generally, the referenced assembly is a class library, and creating a class library requires a different assembly target from the default console executable targets you have created thus far.

Changing the Assembly Target

The compiler allows you to create four[1] different assembly types via the `/target` option:

- *Console executable:* This is the default type of assembly, and all compilation thus far has been to a console executable. (Leaving off the `/target` option or specifying `/target:exe` creates a console executable.)

1. The C# compiler also allows `/target:appcontainerexe` and `/target:winmdobj`; these options are for creating special Windows applications not covered in this book.

- *Class library:* Classes that are shared across multiple executables are generally defined in a class library (`/target:library`).
- *Windows executable:* Windows executables are designed to run in the Microsoft Windows family of operating systems and outside the command console (`/target:winexe`).
- *Module:* To facilitate use of multiple languages within the same assembly, code can be compiled to a module and multiple modules can be combined to form an assembly (`/target:module`).

Assemblies to be shared across multiple applications are generally compiled as class libraries. Consider, for example, a library dedicated to functionality around longitude and latitude coordinates. To compile the `Coordinate`, `Longitude`, and `Latitude` classes into their own library, you would use the command line shown in Output 9.4.

Output 9.4

```
>csc /target:library /out:Coordinates.dll Coordinate.cs IAngle.cs
Latitude.cs Longitude.cs Arc.cs
Microsoft (R) Visual C# Compiler version 1.0.0.50128
Copyright (C) Microsoft Corporation. All rights reserved.
```

Assuming you use .NET and the C# compiler is in the path, this command builds an assembly library called `Coordinates.dll`.

Referencing an Assembly

To access code within a different assembly, the C# compiler allows the developer to reference the assembly on the command line. The option in such a case is `/reference` (`/r` is the abbreviation), followed by the list of references. The `Program` class listing in Listing 9.8 uses the `Coordinate` class, for example, and if you place it into a separate executable, you reference `Coordinates.dll` using the .NET command line shown in Output 9.5.

Output 9.5

```
csc.exe /R:Coordinates.dll Program.cs
```

The Mono command line appears in Output 9.6.

Output 9.6

```
msc.exe /R:Coordinates.dll Program.cs
```

ADVANCED TOPIC

Referencing Assemblies on Mac and Linux

At the time of this book's writing, Microsoft had expressed the expectation that the Mac and Linux versions of the command-line C# compiler would behave just like the Windows version as far as referencing assemblies goes. Nevertheless, some open issues remain regarding how references to `mscorlib.dll` (the class library that contains the desktop CLR's fundamental base classes, such as `object` and `string`) would work. Users of the C# command-line compiler may have to specify the complete path to `mscorlib.dll` on these platforms; consult the platform-specific documentation for details.

ADVANCED TOPIC

Portable Class Libraries

An increasingly common scenario for C# developers is to create programs that run as traditional desktop applications, on mobile devices, gaming platforms, and so on. A good technique to achieve this goal is to put the core application classes common to all versions of the application into a portable class library (PCL); a PCL can be used on many .NET platforms. Of course, a PCL must reference only assemblies that are themselves capable of running on multiple platforms.

The easiest way to create a PCL is to select the portable class library project type in Visual Studio 2012 or later. To create a PCL using the command-line compiler is a bit more difficult but still possible. To do so, specify the `/noconfig` and `/nostdlib` options; this ensures that the default framework class libraries will not be used. Then use the `/reference` option to add references to the special portable metadata libraries in the `Reference Assemblies\Microsoft\Framework\.NETPortable\v4.5` subdirectory of your `Program Files` directory.

ADVANCED TOPIC

Encapsulation of Types

Just as classes serve as an encapsulation boundary for behavior and data, so assemblies provide for similar boundaries among groups of types. Developers can break a system into assemblies and then share those assemblies with multiple applications or integrate them with assemblies provided by third parties.

`public` or `internal` Access Modifiers on Type Declarations

By default, a class without any access modifier is defined as `internal`.[2] The result is that the class is inaccessible from outside the assembly. Even though another assembly references the assembly containing the class, all internal classes within the referenced assemblies will be inaccessible.

Just as `private` and `protected` provide levels of encapsulation to members within a class, so C# supports the use of access modifiers at the class level for control over the encapsulation of the classes within an assembly. The access modifiers available are `public` and `internal`. To expose a class outside the assembly, the assembly must be marked as `public`. Therefore, before compiling the `Coordinates.dll` assembly, it is necessary to modify the type declarations as `public` (see Listing 9.12).

LISTING 9.12: Making Types Available outside an Assembly

```
public struct Coordinate
{
  // ...
}
```

```
public struct Latitude
{
  // ...
}
```

```
public struct Longitude
{
  // ...
}
```

2. Excluding nested types, which are `private` by default.

```
public struct Arc
{
  // ...
}
```

Similarly, declarations such as `class` and `enum` can be either `public` or `internal`.[3]

The internal access modifier is not limited to type declarations; that is, it is also available on type members. As a consequence, you can designate a type as `public` but mark specific methods within the type as `internal` so that the members are available only from within the assembly. It is not possible for the members to have a greater accessibility than the type. If the class is declared as `internal`, public members on the type will be accessible only from within the assembly.

The protected internal Type Modifier

Another type member access modifier is `protected internal`. Members with an accessibility modifier of `protected internal` will be accessible from all locations within the containing assembly *and* from classes that derive from the type, even if the derived class is not in the same assembly. The default state is `private`, so when you add an access modifier (other than `public`), the member becomes slightly more visible. Adding two modifiers compounds this effect.

> **NOTE**
>
> Members with an accessibility modifier of `protected internal` will be accessible from all locations within the containing assembly *and* from classes that derive from the type, even if the derived class is not in the same assembly.

3. You can decorate nested classes with any access modifier available to other class members (`private`, for example). However, outside the class scope, the only access modifiers that are available are `public` and `internal`.

BEGINNER TOPIC

Type Member Accessibility Modifiers

The full list of access modifiers appears in Table 9.1.

TABLE 9.1: Accessibility Modifiers

Modifier	Description
`public`	Declares that the member is accessible anywhere the type is accessible. If the class is `internal`, the member will be internally visible. Public members will be accessible from outside the assembly if the containing type is public.
`internal`	The member is accessible from within the assembly only.
`private`	The member is accessible from within the containing type, but inaccessible otherwise.
`protected`	The member is accessible within the containing type and any subtypes derived from it, regardless of assembly.
`protected internal`	The member is accessible from anywhere within the containing assembly *and* from any types derived from the containing type, even if the derived types are within a different assembly.

Defining Namespaces

As mentioned in Chapter 2, all data types are identified by the combination of their namespace and their name. However, in the CLR, there is no such thing as a "namespace." The type's name actually is the fully qualified type name, including the namespace. For the classes you defined earlier, there was no explicit namespace declaration. Classes such as these are automatically declared as members of the default global namespace. It is likely that such classes will experience a name collision, which occurs when you attempt to define two classes with the same name. Once you begin referencing other assemblies from third parties, the likelihood of a name collision increases even further.

More importantly, there are thousands of types in the .NET Framework and multiple orders of magnitude more outside the framework. Finding the right type for a particular problem, therefore, could potentially be a significant battle.

The resolution to both of these problems is to organize all the types, grouping them into logical related categories called namespaces. For example, classes outside the `System` namespace are generally placed into a namespace corresponding with the company, product name, or both. Classes from Addison-Wesley, for example, are placed into an `Awl` or `AddisonWesley` namespace, and classes from Microsoft (not `System` classes) are located in the `Microsoft` namespace. The second level of a namespace should be a stable product name that will not vary between versions. Stability, in fact, is key at all levels. Changing a namespace name is a version-incompatible change that should be avoided. For this reason, avoid using volatile names (organization hierarchy, fleeting brands, and so on) within a namespace name.

Namespaces should be PascalCase, but if your brand uses nontraditional casing, it is acceptable to use the brand casing. (Consistency is key, so if that will be problematic—with Pascal or brand-based casing—favor the use of whichever convention will produce the greater consistency.) You should use the `namespace` keyword to create a namespace and to assign a class to it, as shown in Listing 9.13.

Listing 9.13: Defining a Namespace

```
// Define the namespace AddisonWesley
namespace AddisonWesley
{
  class Program
  {
      // ...
   }
}
// End of AddisonWesley namespace declaration
```

All content between the namespace declaration's curly braces will then belong within the specified namespace. In Listing 9.13, for example, `Program` is placed into the namespace `AddisonWesley`, making its full name `AddisonWesley.Program`.

NOTE

In the CLR there is no such thing as a "namespace." The type's name actually is the fully qualified type name.

Like classes, namespaces support nesting. This provides for a hierarchical organization of classes. All the `System` classes relating to network APIs are in the namespace `System.Net`, for example, and those relating to the Web are in `System.Web`.

There are two ways to nest namespaces. The first approach is to nest them within one another (similar to classes), as demonstrated in Listing 9.14.

LISTING 9.14: Nesting Namespaces within One Another

```
// Define the namespace AddisonWesley
namespace AddisonWesley
{
  // Define the namespace AddisonWesley.Michaelis
  namespace Michaelis
  {
    // Define the namespace
    // AddisonWesley.Michaelis.EssentialCSharp
    namespace EssentialCSharp
    {
      // Declare the class
      // AddisonWesley.Michaelis.EssentialCSharp.Program
      class Program
      {
          // ...
      }
    }
  }
}
// End of AddisonWesley namespace declaration
```

Such a nesting will assign the `Program` class to the `AddisonWesley.Michaelis.EssentialCSharp` namespace.

The second approach is to use the full namespace in a single namespace declaration in which a period separates each identifier, as shown in Listing 9.15.

LISTING 9.15: Nesting Namespaces Using a Period to Separate Each Identifier

```
// Define the namespace AddisonWesley.Michaelis.EssentialCSharp
namespace AddisonWesley.Michaelis.EssentialCSharp
{
  class Program
  {
      // ...
   }
}
// End of AddisonWesley namespace declaration
```

Regardless of whether a namespace declaration follows the pattern shown in Listing 9.14, that in Listing 9.15, or a combination of the two, the resultant CIL code will be identical. The same namespace may occur multiple times, in multiple files, and even across assemblies. For example, with the convention of one-to-one correlation between files and classes, you can define each class in its own file and surround it with the same namespace declaration.

Given that namespaces are key for organizing types, it is frequently helpful to use the namespace for organizing all the class files. For this reason, it is helpful to create a folder for each namespace, placing a class such as `AddisonWesley.Fezzik.Services.Registration` into a folder hierarchy corresponding to the name.

When using Visual Studio projects, if the project name is `AddisonWesley.Fezzik`, you should create one subfolder called `Services` into which `RegistrationService.cs` is placed. You would then create another subfolder—`Data`, for example—into which you place classes relating to entities within the program—`RealestateProperty`, `Buyer`, and `Seller`, for example.

Guidelines

DO prefix namespace names with a company name to prevent namespaces from different companies having the same name.

DO use a stable, version-independent product name at the second level of a namespace name.

DO NOT define types without placing them into a namespace.

CONSIDER creating a folder structure that matches the namespace hierarchy.

Namespace Alias Qualifier

Namespaces on their own deal with the vast majority of naming conflicts that might arise. Nevertheless, sometimes (albeit rarely) conflict can arise because of an overlap in the namespace and class names. To account for this possibility, the C# 2.0 compiler includes an option for providing an alias with the `/reference` option. For example, if the assemblies `CoordinatesPlus.dll` and `Coordinates.dll` have an overlapping type of `Arc`, you can reference both assemblies on the command line by assigning to one or both references a **namespace alias qualifier** that further distinguishes one class from the other (see Output 9.7).

OUTPUT 9.7

```
csc.exe /R:CoordPlus=CoordinatesPlus.dll /R:Coordinates.dll Program.cs
```

However, adding the alias during compilation is not sufficient on its own. To refer to classes in the aliased assembly, it is necessary to provide an `extern` directive that declares that the namespace alias qualifier is provided externally to the source code (see Listing 9.16).

LISTING 9.16: Using the extern Alias Directive

```
// extern must precede all other namespace elements
extern alias CoordPlus;

using System;
using CoordPlus::AddisonWesley.Michaelis.EssentialCSharp
// Equivalent also allowed
// using CoordPlus.AddisonWesley.Michaelis.EssentialCSharp

using global::AddisonWesley.Michaelis.EssentialCSharp
// Equivalent NOT allowed
// using global.AddisonWesley.Michaelis.EssentialCSharp

public class Program
{
  // ...
}
```

Once the `extern` alias for `CoordPlus` appears, you can reference the namespace using `CoordPlus`, followed by either two colons or a period.

To ensure that the lookup for the type occurs in the global namespace, C# 2.0 allows items to have the `global::` qualifier (but not `global.`, because it could imaginably conflict with a real namespace of `global`).

XML Comments

Chapter 1 introduced comments. However, you can use XML comments for more than just notes to other developers reviewing the source code. XML-based comments follow a practice popularized with Java. Although the C# compiler ignores all comments as far as the resultant executable goes, the developer can use command-line options to instruct the compiler[4] to extract the XML comments into a separate XML file. By taking advantage of the XML file generation, the developer can generate documentation of the API from the XML comments. In addition, C# editors can parse the XML comments in the code and display them to developers as distinct regions (for example, as a different color from the rest of the code), or parse the XML comment data elements and display them to the developer.

Figure 9.2 demonstrates how an IDE can take advantage of XML comments to assist the developer with a tip about the code he is trying to write. Such coding tips offer significant assistance in large programs, especially when multiple developers share code. For this to work, however, the developer obviously must take the time to enter the XML comments within the code and then direct the compiler to create the XML file. The next section explains how to accomplish this.

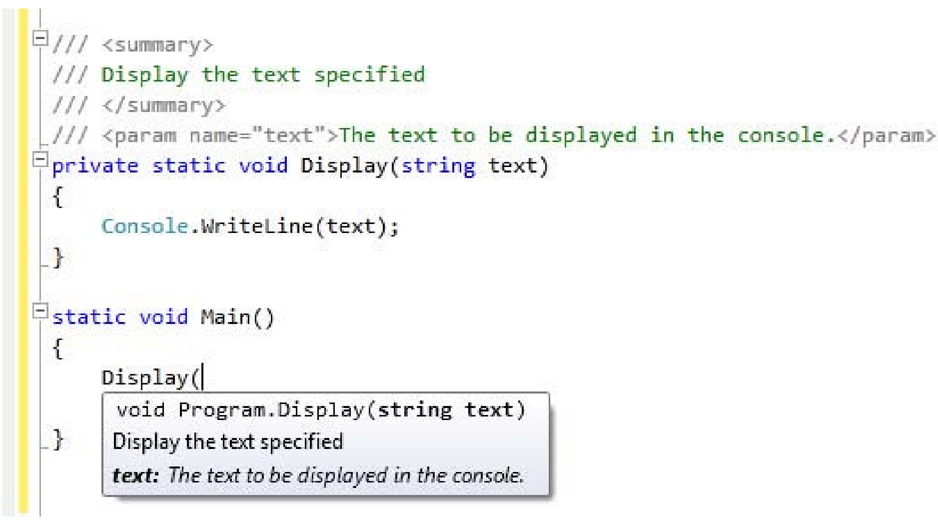


FIGURE 9.2: XML Comments As Tips in Visual Studio IDE

Begin 2.0

Associating XML Comments with Programming Constructs

Consider the listing of the `DataStorage` class, as shown in Listing 9.17.

4. The C# standard does not specify whether the C# compiler or a separate utility should take care of extracting the XML data. However, all mainstream C# compilers include the necessary functionality via a compile switch instead of within an additional utility.

LISTING 9.17: Commenting Code with XML Comments

```
/// <summary>
/// DataStorage is used to persist and retrieve
/// employee data from the files.
/// </summary>
class DataStorage
{
  /// <summary>
  /// Save an employee object to a file
  /// named with the Employee name.
  /// </summary>
  /// <remarks>
  /// This method uses
  /// <seealso cref="System.IO.FileStream"/>
  /// in addition to
  /// <seealso cref="System.IO.StreamWriter"/>
  /// </remarks>
  /// <param name="employee">
  /// The employee to persist to a file</param>
  /// <date>January 1, 2000</date>
  public static void Store(Employee employee)
  {
      // ...
  }

  /**  <summary>
   *  Loads up an employee object
   *  </summary>
   *  <remarks>
   *  This method uses
   *  <seealso cref="System.IO.FileStream"/>
   *  in addition to
   *  <seealso cref="System.IO.StreamReader"/>
   *  </remarks>
   *  <param name="firstName">
   *  The first name of the employee</param>
   *  <param name="lastName">
   *  The last name of the employee</param>
   *  <returns>
   *  The employee object corresponding to the names
   *  </returns>
   *  <date>January 1, 2000</date>**/
  public static Employee Load(
      string firstName, string lastName)
  {
      // ...
  }
}
```

Single-Line XML Comment

XML Delimited Comment (C# 2.0)

2.0

```
class Program
{
  // ...
}
```

Listing 9.17 uses both XML-delimited comments that span multiple lines and single-line XML comments in which each line requires a separate three-forward-slash delimiter (`///`).

Given that XML comments are designed to document the API, they are intended for use only in association with C# declarations, such as the class or method shown in Listing 9.17. Any attempt to place an XML comment inline with the code, unassociated with a declaration, will result in a warning by the compiler. The compiler makes the association simply because the XML comment appears immediately before the declaration.

End 2.0

Although C# allows any XML tag to appear in comments, the C# standard explicitly defines a set of tags to be used. `<seealso cref="System.IO.StreamWriter"/>` is an example of using the `seealso` tag. This tag creates a link between the text and the `System.IO.StreamWriter` class.

Generating an XML Documentation File

The compiler will check that the XML comments are well formed, and will issue a warning if they are not. To generate the XML file, you use the `/doc` option when compiling, as shown in Output 9.8.

Output 9.8

```
>csc /doc:Comments.xml DataStorage.cs
```

The `/doc` option creates an XML file based on the name specified after the colon. Using the `CommentSamples` class listed earlier and the compiler options listed here, the resultant `CommentSamples.XML` file appears as shown in Listing 9.18.

Listing 9.18: `Comments.xml`

```
<?xml version="1.0"?>
<doc>
    <assembly>
        <name>DataStorage</name>
```

```
        </assembly>
        <members>
            <member name="T:DataStorage">
                <summary>
                DataStorage is used to persist and retrieve
                employee data from the files.
                </summary>
            </member>
            <member name="M:DataStorage.Store(Employee)">
                <summary>
                Save an employee object to a file
                named with the Employee name.
                </summary>
                <remarks>
                This method uses
                <seealso cref="T:System.IO.FileStream"/>
                in addition to
                <seealso cref="T:System.IO.StreamWriter"/>
                </remarks>
                <param name="employee">
                The employee to persist to a file</param>
                <date>January 1, 2000</date>
            </member>
            <member name="M:DataStorage.Load(
                     System.String,System.String)">
                <summary>
                Loads up an employee object
                </summary>
                <remarks>
                This method uses
                <seealso cref="T:System.IO.FileStream"/>
                in addition to
                <seealso cref="T:System.IO.StreamReader"/>
                </remarks>
                <param name="firstName">
                The first name of the employee</param>
                <param name="lastName">
                The last name of the employee</param>
                <returns>
                The employee object corresponding to the names
                </returns>
                <date>January 1, 2000</date>*
            </member>
        </members>
    </doc>
```

The resultant file includes only the amount of metadata that is necessary to associate an element back to its corresponding C# declaration. This is important to note, because in general, it is necessary to use the XML output in combination with the generated assembly to produce any meaningful documentation. Fortunately, tools such as the free GhostDoc[5] and the open source project NDoc[6] can generate documentation.

Guidelines

DO provide XML comments on public APIs when they provide more context than the API signature alone. This includes member descriptions, parameter descriptions, and examples of calling the API.

Garbage Collection

Garbage collection is obviously a core function of the runtime. Its purpose is to restore memory consumed by objects that are no longer referenced. The emphasis in this statement is on memory and references: The garbage collector is only responsible for restoring memory; it does not handle other resources such as database connections, handles (files, windows, and so on), network ports, and hardware devices such as serial ports. Also, the garbage collector determines what to clean up based on whether any references remain. Implicitly, this means that the garbage collector works with reference objects and restores memory on the heap only. Additionally, it means that maintaining a reference to an object will delay the garbage collector from reusing the memory consumed by the object.

ADVANCED TOPIC

Garbage Collection in .NET

Many details about the garbage collector pertain to the specific CLI implementation and, therefore, could vary. This section discusses the .NET implementation, because it is the most prevalent.

In .NET, the garbage collector uses a mark-and-compact algorithm. At the beginning of an iteration, it identifies all **root references** to objects. Root references are any references from static variables, CPU registers, and local variables or parameter instances (and f-reachable objects as described later

5. See http://submain.com/ to learn more about GhostDoc.
6. See http://ndoc.sourceforge.net to learn more about NDoc.

in this section). Given this list, the garbage collector is able to walk through the tree identified by each root reference and determine recursively all the objects to which the root references point. In this manner, the garbage collector creates a graph of all reachable objects.

Instead of enumerating all the inaccessible objects, the garbage collector performs garbage collection by compacting all reachable objects next to one another, thereby overwriting any memory consumed by objects that are inaccessible (and therefore qualify as garbage).

Locating and moving all reachable objects requires that the system maintain a consistent state while the garbage collector runs. To achieve this, all managed threads within the process halt during garbage collection. Obviously, this behavior can result in brief pauses in an application, which are generally insignificant unless a particularly large garbage collection cycle is necessary. To reduce the likelihood of a garbage collection cycle occurring at an inopportune time, the `System.GC` object includes a `Collect()` method, which can be called immediately before the critical performing code. This will not prevent the garbage collector from running, but it does reduce the probability that it will run, assuming no intense memory utilization occurs during the critical performance code.

One perhaps surprising aspect of .NET garbage collection behavior is that not all garbage is necessarily cleaned up during an iteration. Studies of object lifetimes reveal that recently created objects are more likely to need garbage collection than long-standing objects. Capitalizing on this behavior, the .NET garbage collector is generational, attempting to clean up short-lived objects more frequently than objects that have already survived a previous garbage collection iteration. Specifically, objects are organized into three generations. Each time an object survives a garbage collection cycle, it is moved to the next generation, until it ends up in generation 2 (counting starts from zero). The garbage collector then runs more frequently for objects in generation 0 than it does for objects in generation 2.

Over time, in spite of the trepidation that .NET stirred during its early beta releases when compared with unmanaged code, .NET's garbage collection has proved extremely efficient. More importantly, the gains realized in development productivity have far outweighed the costs in development for the few cases where managed code is dropped to optimize particular algorithms.

Weak References

All references discussed so far are **strong references** because they maintain an object's accessibility and prevent the garbage collector from cleaning up the memory consumed by the object. The framework also supports the concept of **weak references,** however. Weak references will not prevent garbage collection on an object, but they do maintain a reference so that if the garbage collector does not clean up the object, it can be reused.

Weak references are designed for objects that are expensive to create, yet too expensive to keep around. Consider, for example, a large list of objects loaded from a database and displayed to the user. The loading of this list is potentially expensive, and once the user closes the list, it should be available for garbage collection. However, if the user requests the list multiple times, a second expensive load call will always be required. With weak references, it becomes possible to use code to check whether the list has not yet been cleaned up, and if not, to re-reference the same list. In this way, weak references serve as a memory cache for objects. Objects within the cache are retrieved quickly, but if the garbage collector has recovered the memory of these objects, they will need to be re-created.

Once an object (or collection of objects) is recognized as worthy of potential weak reference consideration, it needs to be assigned to `System.WeakReference` (see Listing 9.19).

LISTING 9.19: Using a Weak Reference

```
// ...

private WeakReference Data;

public FileStream GetData()
{
    FileStream data = (FileStream)Data.Target;
    if (data != null)
    {
        return data;
    }
    else
    {
        // Load data
        // ...

        // Create a weak reference
        // to data for use later.
        Data.Target = data;
    }
```

```
        return data;
    }

    // ...
```

Given the assignment of `WeakReference` (`Data`), you can check for garbage collection by seeing if the weak reference is set to `null`. The key when doing so is to first assign the weak reference to a strong reference (`FileStream data = Data`) to avoid the possibility that between checking for `null` and accessing the data, the garbage collector will run and clean up the weak reference. The strong reference obviously prevents the garbage collector from cleaning up the object, so it must be assigned first (instead of checking `Target` for `null`).

Resource Cleanup

Garbage collection is a key responsibility of the runtime. Nevertheless, it is important to recognize that the garbage collection process centers on the code's memory utilization. It is not about the cleaning up of file handles, database connection strings, ports, or other limited resources.

Finalizers

Finalizers allow developers to write code that will clean up a class's resources. Unlike constructors that are called explicitly using the `new` operator, finalizers cannot be called explicitly from within the code. There is no `new` equivalent such as a `delete` operator. Rather, the garbage collector is responsible for calling a finalizer on an object instance. Therefore, developers cannot determine at compile time exactly when the finalizer will execute. All they know is that the finalizer will run sometime between when an object was last used and when the application shuts down normally. (Finalizers might not execute if the process is terminated abnormally. For instance, events such as the computer being turned off or a forced termination of the process will prevent the finalizer from running.)

> **NOTE**
>
> You cannot determine at compile time exactly when the finalizer will execute.

The finalizer declaration is identical to the destructor syntax of C#'s predecessor—namely, C++. As shown in Listing 9.20, the finalizer declaration is prefixed with a tilde before the name of the class.

LISTING 9.20: Defining a Finalizer

```
using System.IO;

class TemporaryFileStream
{
  public TemporaryFileStream(string fileName)
  {
      File = new FileInfo(fileName);
      Stream = new FileStream(
          File.FullName, FileMode.OpenOrCreate,
          FileAccess.ReadWrite);
  }

  public TemporaryFileStream()
      : this(Path.GetTempFileName()) { }

  // Finalizer
  ~TemporaryFileStream()
  {
      Close();
  }

  public FileStream Stream { get; }
  public FileInfo File { get; }

  public void Close()
  {
      Stream?.Close();
      File?.Delete();
  }
}
```

Finalizers do not allow any parameters to be passed, so they cannot be overloaded. Furthermore, finalizers cannot be called explicitly—that is, only the garbage collector can invoke a finalizer. Access modifiers on finalizers are therefore meaningless, and as such, they are not supported. Finalizers in base classes will be invoked automatically as part of an object finalization call.

NOTE

Finalizers cannot be called explicitly; only the garbage collector can invoke a finalizer.

Because the garbage collector handles all memory management, finalizers are not responsible for de-allocating memory. Rather, they are responsible for freeing up resources such as database connections and file handles—resources that require an explicit activity that the garbage collector doesn't know about.

Finalizers execute on their own thread, making their execution even less deterministic. This indeterminate nature makes an unhandled exception within a finalizer (outside of the debugger) difficult to diagnose because the circumstances that led to the exception are not clear. From the user's perspective, the unhandled exception will be thrown relatively randomly and with little regard for any action the user was performing. For this reason, you should take care to avoid exceptions within finalizers. Instead, you should use defensive programming techniques such as checking for nulls (refer to Listing 9.20).

Deterministic Finalization with the `using` Statement

The problem with finalizers on their own is that they don't support **deterministic finalization** (the ability to know when a finalizer will run). Rather, finalizers serve the important role of being a backup mechanism for cleaning up resources if a developer using a class neglects to call the requisite cleanup code explicitly.

For example, consider the `TemporaryFileStream`, which includes not only a finalizer but also a `Close()` method. This class uses a file resource that could potentially consume a significant amount of disk space. The developer using `TemporaryFileStream` can explicitly call `Close()` to restore the disk space.

Providing a method for deterministic finalization is important because it eliminates a dependency on the indeterminate timing behavior of the finalizer. Even if the developer fails to call `Close()` explicitly, the finalizer will take care of the call. In such a case, the finalizer will run later than if it was called explicitly—but it will be called eventually.

Because of the importance of deterministic finalization, the base class library includes a specific interface for the pattern and C# integrates the pattern into the language. The `IDisposable` interface defines the details of the pattern with a single method called `Dispose()`, which developers call on a resource class to "dispose" of the consumed resources. Listing 9.21 demonstrates the `IDisposable` interface and some code for calling it.

LISTING 9.21: Resource Cleanup with **IDisposable**

```
using System;
using System.IO;

class Program
{
  // ...
  static void Search()
  {
      TemporaryFileStream fileStream =
          new TemporaryFileStream();

      // Use temporary file stream;
      // ...

      fileStream.Dispose();

      // ...
  }
}
```

```
class TemporaryFileStream : IDisposable
{
  public TemporaryFileStream(string fileName)
  {
      File = new FileInfo(fileName);
      Stream = new FileStream(
          File.FullName, FileMode.OpenOrCreate,
          FileAccess.ReadWrite);
  }

  public TemporaryFileStream()
      : this(Path.GetTempFileName()) { }

  ~TemporaryFileStream()
  {
      Dispose(false);
  }

  public FileStream Stream { get; }
  public FileInfo File { get; }

  public void Close()
  {
      Dispose();
  }

  #region IDisposable Members
  public void Dispose()
  {
      Dispose(true);
```

```
        // Turn off calling the finalizer
        System.GC.SuppressFinalize(this);
    }
    #endregion
    public void Dispose(bool disposing)
    {
        // Do not dispose of an owned managed object (one with a
        // finalizer) if called by member finalize,
        // as the owned managed objects finalize method
        // will be (or has been) called by finalization queue
        // processing already
        if (disposing)
        {
            Stream?.Close();
        }
        File?.Delete();
    }
}
```

From `Program.Search()`, there is an explicit call to `Dispose()` after using the `TemporaryFileStream`. `Dispose()` is the method responsible for cleaning up the resources (in this case, a file) that are not related to memory and, therefore, subject to cleanup implicitly by the garbage collector. Nevertheless, the execution here contains a hole that would prevent execution of `Dispose()`—namely, the chance that an exception will occur between the time when `TemporaryFileStream` is instantiated and the time when `Dispose()` is called. If this happens, `Dispose()` will not be invoked and the resource cleanup will have to rely on the finalizer. To avoid this problem, callers need to implement a try/finally block. Instead of requiring programmers to code such a block explicitly, C# provides a `using` statement expressly for the purpose (Listing 9.22).

LISTING 9.22: Invoking the `using` Statement

```
class Program
{
  // ...

  static void Search()
  {
      using (TemporaryFileStream fileStream1 =
          new TemporaryFileStream(),
          fileStream2 = new TemporaryFileStream())
      {
          // Use temporary file stream;
      }
  }
}
```

The resultant CIL code is identical to the code that would be created if the programmer specified an explicit try/finally block, where `fileStream.Dispose()` is called in the finally block. The `using` statement, however, provides a syntax shortcut for the try/finally block.

Within a `using` statement, you can instantiate more than one variable by separating each variable from the others with a comma. The key considerations are that all variables must be of the same type and that they implement `IDisposable`. To enforce the use of the same type, the data type is specified only once rather than before each variable declaration.

Garbage Collection, Finalization, and `IDisposable`

There are several additional noteworthy items to point out in Listing 9.21. First, the `IDisposable.Dispose()` method contains an important call to `System.GC.SuppressFinalize()`. Its purpose is to remove the `TemporaryFileStream` class instance from the **finalization (f-reachable) queue.** This is possible because all cleanup was done in the `Dispose()` method rather than waiting for the finalizer to execute.

Without the call to `SuppressFinalize()`, the instance of the object will be included in the f-reachable queue—a list of all the objects that are mostly ready for garbage collection except they also have finalization implementations. The runtime cannot garbage-collect objects with finalizers until after their finalization methods have been called. However, garbage collection itself does not call the finalization method. Rather, references to finalization objects are added to the f-reachable queue, and are processed by an additional thread at a time deemed appropriate based on the execution context. In an ironic twist, this approach delays garbage collection for the managed resources—when it is most likely that these very resources should likely be cleaned up earlier. The reason for the delay is that the f-reachable queue is a list of "references"; as such, the objects are not considered garbage until after their finalization methods are called and the object references are removed from the f-reachable queue.

NOTE

Objects with finalizers that are not explicitly disposed will end up with an extended object lifetime. Even after all explicit references have gone out of scope, the f-reachable queue will have references, keeping the object alive until the f-reachable queue processing is complete.

It is for this reason that `Dispose()` invokes `System.GC.SuppressFinalize`. Invoking this method informs the runtime not to add this object to the finalization queue, but instead to allow the garbage collector to de-allocate the object when it no longer has any references (including any f-reachable references).

Second, `Dispose()` calls `Dispose(bool disposing)` with an argument of `true`. The result is that the `Dispose()` method on `Stream` is invoked (cleaning up its resources and suppressing its finalization). Next, the temporary file itself is deleted immediately upon calling `Dispose()`. This important call eliminates the need to wait for the finalization queue to be processed before cleaning up potentially expensive resources.

Third, rather than calling `Close()`, the finalizer now calls `Dispose (bool disposing)` with an argument of `false`. The result is that `Stream` is not closed (disposed) even though the file is deleted. The condition around closing `Stream` ensures that if `Dispose(bool disposing)` is called from the finalizer, the `Stream` instance itself will also be queued up for finalization processing (or possibly it would have already run depending on the order). Therefore, when executing the finalizer, objects owned by the managed resource should not be cleaned up, as this action will be the responsibility of the finalization queue.

Fourth, you should use caution when creating both a `Close()` type and a `Dispose()` method. It is not clear by looking at only the API that `Close()` calls `Dispose()`, so developers will be left wondering whether they need to explicitly call `Close()` and `Dispose()`.

Language Contrast: C++—Deterministic Destruction

Although finalizers are similar to destructors in C++, the fact that their execution cannot be determined at compile time makes them distinctly different. The garbage collector calls C# finalizers sometime after they were last used, but before the program shuts down; C++ destructors are automatically called when the object (not a pointer) goes out of scope.

Although running the garbage collector can be a relatively expensive process, the fact that garbage collection is intelligent enough to delay running until process utilization is somewhat reduced offers an advantage over deterministic destructors, which will run at compile-time–defined locations, even when a processor is in high demand.

Guidelines

DO implement a finalizer method only on objects with resources that are scarce or expensive, even though finalization delays garbage collection.

DO implement `IDisposable` to support deterministic finalization on classes with finalizers.

DO implement a finalizer method on classes that implement `IDisposable` in case `Dispose()` is not invoked explicitly.

DO refactor a finalization method to call the same code as `IDisposable`, perhaps simply calling the `Dispose()` method.

DO NOT throw exceptions from finalizer methods.

DO call `System.GC.SuppressFinalize()` from `Dispose()` to avoid repeating resource cleanup and delaying garbage collection on an object.

DO ensure that `Dispose()` is idempotent (it should be possible to call `Dispose()` multiple times).

DO keep `Dispose()` simple, focusing on resource cleanup required by finalization.

AVOID calling `Dispose ()` on owned objects that have a finalizer. Instead, rely on the finalization queue to clean up the instance.

AVOID referencing other objects that are not being finalized during finalization.

DO invoke a base class's `Dispose()` method when overriding `Dispose()`.

CONSIDER ensuring that an object becomes unusable after `Dispose()` is called. After an object has been disposed, methods other than `Dispose()` (which could potentially be called multiple times) should throw an `ObjectDisposedException`.

DO implement `IDisposable` on types that own disposable fields (or properties) and dispose of said instances.

ADVANCED TOPIC

Exception Propagating from Constructors

Even when an exception propagates out of a constructor, the object is still instantiated, although no new instance is returned by the new operator. If the type defines a finalizer, the method will run when the object becomes eligible for garbage collection (providing additional motivation to ensure the finalize method can run on partially constructed objects). Also note that if a constructor prematurely shares its `this` reference, it will still be accessible even if the constructor throws an exception. Do not allow this scenario to occur.

ADVANCED TOPIC

Resurrecting Objects

By the time an object's finalization method is called, all references to the object have disappeared and the only step before garbage collection is running the finalization code. Even so, it is possible to add a reference inadvertently for a finalization object back into the root reference's graph. In such a case, the re-referenced object will no longer be inaccessible; in turn, it will not be ready for garbage collection. However, if the finalization method for the object has already run, it will not necessarily run again unless it is explicitly marked for finalization (using the `GC.ReRegisterFinalize()` method).

Obviously, resurrecting objects in this manner is peculiar behavior, and you should generally avoid it. Finalization code should be simple and should focus on cleaning up only the resources that it references.

Lazy Initialization

In this preceding section, we discussed how to deterministically dispose of an object with a `using` statement and how the finalization queue will dispose of resources in the event that no deterministic approach is used.

A related pattern is called **lazy initialization** or **lazy loading.** Using lazy initialization, you can create (or obtain) objects when you need them rather than beforehand—the latter can be an especially problematic situation when those objects are never used. Consider the `FileStream` property of Listing 9.23.

LISTING 9.23: Lazy Loading a Property

```
using System.IO;

class DataCache
{
  // ...

        public TemporaryFileStream FileStream =>
            InternalFileStream??(InternalFileStream =
                new TemporaryFileStream());

        private TemporaryFileStream InternalFileStream
            { get; set; } = null;
  // ...
}
```

In the FileStream expression-bodied property, we check whether InternalFileStream is not null before returning its value directly. If InternalFileStream is null, we first instantiate the TemporaryFileStream object and assign it to InternalFileStream before returning the new instance. Thus, the TemporaryFileStream required in the FileStream property is created only when the getter on the property is called. If the getter is never invoked, the TemporaryFileStream object would not be instantiated and we would save whatever execution time such an instantiation would cost. Obviously, if the instantiation is negligible or inevitable (and postponing the inevitable is less desirable), simply assigning it during declaration or in the constructor makes sense.

Begin 4.0

ADVANCED TOPIC

Lazy Loading with Generics and Lambda Expressions

Starting with .NET Framework 4.0, a new class was added to the CLR to assist with lazy initialization: System.Lazy<T>. Listing 9.24 demonstrates how to use it.

LISTING 9.24: Lazy Loading a Property with System.Lazy<T>

```
using System.IO;

class DataCache
{
  // ...

 public TemporaryFileStream FileStream =>
     InternalFileStream.Value;
 private Lazy<TemporaryFileStream> InternalFileStream { get; }
     = new Lazy<TemporaryFileStream>(
         () => new TemporaryFileStream() );

  // ...
}
```

The System.Lazy<T> class takes a type parameter (T) that identifies which type the Value property on System.Lazy<T> will return. Instead of assigning a fully constructed TemporaryFileStream to the _FileStream field, an instance of Lazy<TemporaryFileStream> is assigned (a lightweight call), delaying the instantiation of the TemporaryFileStream itself, until the Value property (and therefore the FileStream property) is accessed.

If in addition to type parameters (generics) you use delegates, you can even provide a function for how to initialize an object when the `Value` property is accessed. Listing 9.24 demonstrates passing the delegate—a lambda expression in this case—into the constructor for `System.Lazy<T>`.

Note that the lambda expression itself, `() => new TemporaryFileStream (FileStreamName)`, does not execute until `Value` is called. Rather, the lambda expression provides a means of passing the instructions for what will happen; it does not actually execute those instructions until explicitly requested to do so.

One obvious question is when you should use the `System.Lazy<T>` rather than the approach outlined in Listing 9.23. The difference is negligible: In fact, Listing 9.23 may actually be simpler. That is, it is simpler until there are multiple threads involved, such that a race condition might occur regarding the instantiation. In Listing 9.23, more than one check for null might potentially occur before instantiation, resulting in multiple instances being created. In contrast, `System.Lazy<T>` provides a thread-safe mechanism ensuring that one and only one object will be created.

End 4.0

SUMMARY

This chapter provided a whirlwind tour of many topics related to building solid class libraries. All the topics pertain to internal development as well, but they are much more critical to building robust classes. Ultimately, the focus here was on forming more robust and programmable APIs. In the category of robustness, we can include namespaces and garbage collection. Both of these topics fit in the programmability category as well, along with overriding `object`'s virtual members, operator overloading, and XML comments for documentation.

Exception handling uses inheritance heavily by defining an exception hierarchy and enforcing custom exceptions to fit within this hierarchy. Furthermore, the C# compiler uses inheritance to verify catch block order. In the next chapter, you will see why inheritance is such a core part of exception handling.

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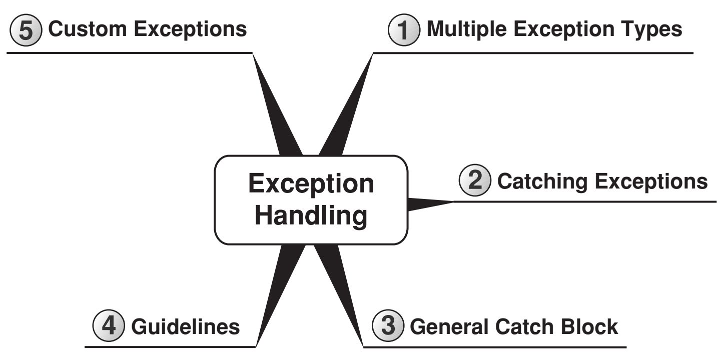
10

Exception Handling

CHAPTER 4 DISCUSSED USING THE try/catch/finally blocks for standard exception handling. In that chapter, the catch block always caught exceptions of type `System.Exception`. This chapter defines some additional details of exception handling—specifically, details surrounding additional exception types, defining custom exceptions, and multiple catch blocks for handling each type. This chapter also details exceptions because of their reliance on inheritance.



Multiple Exception Types

Listing 10.1 throws a `System.ArgumentException`, not the `System.Exception` type demonstrated in Chapter 4. C# allows code to throw any type that derives (perhaps indirectly) from `System.Exception`.

To throw an exception, you simply prefix the exception instance with the keyword `throw`. The type of exception used is obviously the type that best describes the circumstances surrounding the error that caused the exception.

For example, consider the `TextNumberParser.Parse()` method in Listing 10.1.

Begin 6.0

LISTING 10.1: Throwing an Exception

```
public sealed class TextNumberParser
{
  public static int Parse(string textDigit)
  {
      string[] digitTexts =
          { "zero", "one", "two", "three", "four",
              "five", "six", "seven", "eight", "nine" };

      int result = Array.IndexOf(
          digitTexts, textDigit.ToLower());

      if (result < 0)
      {
          // Leveraging C# 6.0's nameof operator.
          throw new ArgumentException(
              "The argument did not represent a digit",
              nameof(textDigit));
      }

      return result;
  }
}
```

Instead of throwing `System.Exception`, it is more appropriate to throw `ArgumentException` because the type itself indicates what went wrong and includes special parameters for identifying which parameter was at fault.

Two similar exceptions are `ArgumentNullException` and `NullReferenceException`. `ArgumentNullException` should be thrown for the inappropriate passing of null arguments. This is a special case of an invalid parameter exception that would more generally (when it isn't null) be thrown as an `ArgumentException` or an `ArgumentOutOfRangeException`. `NullReferenceException` is generally an exception that the underlying runtime will throw only with an attempt to dereference a null value—that is, an attempt to call a member on an object whose value is null. Instead of triggering a `NullReferenceException` to be thrown, programmers should check parameters for `null` before accessing them and then throw an

ArgumentNullException, which can provide more contextual information, such as the parameter name. If there is an innocuous way to proceed even if an argument is null, be sure to use the C# 6.0 null propagation operator to avoid the runtime throwing a NullReferenceException.

One important characteristic of the argument exception types (including ArgumentNullException, ArgumentNullException, and ArgumentOutOfRangeException) is that each has a constructor parameter that allows identification of the argument name as a string. Prior to C# 6.0 this meant hardcoding a magic string ("textDigit", for example) to identify the parameter name. The problem with this approach is that if the parameter name ever changed, developers had to remember to update the magic string. Fortunately, C# 6.0 provides a new operator, nameof, that takes the parameter name identifier and generates the parameter name at compile time (see nameof(textDigit) in Listing 10.1). The advantage of this approach is that now the IDE can use refactoring tools (such as automatic renaming) to change the identifier everywhere, including when it is used as an argument to the nameof operator. Additionally, if the parameter name changes (without the use of a refactoring tool), the compiler will generate an error if the identifier passed to the nameof operator no longer exists. Moving forward, with C# 6.0 (or later), the general guideline is to always use the nameof operator for the parameter name of an argument type exception.

Several other exceptions are intended only for the runtime and derive (sometimes indirectly) from System.SystemException. They include System.StackOverflowException, System.OutOfMemoryException, System.Runtime.InteropServices.COMException, System.ExecutionEngineException, and System.Runtime.InteropServices.SEHException. Do not throw exceptions of these types. Similarly, you should avoid throwing a System.Exception or System.ApplicationException, as these exceptions are so general that they provide little indication of the cause of or resolution to the problem. Instead, throw the most derived exception that fits the scenario. Obviously, developers should avoid creating APIs that could potentially result in a system failure. However, if the executing code reaches a certain state such that continuing to execute is unsafe or unrecoverable, it should call System.Environment.FailFast(). This will immediately terminate the process after writing a message to the Windows Application event log, and will even include the message as part of Windows Error Reporting if the user so chooses.

Guidelines

DO throw `ArgumentException` or one of its subtypes if bad arguments are passed to a member. Prefer the most derived exception type (`ArgumentNullException`, for example), if applicable.

DO set the `ParamName` property when throwing an `ArgumentException` or one of the subclasses.

DO use `nameof` for the `paramName` argument passed into argument exception types like `ArgumentException`, `ArgumentOutOfRangeException`, and `ArgumentNullException` that take such a parameter.

DO throw the most specific (most derived) exception that makes sense.

DO NOT throw a `NullReferenceException`. Instead, throw `ArgumentNullException` when a value is unexpectedly null.

DO NOT throw a `System.SystemException` or an exception type that derives from it.

DO NOT throw a `System.Exception` or `System.ApplicationException`.

CONSIDER terminating the process by calling `System.Environment.FailFast()` if the program encounters a scenario where it is unsafe for further execution.

End 6.0

Catching Exceptions

Throwing a particular exception type enables the catcher to use the exception's type itself to identify the problem. It is not necessary, in other words, to catch the exception and use a `switch` statement on the exception message to determine which action to take in light of the exception. Instead, C# allows for multiple catch blocks, each targeting a specific exception type, as Listing 10.2 shows.

Listing 10.2: Catching Different Exception Types

```
using System;

public sealed class Program
{
  public static void Main(string[] args)
  {
      try
      {
              // ...
              throw new InvalidOperationException(
```

```
                "Arbitrary exception");
            // ...
        }
        catch(Win32Exception exception)
            when(exception.ErrorCode == 42)
        {
            // Handle Win32Exception where
            // ErrorCode is 42.
        }
        catch (NullReferenceException exception)
        {
            // Handle NullReferenceException
        }
        catch (ArgumentException exception)
        {
            // Handle ArgumentException
        }
        catch (InvalidOperationException exception)
        {
           bool exceptionHandled=false;
            // Handle InvalidOperationException
           // ...
            if(!exceptionHandled)
            {
                 throw;
            }
         }
        catch (SystemException)
        {
            // Handle SystemException
        }
        catch (Exception exception)
        {
            // Handle Exception
        }
        finally
        {
            // Handle any cleanup code here as it runs
            // regardless of whether there is an exception
        }
    }
}
```

Listing 10.2 includes five catch blocks, each handling a different type of exception. When an exception occurs, the execution will jump to the catch block with the exception type that most closely matches the exception. The closeness of a match is determined by the inheritance chain. For example, even though the exception thrown is of type `System.Exception`, this “is a” relationship occurs through inheritance because `System.InvalidOperationException` ultimately derives from `System.Exception`. Since `InvalidOperationException` most closely matches the exception thrown, `catch(InvalidOperationException...)` will catch the exception instead of the `catch(Exception...)` block.

Starting with C# 6.0, an additional conditional expression is available for catch blocks. Rather than limiting whether a catch block matches based only on an exception type match, C# 6.0 adds support for a conditional clause. The `when` clause allows you to supply a Boolean expression; the catch block handles the exception only if the condition is true. In Listing 10.2, this is an equality comparison operator. Nevertheless, you could, for example, make a method call to validate a condition.

Of course, you could also simply place the conditional check as an `if` block within the catch body. However, doing so causes the catch block to become the handler for the exception before the condition is checked. It is difficult to write code that allows a different catch block to handle the exception in the scenario where the condition is not met. However, with the **exception condition,** it is now possible to examine the program state (including the exception) without having to catch and rethrow the exception.

Use conditional clauses with caution; if the conditional expression itself throws an exception, then that new exception is ignored and the condition is treated as false. For this reason, you should avoid throwing exceptions for the exception conditional expression.

Catch blocks must appear in order, from most specific to most general, to avoid a compile-time error. For example, moving the `catch(Exception...)` block before any of the other exceptions will result in a compile error, since all prior exceptions derive from `System.Exception` at some point in their inheritance chain.

As shown with the catch `(SystemException){ })` block, a named parameter for the catch block is not required. In fact, a final catch without even the type parameter is allowable, as you will see in the next section.

Rethrowing an Existing Exception

In the `InvalidOperationException` catch block, a throw statement appears without any identification of the exception to throw (`throw` is on its own), even though an exception instance (`exception`) appears in the catch block scope that could be rethrown. Throwing a specific exception would update all the stack information to match the new throw location. As a result, all the stack information indicating the call site where the exception originally occurred would be lost, making it significantly more difficult to diagnose the problem. For this reason, C# supports a throw statement without the explicit exception reference as long as it occurs within a catch block. This way, code can examine the exception to determine if it is possible to fully handle it, and if not, rethrow the exception (even though not specified explicitly) as though it was never caught and without replacing any stack information.

ADVANCED TOPIC

Begin 5.0

Throwing Existing Exceptions without Replacing Stack Information

In C# 5.0, a mechanism was added that enables the throwing of a previously thrown exception without losing the stack trace information in the original exception. This allows you to rethrow exceptions, for example, even from outside a catch block and, therefore, without using `throw;`. Although it is fairly rare to need to do this, on some occasions exceptions are wrapped or saved until the program execution moves outside the catch block. For example, multithreaded code might wrap an exception with an `AggregateException`. The .NET Framework 4.5 provides a `System.Runtime.ExceptionServices.ExceptionDispatchInfo` class specifically to handle this scenario through the use of its static `Catch()` and instance `Throw()` methods. Listing 10.3 demonstrates rethrowing the exception without resetting the stack trace information or using an empty throw statement.

LISTING 10.3: Using ExceptionDispatchInfo to Rethrow an Exception

```
using System
using System.Runtime.ExceptionServices;
using System.Threading.Tasks;
Task task = WriteWebRequestSizeAsync(url);
try
{
  while (!task.Wait(100))
  {
      Console.Write(".");
  }
}
catch(AggregateException exception)
{
```

```
    exception = exception.Flatten();
    ExceptionDispatchInfo.Capture(
        exception.InnerException).Throw();
}
```

With the ExeptionDispatchInfo.Throw() method, the compiler doesn't treat it as a return statement in the same way that it might a normal throw statement. For example, if the method signature returned a value but no value was returned from the code path with ExceptionDispatchInfo.Throw(), the compiler would issue an error indicating no value was returned. On occasion, therefore, developers may be forced to follow ExceptionDispatchInfo.Throw() with a return statement even though such a statement would never execute at runtime—the exception would be thrown instead.

End 5.0

Language Contrast: Java—Exception Specifiers

C# has no equivalent to Java's exception specifiers. With exception specifiers, the Java compiler is able to verify that all possible exceptions thrown within a function (or a function's call hierarchy) are either caught or declared as possibly rethrown. The C# team considered this option and concluded that the maintenance burden that it imposed was not worth the perceived benefit. Therefore, it is not necessary to maintain a list of all possible exceptions throughout a particular call stack, but neither is it feasible to easily determine the possible exceptions. (As it turns out, this wasn't possible for Java, either. Calling virtual methods or using late binding, such as reflection, made it impossible to fully resolve at compile time which exceptions a method could possibly throw.)

Begin 2.0

General Catch Block

C# requires that any object that code throws must derive from System.Exception. However, this requirement is not universal to all languages. C/C++, for example, allows any object type to be thrown, including managed exceptions that don't derive from System.Exception. Starting with C# 2.0, all exceptions, whether deriving from `System.Exception` or not, will propagate into C# assemblies as derived from `System.Exception`. The result is that `System.Exception` catch blocks will catch all exceptions not caught by earlier blocks.

C# also supports a **general catch block** (`catch{ }`) that behaves identically to the `catch(System.Exception exception)` block except that there is no type or variable name. Also, the general catch block must appear last within the list of catch blocks. Since the general catch block is identical to the `catch(System.Exception exception)` block and the general catch block must appear last, the compiler issues a warning if both exist within the same try/catch statement because the general catch block will never be invoked (see the Advanced Topic, "General Catch Blocks in C# 1.0," for more information on general catch blocks).

ADVANCED TOPIC

General Catch Blocks in C# 1.0

In C# 1.0, if a non–`System.Exception`-derived exception was thrown from a method call (residing in an assembly not written in C#), the exception would not be caught by a `catch(System.Exception)` block. If a different language throws a `string`, for example, the exception could go unhandled. To avoid this, C# includes a catch block that takes no parameters. The term for such a catch block is general catch block, and Listing 10.4 includes one.

LISTING 10.4: Catching Any Exception

```
using System

public sealed class Program
{
  public static void Main()
  {
      try
      {
              // ...
              throw new InvalidOperationException (
                  "Arbitrary exception");
              // ...
      }
      catch (NullReferenceException exception)
      {
          // Handle NullReferenceException
```

2.0

```
        }
        catch (ArgumentException exception)
        {
            // Handle ArgumentException
        }
        catch (InvalidOperationException exception)
        {
            // Handle ApplicationException
         }
        catch (SystemException exception)
        {
            // Handle SystemException
        }
        catch (Exception exception)
        {
            // Handle Exception
        }
        catch
        {
            // Any unhandled exception
        }
        finally
        {
            // Handle any cleanup code here as it runs
            // regardless of whether there is an exception
        }
    }
  }
```

The general catch block will catch all exceptions, regardless of whether they derive from `System.Exception`, assuming an earlier catch block does not catch them. The disadvantage of such a block is simply that there is no exception instance to access, and therefore no way to know the appropriate course of action. It wouldn't even be possible to recognize the unlikely case where such an exception is innocuous. The best course of action is to handle the exception with some cleanup code before shutting down the application. The catch block could save any volatile data, for example, before shutting down the application or rethrowing the exception.

End 2.0

ADVANCED TOPIC

Empty Catch Block Internals

The CIL code corresponding to an empty catch block is, in fact, a `catch(object)` block. Thus, regardless of the type thrown, the empty catch block will catch it. Interestingly, it is not possible to explicitly declare a `catch(object)` exception block within C# code. Therefore, there is no means of catching a non–`System.Exception`-derived exception and having an exception instance to scrutinize.

In fact, unmanaged exceptions from languages such as C++ generally result in `System.Runtime.InteropServices.SEHException`-type exceptions, which derive from the `System.Exception` type. Therefore, not only can the unmanaged type exceptions be caught using a general catch block, but the non–`System.Exception`-managed types that are thrown can be caught as well—for instance, types such as `string`.

Guidelines for Exception Handling

Exception handling provides much-needed structure to the error-handling mechanisms that preceded it. However, it can still lead to some unwieldy results if used haphazardly. The following guidelines offer some best practices for exception handling.

- *Catch only the exceptions that you can handle.*

  Generally it is possible to handle some types of exceptions but not others. For example, opening a file for exclusive read-write access may throw a `System.IO.IOException` because the file is already in use. In catching this type of exception, the code can report to the user that the file is in use and allow the user the option of canceling the operation or retrying it. Only exceptions for which there is a known action should be caught. Other exception types should be left for callers higher in the stack.

- *Don't hide (bury) exceptions you don't fully handle.*

  New programmers are often tempted to catch all exceptions and then continue executing instead of reporting an unhandled exception to the user. However, this practice may result in a critical system problem going undetected. Unless code takes explicit action to handle an exception or explicitly determines certain exceptions to be innocuous, catch blocks should rethrow exceptions instead of catching them and hiding them from the caller. In most cases, `catch(System.Exception)` and general catch blocks should occur higher in the call stack, unless the block ends by rethrowing the exception.

Begin 4.0

- *Use* `System.Exception` *and general catch blocks rarely.*
  Almost all exceptions derive from `System.Exception`. However, the best way to handle some `System.Exceptions` is to allow them to go unhandled or to gracefully shut down the application sooner rather than later. These exceptions include things such as `System.OutOfMemoryException` and `System.StackOverflowException`. In CLR 4, such exceptions defaulted to nonrecoverable, such that catching them without rethrowing them would cause the CLR to rethrow them anyway. These exceptions are runtime exceptions that the developer cannot write code to recover from. Therefore, the best course of action is to shut down the application—something the runtime will force in CLR 4 and later. Code prior to CLR 4 should catch such exceptions only to run cleanup or emergency code (such as saving any volatile data) before shutting down the application or rethrowing the exception with `throw;`.

End 4.0

- *Avoid exception reporting or logging lower in the call stack.*
  Often, programmers are tempted to log exceptions or report exceptions to the user at the soonest possible location in the call stack. However, these locations are seldom able to handle the exception fully; instead, they resort to rethrowing the exception. Such catch blocks should not log the exception or report it to a user while in the bowels of the call stack. If the exception is logged and rethrown, the callers higher in the call stack may do the same, resulting in duplicate log entries of the exception. Worse, displaying the exception to the user may not be appropriate for the type of application. (Using `System.Console.WriteLine()` in a Windows application will never be seen by the user, for example, and displaying a dialog in an unattended command-line process may go unnoticed and freeze the application.) Logging- and exception-related user interfaces should be reserved for use higher up in the call stack.
- *Use* `throw;` *rather than* `throw <exception object>` *inside a catch block.*
  It is possible to rethrow an exception inside a catch block. For example, the implementation of `catch(ArgumentNullException exception)` could include a call to `throw exception`. However, rethrowing the exception like this will reset the stack trace to the location of the rethrown call, instead of reusing the original throw point location. Therefore, unless you are rethrowing with a different

exception type or intentionally hiding the original call stack, use `throw;` to allow the same exception to propagate up the call stack.

- *Avoid throwing exceptions from exception conditionals.*
  When providing an exception conditional, avoid code that throws an exception. Doing so will result in a false condition and the exception occurrence will be ignored. For this reason, consider placing complicated conditional checks into a separate method that is wrapped in a try/catch block that handles the exception explicitly.
- *Avoid exception conditionals that might change over time.*
  If an exception conditional evaluates conditions such as exception messages that could potentially change with localization or changed message, the expected exception condition will not get caught, unexpectedly changing the business logic. For this reason, ensure exception conditions are valid over time.
- *Use caution when rethrowing different exceptions.*
  From inside a catch block, rethrowing a different exception will not only reset the throw point, but also hide the original exception. To preserve the original exception, set the new exception's `InnerException` property, generally assignable via the constructor. Rethrowing a different exception should be reserved for the following situations:
  1. Changing the exception type clarifies the problem.
     For example, in a call to `Logon(User user)`, rethrowing a different exception type is perhaps more appropriate than propagating `System.IO.IOException` when the file with the user list is inaccessible.
  2. Private data is part of the original exception.
     In the preceding scenario, if the file path is included in the original `System.IO.IOException`, thereby exposing private security information about the system, the exception should be wrapped. This assumes, of course, that `InnerException` is not set with the original exception. (Funnily enough, a very early version of CLR v1 [pre-alpha, even] had an exception that said something like "Security exception: You do not have permission to determine the path of `c:\temp\foo.txt`".)
  3. The exception type is too specific for the caller to handle appropriately.

Begin 6.0

End 6.0

For example, instead of throwing an exception specific to a particular database system, a more generic exception is used so that database-specific code higher in the call stack can be avoided.

Guidelines

AVOID exception reporting or logging lower in the call stack.

DO NOT over-catch. Exceptions should be allowed to propagate up the call stack unless it is clearly understood how to programmatically address those errors lower in the stack.

CONSIDER catching a specific exception when you understand why it was thrown in a given context and can respond to the failure programmatically.

AVOID catching `System.Exception` or `System.SystemException` except in top-level exception handlers that perform final cleanup operations before rethrowing the exception.

DO use `throw` rather than `throw <exception object>` inside a catch block.

DO use caution when rethrowing different exceptions.

DO NOT throw a `NullRefernceException`, favoring `ArgumentNullException` instead when a value is unexpectedly null.

AVOID throwing exceptions from exception conditionals.

AVOID exception conditionals that might change over time.

Defining Custom Exceptions

Once throwing an exception becomes the best course of action, it is preferable to use framework exceptions because they are well established and understood. Instead of throwing a custom invalid argument exception, for example, it is preferable to use the `System.ArgumentException` type. However, if the developers using a particular API will take special action—the exception-handling logic will vary to handle a custom exception type, for instance—it is appropriate to define a custom exception. For example, if a mapping API receives an address for which the ZIP code is invalid, instead of throwing `System.ArgumentException`, it may be better to throw a custom `InvalidAddressException`. The key is whether the caller is likely to write a specific `InvalidAddressException` catch block with special handling rather than just a generic `System.ArgumentException` catch block.

Defining a custom exception simply involves deriving from `System.Exception` or some other exception type. Listing 10.5 provides an example.

Listing 10.5: Creating a Custom Exception

```
class DatabaseException : System.Exception
{
  public DatabaseException(
      System.Data.SqlClient.SQLException exception)
  {
      InnerException = exception;
      // ...
  }

  public DatabaseException(
      System.Data.OracleClient.OracleException exception)
  {
      InnerException = exception;
      // ...
  }

  public DatabaseException()
  {
      // ...
  }

  public DatabaseException(string message)
  {
      // ...
  }

  public DatabaseException(
      string message, Exception innerException)
  {
      InnerException = innerException;
      // ...
  }
}
```

This custom exception might be created to wrap proprietary database exceptions. Since Oracle and SQL Server (for example) throw different exceptions for similar errors, an application could define a custom exception that standardizes the database-specific exceptions into a common exception wrapper that the application can handle in a standard manner. That way, whether the application was using an Oracle or a SQL Server back-end database, the same catch block could be used to handle the error higher up the stack.

The only requirement for a custom exception is that it derives from `System.Exception` or one of its descendants. However, there are several more good practices for custom exceptions:

- All exceptions should use the "Exception" suffix. This way, their purpose is easily established from their name.
- Generally, all exceptions should include constructors that take no parameters, a string parameter, and a parameter set consisting of a string and an inner exception. Furthermore, since exceptions are usually constructed within the same statement in which they are thrown, any additional exception data should also be allowed as part of the constructor. (The obvious exception to creating all these constructors is if certain data is required and a constructor circumvents the requirements.)
- The inheritance chain should be kept relatively shallow (with fewer than approximately five levels).

The inner exception serves an important purpose when rethrowing an exception that is different from the one that was caught. For example, if a `System.Data.SqlClient.SqlException` is thrown by a database call but is caught within the data access layer to be rethrown as a `DatabaseException`, the `DatabaseException` constructor that takes the `SqlException` (or inner exception) will save the original `SqlException` in the `InnerException` property. That way, when requiring additional details about the original exception, developers can retrieve the exception from the `InnerException` property (for example, `exception.InnerException`).

Guidelines

DO NOT create a new exception type if the exception would not be handled differently than an existing CLR exception. Throw the existing framework exception instead.

DO create a new exception type to communicate a unique program error that cannot be communicated using an existing CLR exception and can be programmatically handled in a different way than any other existing CLR exception type.

DO provide a parameterless constructor on all custom exception types. Also provide constructors that take a message and an inner exception.

DO end exception class names with the "Exception" suffix.

DO make exceptions runtime-serializable.

CONSIDER providing exception properties for programmatic access to extra information relevant to the exception.

AVOID deep exception hierarchies.

ADVANCED TOPIC

Serializable Exceptions

Serializable objects are objects that the runtime can persist into a stream—a file stream, for example—and then be reinstantiated out of the stream. In the case of exceptions, this behavior may be necessary for certain distributed communication technologies. To support serialization, exception declarations should either include the `System.SerializableAttribute` attribute or implement `ISerializable`. Furthermore, they must include a constructor that takes `System.Runtime.Serialization.SerializationInfo` and `System.Runtime.Serialization.StreamingContext`. Listing 10.6 shows an example of using `System.SerializableAttribute`.

LISTING 10.6: Defining a Serializable Exception

```
// Supporting serialization via an attribute
[Serializable]
class DatabaseException : System.Exception
{
  // ...

  // Used for deserialization of exceptions
  public DatabaseException(
      SerializationInfo serializationInfo,
      StreamingContext context)
  {
      //...
  }

}
```

The preceding `DatabaseException` example demonstrates both the attribute and the constructor requirement for making an exception serializable.

Rethrowing a Wrapped Exception

On occasion, an exception thrown at a lower level in the stack will no longer make sense when caught at a higher level. For example, consider a `System.IO.IOException` that occurs because a system is out of disk space on the server. A client catching such an exception would not necessarily be able to understand the context of why there was even I/O activity. Similarly, consider a geographic coordinate request API that throws a `System.UnauthorizedAccessException` (an exception totally unrelated to the API called). In this second example, the caller has no context or understanding of what the API call has to do with security. From the perspective of the code that invokes the API, these exceptions cause more confusion than they help diagnose. Instead of exposing such exceptions to the client, it might make sense to first catch the exception and then throw a different exception, such as `InvalidOperationException` (or even perhaps a custom exception), as a means of communicating that the system is in an invalid state. In such scenarios, be sure to set the `InnerException` property of the wrapping exception (generally via the constructor call such as `new InvalidOperationException(String, Exception)`) so that there is additional context that can be used for diagnostic purposes by someone closer to the framework that was invoked.

An important detail to remember when considering whether to wrap and rethrow an exception is the fact that the original stack trace—which provides the context of where the exception was thrown—will be replaced with the new stack trace of where the wrapping exception is thrown (assuming `ExceptionDispatchInfo` is not used). Fortunately, when the original exception is embedded into the wrapping exception, the original stack trace is still available.

Ultimately, the intended recipient of the exception is the programmer writing code that calls your API—possibly incorrectly. Therefore, you should provide as much information to her that indicates both what the programmer did wrong and—perhaps more importantly—how to fix it. The exception type is a critical piece of the communication mechanism. Therefore, you must choose the type carefully.

Guidelines

CONSIDER wrapping specific exceptions thrown from the lower layer in a more appropriate exception if the lower-layer exception does not make sense in the context of the higher-layer operation.

DO specify the inner exception when wrapping exceptions.

DO target developers as the audience for exceptions, identifying both the problem and the mechanism to resolve it, where possible.

DO use an empty throw statement (`throw;`) when rethrowing the same exception rather than passing the exception as an argument to `throw`.

BEGINNER TOPIC

Checked and Unchecked Conversions

As we first discussed in a Chapter 2 Advanced Topic, C# provides special keywords for marking a code block with instructions to the runtime of what should happen if the target data type is too small to contain the assigned data. By default, if the target data type cannot contain the assigned data, the data will truncate during assignment. For an example, see Listing 10.7.

Listing 10.7: Overflowing an Integer Value

```
using System;

public class Program
{
  public static void Main()
  {
      // int.MaxValue equals 2147483647
      int n = int.MaxValue;
      n = n + 1 ;
      System.Console.WriteLine(n);
  }
}
```

The results of Listing 10.7 appear in Output 10.1.

Output 10.1

```
-2147483648
```

The code in Listing 10.7 writes the value `-2147483648` to the console. However, placing the code within a checked block or using the `checked` option when running the compiler will cause the runtime to throw an exception of type `System.OverflowException`. The syntax for a checked block uses the `checked` keyword, as shown in Listing 10.8.

Listing 10.8: A Checked Block Example

```
using System;

public class Program
{
```

```
    public static void Main()
    {
        checked
        {
            // int.MaxValue equals 2147483647
            int n = int.MaxValue;
            n = n + 1 ;
            System.Console.WriteLine(n);
        }
    }
}
```

If the calculation involves only constants, the calculation will be checked by default. The results of Listing 10.8 appear in Output 10.2.

Output 10.2

```
Unhandled Exception: System.OverflowException: Arithmetic operation
resulted in an overflow. at Program.Main() in ...Program.cs:line 12
```

In addition, depending on the version of Windows and whether a debugger is installed, a dialog may appear that prompts the user to send an error message to Microsoft, check for a solution, or debug the application. Also, the location information (`Program.cs:line X`) will appear only in debug compilations—that is, compilations using the `/Debug` option of the Microsoft `csc.exe` compiler. The result is that an exception is thrown if, within the checked block, an overflow assignment occurs at runtime.

The C# compiler provides a command-line option for changing the default checked behavior from unchecked to checked. C# also supports an unchecked block that truncates the data instead of throwing an exception for assignments within the block (see Listing 10.9).

Listing 10.9: An Unchecked Block Example

```
using System;

public class Program
{
    public static void Main()
    {
        unchecked
        {
            // int.MaxValue equals 2147483647
            int n = int.MaxValue;
            n = n + 1 ;
```

```
            System.Console.WriteLine(n);
        }
    }
}
```

The results of Listing 10.8 appear in Output 10.3.

OUTPUT 10.3

```
-2147483648
```

Even if the checked option is on during compilation, the `unchecked` keyword in the code in Listing 10.8 will prevent the runtime from throwing an exception during execution.

Equivalent checked and unchecked expressions are available for cases where statements are not allowed. For example, a field initializer may consist of an expression, rather than a statement:

```
int _Number = unchecked(int.MaxValue + 1);
```

SUMMARY

Throwing an exception causes a significant performance hit. A single exception causes lots of runtime stack information to be loaded and processed—data that would not otherwise be loaded—and it takes a considerable amount of time to handle. As pointed out in Chapter 4, you should use exceptions only to handle exceptional circumstances; APIs should provide mechanisms to check whether an exception will be thrown instead of forcing a particular API to be called to determine whether an exception will be thrown.

The next chapter introduces generics—a C# 2.0 feature that significantly enhances code written in C# 1.0. In fact, it essentially deprecates any use of the `System.Collections` namespace, which was formerly used in nearly every project.

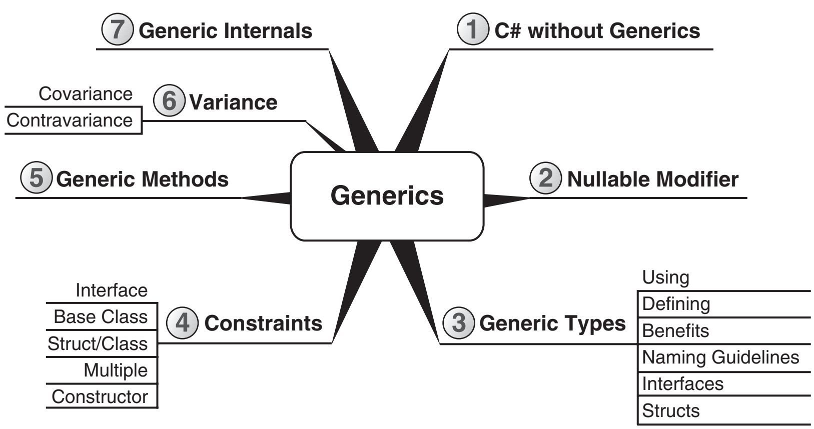
11

Generics

Begin 2.0

AS YOUR PROJECTS BECOME MORE sophisticated, you will need a better way to reuse and customize existing software. To facilitate code reuse, especially the reuse of algorithms, C# includes a feature called **generics.** Just as methods are powerful because they can take arguments, so types and methods that take type arguments have significantly more functionality.

Generics are lexically similar to generic types in Java and templates in C++. In all three languages, these features enable the implementation of algorithms and patterns once, rather than requiring separate implementations for each type the algorithm or pattern operates upon. However, C# generics are very different from both Java generics and C++ templates in the details of their implementation and impact upon the type system of their respective languages. Generics were added to the runtime and C# in version 2.0.



C# without Generics

We begin the discussion of generics by examining a class that does not use generics. This class, `System.Collections.Stack`, represents a collection of objects such that the last item to be added to the collection is the first item retrieved from the collection (last in, first out [LIFO]). `Push()` and `Pop()`, the two main methods of the `Stack` class, add items to the stack and remove them from the stack, respectively. The declarations for the methods on the stack class appear in Listing 11.1.

LISTING 11.1: The `System.Collections.Stack` Method Signatures

```
public class Stack
{
   public virtual object Pop() { ... }
   public virtual void Push(object obj) { ... }
   // ...
}
```

Programs frequently use stack type collections to facilitate multiple undo operations. For example, Listing 11.2 uses the `System.Collections.Stack` class for undo operations within a program that simulates the Etch A Sketch game.

LISTING 11.2: Supporting Undo in a Program Similar to the Etch A Sketch Game

```
using System;
using System.Collections;

class Program
{
  // ...

  public void Sketch()
  {
      Stack path = new Stack();
      Cell currentPosition;
      ConsoleKeyInfo key;  // Added in C# 2.0

      do
      {
          // Etch in the direction indicated by the
          // arrow keys that the user enters
          key = Move();
```

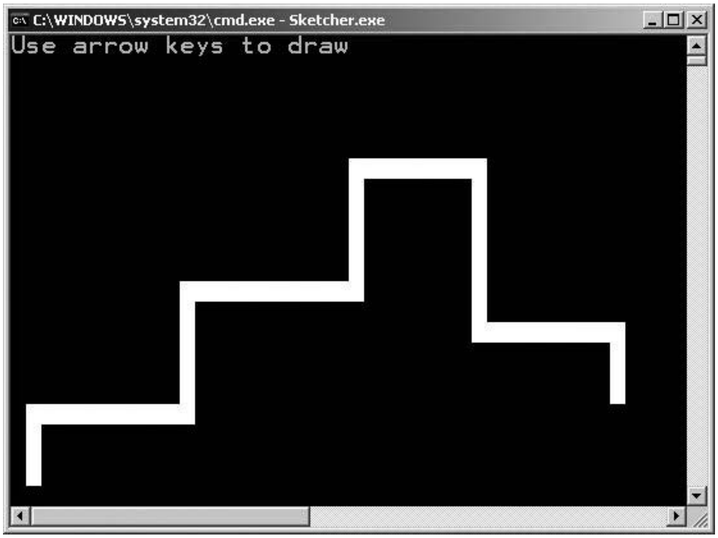
2.0

```
            switch (key.Key)
            {
                case ConsoleKey.Z:
                    // Undo the previous Move
                    if (path.Count >= 1)
                    {
                        currentPosition = (Cell)path.Pop();
                        Console.SetCursorPosition(
                            currentPosition.X, currentPosition.Y);
                        Undo();
                    }
                    break;

                case ConsoleKey.DownArrow:
                case ConsoleKey.UpArrow:
                case ConsoleKey.LeftArrow:
                case ConsoleKey.RightArrow:
                    // SaveState()
                    currentPosition = new Cell(
                        Console.CursorLeft, Console.CursorTop);
                    path.Push(currentPosition);
                    break;

                default:
                    Console.Beep();  // Added in C# 2.0
                    break;
            }

        }
        while (key.Key != ConsoleKey.X);  // Use X to quit

    }
}

public struct Cell
{
    // Use read-only field prior to C# 6.0
    public int X { get; }
    public int Y { get; }
    public Cell(int x, int y)
    {
        X = x;
        Y = y;
    }
}
```

2.0

The results of Listing 11.2 appear in Output 11.1 on the next page.

OUTPUT 11.1



Using the variable path, which is declared as a System.Collections.Stack, you save the previous move by passing a custom type, Cell, into the Stack.Push() method using path.Push(currentPosition). If the user enters a Z (or presses Ctrl+Z), you undo the previous move by retrieving it from the stack using a Pop() method, setting the cursor position to be the previous position, and calling Undo().

Although this code is functional, there is a fundamental shortcoming in the System.Collections.Stack class. As shown in Listing 11.1, the Stack class collects values of type object. Because every object in the CLR derives from object, Stack provides no validation that the elements you place into it are homogenous or are of the intended type. For example, instead of passing currentPosition, you can pass a string in which X and Y are concatenated with a decimal point between them. However, the compiler must allow the inconsistent data types because the stack class is written to take any object, regardless of its more specific type.

2.0 Furthermore, when retrieving the data from the stack using the Pop() method, you must cast the return value to a Cell. But if the type of the value returned from the Pop() method is not Cell, an exception is thrown. By deferring type checking until runtime by using a cast, you make the program more brittle. The fundamental problem with creating classes that can work with multiple data types without generics is that they must work with a common base class (or interface), usually `object`.

Using value types, such as a struct or an integer, with classes that use `object` exacerbates the problem. If you pass a value type to the `Stack.Push()` method, for example, the runtime automatically boxes it. Similarly, when you retrieve a value type, you need to explicitly unbox the data and cast the `object` reference you obtain from the `Pop()` method into a value type. Casting a reference type to a base class or interface has a negligible performance impact, but the box operation for a value type introduces more overhead, because it must allocate memory, copy the value, and then later garbage-collect that memory.

C# is a language that encourages "type safety": The language is designed so that many type errors, such as assigning an integer to a variable of type `string`, can be caught at compile time. The fundamental problem is that the stack class is not as type-safe as one expects a C# program to be. To change the stack class to enforce type safety to restrict the contents of the stack to be a particular data type (without using generic types), you must create a specialized stack class, as in Listing 11.3.

Listing 11.3: Defining a Specialized Stack Class

```
public class CellStack
{
  public virtual Cell Pop();
  public virtual void Push(Cell cell);
  // ...
}
```

Because `CellStack` can store only objects of type `Cell`, this solution requires a custom implementation of the stack methods, which is less than ideal. Implementing a type-safe stack of integers would require yet another custom implementation; each implementation would look remarkably like every other one. There would be lots of duplicated, redundant code.

2.0

BEGINNER TOPIC

Another Example: Nullable Value Types

Chapter 2 introduced the capability of declaring variables that could contain `null` by using the nullable modifier, `?`, when declaring a value type variable. C# began supporting this functionality only in version 2.0 because the right implementation required generics. Prior to the introduction of generics, programmers faced essentially two options.

The first option was to declare a nullable data type for each value type that needs to handle null values, as shown in Listing 11.4.

Listing 11.4: Declaring Versions of Various Value Types That Store `null`

```
struct NullableInt
{
    /// <summary>
    /// Provides the value when HasValue returns true.
    /// </summary>
    public int Value{ get; private set; }

    /// <summary>
    /// Indicates whether there is a value or whether
    /// the value is "null".
    /// </summary>
    public bool HasValue{ get; private set; }

    // ...
}

struct NullableGuid
{
    /// <summary>
    /// Provides the value when HasValue returns true.
    /// </summary>
    public Guid Value{ get; private set; }

    /// <summary>
    /// Indicates whether there is a value or whether
    /// the value is "null".
    /// </summary>
    public bool HasValue{ get; private set; }

    ...
}
...
```

2.0 Listing 11.4 shows possible implementations of `NullableInt` and `NullableGuid`. If a program required additional nullable value types, you would have to create yet another struct with the properties modified to use the desired value type. Any improvement of the implementation (adding a user-defined implicit conversion from the underlying type to the nullable type, for example) would require modifying all of the nullable type declarations.

An alternative strategy for implementing a nullable type without generics is to make a single type with a `Value` property of type `object`, as shown in Listing 11.5.

LISTING 11.5: Declaring a Nullable Type That Contains a `Value` Property of Type `object`

```
  struct Nullable
{
      /// <summary>
      /// Provides the value when HasValue returns true.
      /// </summary>
      public object Value{ get; private set; }

      /// <summary>
      /// Indicates whether there is a value or whether
      /// the value is "null".
      /// </summary>
      public bool HasValue{ get; private set; }

      ...
  }
```

Although this option requires only one implementation of a nullable type, the runtime always boxes value types when setting the `Value` property. Furthermore, retrieving the underlying value from the `Value` property requires a cast operation, which might potentially be invalid at runtime.

Neither option is particularly attractive. To eliminate this problem, C# 2.0 introduced generics to C#. (And, in fact, nullable types are actually implemented as the generic type `Nullable<T>`.)

Introducing Generic Types

Generics provide a facility for creating data structures that can be specialized to handle specific types. Programmers define these **parameterized types** so that each variable of a particular generic type has the same internal algorithm, but the types of data and method signatures can vary based on the type arguments provided for the type parameters.

2.0

To minimize the learning curve for developers, C# designers chose syntax that superficially resembles C++ templates. In C#, the syntax for generic classes and structures uses angle brackets to both declare the generic type parameters in the type declaration and specify the generic type arguments when the type is used.

Using a Generic Class

Listing 11.6 shows how you can specify the actual type argument used by the generic class. You instruct the `path` variable to be the "Stack of Cell" type by specifying `Cell` within angle bracket notation in both the object creation expression and the declaration statement. In other words, when declaring a variable (`path` in this case) using a generic data type, C# requires the developer to identify the actual type arguments used by the generic type. Listing 11.6 illustrates this process with the new generic `Stack` class.

Listing 11.6: Implementing Undo with a Generic `Stack` Class

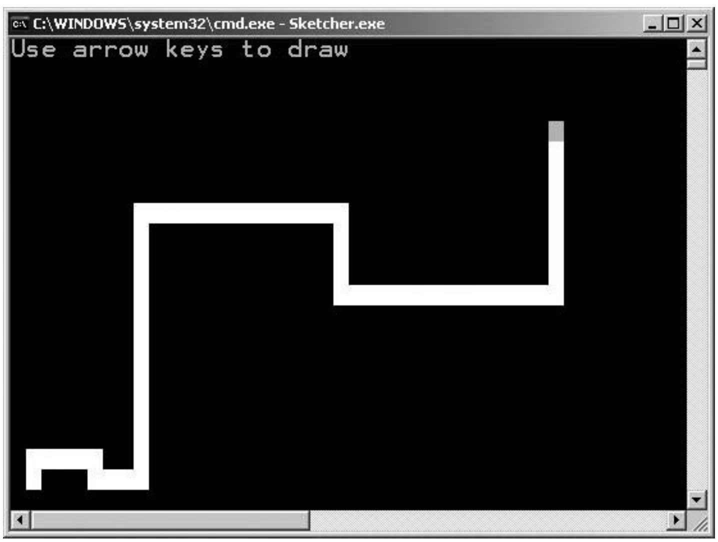
2.0

```
using System;
using System.Collections.Generic;

class Program
{
  // ...

  public void Sketch()
  {
        Stack<Cell> path;          // Generic variable declaration
        path = new Stack<Cell>();  // Generic object instantiation
        Cell currentPosition;
        ConsoleKeyInfo key;

        do
        {
            // Etch in the direction indicated by the
            // arrow keys entered by the user.
            key = Move();

            switch (key.Key)
            {
                case ConsoleKey.Z:
                    // Undo the previous Move.
                    if (path.Count >= 1)
                    {
                        // No cast required.
                        currentPosition = path.Pop();
                        Console.SetCursorPosition(
                            currentPosition.X, currentPosition.Y);
                        Undo();
                    }
```

```
                    break;

                case ConsoleKey.DownArrow:
                case ConsoleKey.UpArrow:
                case ConsoleKey.LeftArrow:
                case ConsoleKey.RightArrow:
                    // SaveState()
                    currentPosition = new Cell(
                        Console.CursorLeft, Console.CursorTop);
                    // Only type Cell allowed in call to Push().
                    path.Push(currentPosition);
                    break;

                default:
                    Console.Beep();  // Added in C# 2.0
                    break;
            }

        } while (key.Key != ConsoleKey.X);  // Use X to quit.
    }
}
```

The results of Listing 11.6 appear in Output 11.2.

OUTPUT 11.2



2.0

In the path declaration shown in Listing 11.6, you declare a variable and initialize it with a new instance of the `System.Collections.Generic.Stack<Cell>` class. You specify in angle brackets that the data type of the stack's elements is `Cell`. As a result, every object added to and retrieved from `path` is of type `Cell`. In turn, you no longer need to cast the return of `path.Pop()` or ensure that only `Cell` type objects are added to `path` in the `Push()` method.

Defining a Simple Generic Class

Generics allow you to author algorithms and patterns, and reuse the code for different data types. Listing 11.7 creates a generic `Stack<T>` class similar to the `System.Collections.Generic.Stack<T>` class used in the code in Listing 11.6. You specify a **type parameter** (in this case, `T`) within angle brackets after the class name. The generic `Stack<T>` can then be supplied with a single type argument that is "substituted" everywhere T appears in the class. Thus the stack can store items of any stated type, without duplicating code or converting the item to type `object`. The type parameter `T` is a placeholder that must be supplied with a type argument. In Listing 11.7, you can see that the type parameter will be used for the internal `Items` array, the type for the parameter to the `Push()` method, and the return type for the `Pop()` method.

LISTING 11.7: Declaring a Generic Class, `Stack<T>`

```
public class Stack<T>
{
    // Use read-only field prior to C# 6.0
    private T[] InternalItems { get; }

    public void Push(T data)
    {
        ...
    }

    public T Pop()
    {
        ...
    }
}
```

2.0

Benefits of Generics

There are several advantages to using a generic class over a nongeneric version (such as the `System.Collections.Generic.Stack<T>` class used earlier instead of the original `System.Collections.Stack` type).

1. Generics facilitate increased type safety, preventing data types other than those explicitly intended by the members within the parameterized class. In Listing 11.7, the parameterized stack class restricts you to the `Cell` data type when using `Stack<Cell>`. (For example, the statement `path.Push("garbage")` produces a compile-time error indicating that there is no overloaded method for `System.Collections.Generic.Stack<T>.Push(T)` that can work with the string, because it cannot be converted to a `Cell`.)
2. Compile-time type checking reduces the likelihood of `InvalidCastException` type errors at runtime.
3. Using value types with generic class members no longer causes a boxing conversion to `object`. (For example, `path.Pop()` and `path.Push()` do not require an item to be boxed when added or unboxed when removed.)
4. Generics in C# reduce code bloat. Generic types retain the benefits of specific class versions, without the overhead. (For example, it is no longer necessary to define a class such as `CellStack`.)
5. Performance improves because casting from an object is no longer required, thereby eliminating a type check operation. Also, performance improves because boxing is no longer necessary for value types.
6. Generics reduce memory consumption by avoiding boxing and, therefore, consuming less memory on the heap.
7. Code becomes more readable because of fewer casting checks and because of the need for fewer type-specific implementations.
8. Editors that assist coding via some type of IntelliSense work directly with return parameters from generic classes. There is no need to cast the return data for IntelliSense to work.

At their core, generics offer the ability to code pattern implementations and then reuse those implementations wherever the patterns appear. Patterns describe problems that occur repeatedly within code, and templates provide a single implementation for these repeating patterns.

2.0

Type Parameter Naming Guidelines

Just as when you name a method's formal parameter, so you should be as descriptive as possible when naming a type parameter. Furthermore, to distinguish the parameter as being a type parameter, its name should include a T prefix. For example, in defining a class such as `EntityCollection<TEntity>`, you use the type parameter name "TEntity."

The only time you would not use a descriptive type parameter name is when such a description would not add any value. For example, using "T" in the `Stack<T>` class is appropriate, since the indication that "T" is a type parameter is sufficiently descriptive; the stack works for any type.

In the next section, you will learn about constraints. It is a good practice to use constraint-descriptive type names. For example, if a type parameter must implement `IComponent`, consider a type name of "TComponent."

Guidelines

DO choose meaningful names for type parameters and prefix the name with **T**.

CONSIDER indicating a constraint in the name of a type parameter.

Generic Interfaces and Structs

C# supports the use of generics throughout the language, including interfaces and structs. The syntax is identical to that used by classes. To declare an interface with a type parameter, place the type parameter in angle brackets immediately after the interface name, as shown in the example of `IPair<T>` in Listing 11.8.

Listing 11.8: Declaring a Generic Interface

```
interface IPair<T>
{
    T First { get; set; }
    T Second { get; set; }
}
```

This interface represents pairs of like objects, such as the coordinates of a
2.0 point, a person's genetic parents, or nodes of a binary tree. The type contained in the pair is the same for both items.

To implement the interface, you use the same syntax as you would for a nongeneric class. Note that it is legal, and indeed common, for the type argument for one generic type to be a type parameter of another, as shown in Listing 11.9. The type argument of the interface is the type parameter declared by the class. In addition, this example uses a struct rather than a class, demonstrating that C# supports custom generic value types.

Listing 11.9: Implementing a Generic Interface

```
public struct Pair<T>: IPair<T>
{
    public T First { get; set; }
    public T Second { get; set; }
}
```

Support for generic interfaces is especially important for collection classes, where generics are most prevalent. Before generics, developers relied on a series of interfaces within the `System.Collections` namespace. Like their implementing classes, these interfaces worked only with type `object`, and as a result, the interface forced all access to and from these collection classes to require a cast. By using type-safe generic interfaces, you can avoid cast operations.

ADVANCED TOPIC

Implementing the Same Interface Multiple Times on a Single Class

Two different constructions of the same generic interface are considered to be different types. As a consequence, "the same" generic interface can be implemented multiple times by a class or struct. Consider the example in Listing 11.10.

Listing 11.10: Duplicating an Interface Implementation on a Single Class

```
public interface IContainer<T>
{
    ICollection<T> Items  { get; set; }
    {
        get;
        set;
    }
}

public class Person: IContainer<Address>,
    IContainer<Phone>, IContainer<Email>
{
```

2.0

```
        ICollection<Address> IContainer<Address>.Items
        {
            get{...}
            set{...}
        }
        ICollection<Phone> IContainer<Phone>.Items
        {
            get{...}
            set{...}
        }
        ICollection<Email> IContainer<Email>.Items
        {
            get{...}
            set{...}
        }
    }
```

In this example, the `Items` property appears multiple times using an explicit interface implementation with a varying type parameter. Without generics, this would not be possible; instead, the compiler would allow only one explicit `IContainer.Items` property.

However, this technique of implementing multiple versions of "the same" interface is considered by many to be a "bad code smell" because it is potentially confusing (particularly if the interface permits covariant or contravariant conversions). Moreover, the `Person` class here seems potentially badly designed; one does not normally think of a person as being "a thing that can provide a set of email addresses." When you feel tempted to make a class implement three versions of the same interface, consider whether it might be better to make it instead implement three properties—for example, `EmailAddresses`, `PhoneNumbers`, and `MailingAddresses`—each of which returns the appropriate construction of the generic interface.

Guidelines

AVOID implementing multiple constructions of the same generic interface in one type.

2.0

Defining a Constructor and a Finalizer

Perhaps surprisingly, the constructors (and finalizer) of a generic class or struct do not require type parameters; in other words, they do not require

`Pair<T>(){...}`. In the pair example in Listing 11.11, the constructor is declared using `public Pair(T first, T second)`.

LISTING 11.11: Declaring a Generic Type's Constructor

```
public struct Pair<T>: IPair<T>
{
  public Pair(T first, T second)
  {
      First = first;
      Second = second;
  }

  public T First  { get; set; }
  public T Second  { get; set; }
}
```

Specifying a Default Value

Listing 11.11 included a constructor that takes the initial values for both `First` and `Second`, and assigns them to `_First` and `_Second`. Since `Pair<T>` is a struct, any constructor you provide must initialize all fields. This presents a problem, however. Consider a constructor for `Pair<T>` that initializes only half of the pair at instantiation time.

Defining such a constructor, as shown in Listing 11.12, causes a compile-time error because the field `_Second` is still uninitialized at the end of the constructor. Providing initialization for `_Second` presents a problem because you don't know the data type of `T`. If it is a reference type, `null` would work, but this approach would not work if `T` were a non-nullable value type.

LISTING 11.12: Not Initializing All Fields, Causing a Compile-Time Error

```
public struct Pair<T>: IPair<T>
{
  // ERROR:  Field 'Pair<T>._second' must be fully assigned
  //         before control leaves the constructor
  // public Pair(T first)
  // {
  //     First = first;
  // }

  // ...
}
```

2.0

To deal with this scenario, C# provides the `default` operator, first discussed in Chapter 8. In Chapter 8, we showed how the default value of `int` could be specified with `default(int)`. In the case of `T`, which `_Second` requires, you can use `default(T)` as shown in Listing 11.13.

LISTING 11.13: Initializing a Field with the `default` Operator

```
public struct Pair<T>: IPair<T>
{
  public Pair(T first)
  {
      First = first;
      Second = default(T);
  }

  // ...
}
```

The `default` operator can provide the default value for any type, including type parameters.

Multiple Type Parameters

Generic types may declare any number of type parameters. The initial `Pair<T>` example contains only one type parameter. To enable support for storing a dichotomous pair of objects, such as a name/value pair, you could create a new version of the type that declares two type parameters, as shown in Listing 11.14.

LISTING 11.14: Declaring a Generic with Multiple Type Parameters

2.0

```
interface IPair<TFirst, TSecond>
{
    TFirst First { get; set; }
    TSecond Second { get; set; }
}

public struct Pair<TFirst, TSecond>: IPair<TFirst, TSecond>
{
    public Pair(TFirst first, TSecond second)
    {
        First = first;
        Second = second;
    }

    public TFirst First { get; set; }
```

```
    public TSecond Second { get; set; }
}
```

When you use the Pair<TFirst, TSecond> class, you supply multiple type parameters within the angle brackets of the declaration and instantiation statements; you then supply matching types to the parameters of the methods when you call them. Listing 11.15 illustrates this approach.

LISTING 11.15: Using a Type with Multiple Type Parameters

```
Pair<int, string> historicalEvent =
    new Pair<int, string>(1914,
        "Shackleton leaves for South Pole on ship Endurance");
Console.WriteLine("{0}: {1}",
    historicalEvent.First, historicalEvent.Second);
```

The number of type parameters—that is, the **arity**—uniquely distinguishes the class from others of the same name. Therefore, it is possible to define both `Pair<T>` and `Pair<TFirst, TSecond>` within the same namespace because of the arity variation. Furthermore, because of their close semantic relationship, generics that differ only by arity should be placed into the same C# file.

Guidelines

DO place multiple generic classes into a single file if they differ only by the number of generic parameters.

Arity in Abundance

Begin 4.0

In C# 4.0, the CLR team defined nine new generic types, all called `Tuple`. As with `Pair<...>`, it was possible to reuse the same name because of the variation in arity (each class had a different number of type parameters), as shown in Listing 11.16.

2.0

LISTING 11.16: Using Arity to Overload a Type Definition

```
public class Tuple { ... }
public class Tuple<T1>:
  IStructuralEquatable, IStructuralComparable, IComparable {...}
public class Tuple<T1, T2>: ... {...}
```

```
public class Tuple<T1, T2, T3>: ... {...}
public class Tuple<T1, T2, T3, T4>: ... {...}
public class Tuple<T1, T2, T3, T4, T5>: ... {...}
public class Tuple<T1, T2, T3, T4, T5, T6>: ... {...}
public class Tuple<T1, T2, T3, T4, T5, T6, T7>: ... {...}
public class Tuple<T1, T2, T3, T4, T5, T6, T7, TRest>: ... {...}
```

The `Tuple<…>` set of classes was designed for the same purpose as the `Pair<T>` and `Pair<TFirst, TSecond>` classes, except together they can handle seven type arguments. In fact, using the last `Tuple` shown in Listing 11.16, `TRest` can be used to store another `Tuple`, making the number of elements of the tuple practically unlimited.

Another interesting member of the tuple family of classes is the nongeneric `Tuple` class. This class has eight static "factory" methods for instantiating the various generic tuple types. Although each generic type could be instantiated directly using its constructor, the `Tuple` type's factory methods allow for inference of the type arguments. Listing 11.17 shows the difference.

LISTING 11.17: Using a Tuple's `Create()` Factory Methods

```
Tuple<string, Contact> keyValuePair;
keyValuePair =
  Tuple.Create(
      "555-55-5555", new Contact("Inigo Montoya"));
keyValuePair =
  new Tuple<string, Contact>(
      "555-55-5555", new Contact("Inigo Montoya"));
```

Obviously, when the `Tuple` gets large, the number of type parameters to specify could be cumbersome without the `Create()` factory methods.

As you might have deduced from the fact that the framework libraries declare eight different generic tuple types, there is no support in the CLR type system for "variadic" generic types. Methods can take an arbitrary number of arguments by using "parameter arrays," but there is no corresponding technique for generic types; every generic type must be of a specific arity.

End 4.0

2.0

Nested Generic Types

Type parameters on a containing generic type will "cascade" down to any nested types automatically. If the containing type declares a type parameter `T`, for example, all nested types will also be generic and type parameter

`T` will be available on the nested type as well. If the nested type includes its own type parameter named `T`, this will hide the type parameter within the containing type and any reference to `T` in the nested type will refer to the nested `T` type parameter. Fortunately, reuse of the same type parameter name within the nested type will cause a compiler warning to prevent accidental overlap (see Listing 11.18).

LISTING 11.18: Nested Generic Types

```
class Container<T, U>
{
  // Nested classes inherit type parameters.
  // Reusing a type parameter name will cause
  // a warning.
  class Nested<U>
  {
      void Method(T param0, U param1)
      {
      }
  }
}
```

The containing type's type parameters are accessible in the nested type the same way that members of the containing type are also accessible from the nested type. The rule is simply that a type parameter is available anywhere within the body of the type that declares it.

Guidelines

AVOID shadowing a type parameter of an outer type with an identically named type parameter of a nested type.

Constraints

Generics support the ability to define constraints on type parameters. These constraints ensure that the types provided as type arguments conform to various rules. Take, for example, the `BinaryTree<T>` class shown in Listing 11.19. 2.0

LISTING 11.19: Declaring a `BinaryTree<T>` Class with No Constraints

```
public class BinaryTree<T>
{
```

```
    public BinaryTree ( T item)
    {
        Item = item;
    }

    public T Item { get; set; }
    public Pair<BinaryTree<T>> SubItems { get; set; }
}
```

(An interesting side note is that `BinaryTree<T>` uses `Pair<T>` internally, which is possible because `Pair<T>` is simply another type.)

Suppose you want the tree to sort the values within the `Pair<T>` value as it is assigned to the `SubItems` property. To achieve the sorting, the `SubItems` set accessor uses the `CompareTo()` method of the supplied key, as shown in Listing 11.20.

LISTING 11.20: Needing the Type Parameter to Support an Interface

```
public class BinaryTree<T>
{
    public T Item { get; set; }
    public Pair<BinaryTree<T>> SubItems
    {
        get{ return _SubItems; }
        set
        {
            IComparable<T> first;
            // ERROR: Cannot implicitly convert type...
            first = value.First;  // Explicit cast required

            if (first.CompareTo(value.Second) < 0)
            {
                // first is less than second.
                // ...
            }
            else
            {
                // first and second are the same or
                // second is less than first.
                // ...
            }
            _SubItems = value;
        }
    }
    private Pair<BinaryTree<T>> _SubItems;
}
```

2.0

At compile time, the type parameter `T` is an unconstrained generic. When the code is written as shown in Listing 11.20, the compiler assumes that the only members available on `T` are those inherited from the base type `object`, since every type has `object` as a base class. Only methods such as `ToString()`, therefore, are available to call on an instance of the type parameter `T`. As a result, the compiler displays a compilation error because the `CompareTo()` method is not defined on type `object`.

You can cast the `T` parameter to the `IComparable<T>` interface to access the `CompareTo()` method, as shown in Listing 11.21.

LISTING 11.21: Needing the Type Parameter to Support an Interface or Exception Thrown

```
public class BinaryTree<T>
{
    public T Item { get; set; }
    public Pair<BinaryTree<T>> SubItems
    {
        get{ return _SubItems; }
        set
        {
            IComparable<T> first;
            first = (IComparable<T>)value.First.Item;

            if (first.CompareTo(value.Second.Item) < 0)
            {
                // first is less than second.
                ...
            }
            else
            {
                // second is less than or equal to first.
                ...
            }
            _SubItems = value;
        }
    }
    private Pair<BinaryTree<T>> _SubItems;
}
```

Unfortunately, if you now declare a `BinaryTree<SomeType>` class variable but the type argument does not implement the `IComparable<SomeType>` interface, you will encounter an execution-time error—specifically, an `InvalidCastException`. This eliminates a key reason for having generics in the first place: to improve type safety. 2.0

To avoid this exception and instead generate a compile-time error if the type argument does not implement the interface, C# allows you to supply an optional list of **constraints** for each type parameter declared in the generic type. A constraint declares the characteristics that the generic type requires of the type argument supplied for each type parameter. You declare a constraint using the `where` keyword, followed by a "parameter–requirements" pair, where the parameter must be one of those declared in the generic type and the requirements describe the class or interfaces to which the type argument must be convertible, the presence of a default constructor, or a reference/value type restriction.

Interface Constraints

To ensure that a binary tree has its nodes correctly ordered, you can use the `CompareTo()` method in the `BinaryTree` class. To do this most effectively, you should impose a constraint on the `T` type parameter. That is, you need the `T` type parameter to implement the `IComparable<T>` interface. The syntax for declaring this constraint appears in Listing 11.22.

Listing 11.22: Declaring an Interface Constraint

```
public class BinaryTree<T>
    where T: System.IComparable<T>
{
    public T Item { get; set; }
    public Pair<BinaryTree<T>> SubItems
    {
        get{ return _SubItems; }
        set
        {
            IComparable<T> first;
            // Notice that the cast can now be eliminated.
            first = value.First.Item;

            if (first.CompareTo(value.Second.Item) < 0)
            {
                // first is less than second.
                ...
            }
            else
            {
                // second is less than or equal to first.
                ...
            }
            _SubItems = value;
        }
    }
    private Pair<BinaryTree<T>> _SubItems;
}
```

2.0

When given the interface constraint addition in Listing 11.22, the compiler ensures that each time you use the `BinaryTree<T>` class, you specify a type parameter that implements the corresponding construction of the `IComparable<T>` interface. Furthermore, you no longer need to explicitly cast the variable to an `IComparable<T>` interface before calling the `CompareTo()` method. Casting is not even required to access members that use explicit interface implementation, which in other contexts would hide the member without a cast. When calling a method on a value typed as a generic type parameter, the compiler checks whether the method matches any method on any of the interfaces declared as constraints.

If you tried to create a `BinaryTree<T>` variable using `System.Text.StringBuilder` as the type parameter, you would receive a compiler error because `StringBuilder` does not implement `IComparable<StringBuilder>`. The error is similar to the one shown in Output 11.3.

OUTPUT 11.3

```
error CS0311: The type 'System.Text.StringBuilder' cannot be used as type
parameter 'T' in the generic type or method 'BinaryTree<T>'. There is no
implicit reference conversion from 'System.Text.StringBuilder' to
'System.IComparable<System.Text.StringBuilder>'.
```

To specify an interface for the constraint, you declare an **interface type constraint.** This constraint even circumvents the need to cast so as to call an explicit interface member implementation.

Class Type Constraints

Sometimes you might want to constrain a type argument to be convertible to a particular class type. You do this using a **class type constraint,** as shown in Listing 11.23.

LISTING 11.23: Declaring a Class Type Constraint

```
public class EntityDictionary<TKey, TValue>
    : System.Collections.Generic.Dictionary<TKey, TValue>
    where TValue : EntityBase
{
    ...
}
```

2.0

In Listing 11.23, `EntityDictionary<TKey, TValue>` requires that all type arguments provided for the type parameter `TValue` be implicitly convertible to the `EntityBase` class. By requiring the conversion, it becomes possible to use the members of EntityBase on values of type TValue within the generic implementation, because the constraint will ensure that all type arguments can be implicitly converted to the EntityBase class.

The syntax for the class type constraint is the same as that for the interface type constraint, except that class type constraints must appear before any interface type constraints (just as the base class must appear before implemented interfaces in a class declaration). However, unlike interface constraints, multiple base class constraints are not allowed since it is not possible to derive from multiple unrelated classes. Similarly, base class constraints cannot specify sealed classes or nonclass types. For example, C# does not allow a type parameter to be constrained to string or System.Nullable<T> because there would then be only one possible type argument for that type parameter—that's hardly "generic." If the type parameter is constrained to a single type, there is no need for the type parameter in the first place; just use that type directly.

Certain "special" types are not legal as class type constraints. See the Advanced Topic "Constraint Limitations," later in this chapter, for details.

struct/class Constraints

Another valuable generic constraint is the ability to restrict type arguments to be any non-nullable value type or any reference type. Instead, C# provides special syntax that works for reference types as well. Rather than specifying a class from which T must derive, you simply use the keyword struct or class, as shown in Listing 11.24.

Listing 11.24: Specifying the Type Parameter As a Value Type

```
public struct Nullable<T> :
     IFormattable, IComparable,
     IComparable<Nullable<T>>, INullable
     where T : struct
{
    // ...
}
```

2.0

Note that the class constraint—somewhat confusingly—does not restrict the type argument to class types; rather, it restricts it to reference types. A type argument supplied for a type parameter constrained with the class constraint may be any class, interface, delegate, or array type.

Because a class type constraint requires a particular class, using a `struct` constraint with a class type constraint would be contradictory. Therefore, you cannot combine `struct` and `class` constraints.

The `struct` constraint has one special characteristic: Nullable value types do not satisfy the constraint. Why? Nullable value types are implemented as the generic type `Nullable<T>`, which itself applies the `struct` constraint to T. If nullable value types satisfied that constraint, it would be possible to define the nonsense type `Nullable<Nullable<int>>`. A doubly nullable integer is confusing to the point of being meaningless. (As expected, the shorthand syntax `int??` is also disallowed.)

Multiple Constraints

For any given type parameter, you may specify any number of interface type constraints, but no more than one class type constraint (just as a class may implement any number of interfaces but inherit from only one other class). Each new constraint is declared in a comma-delimited list following the generic type parameter and a colon. If there is more than one type parameter, each must be preceded by the `where` keyword. In Listing 11.25, the generic `EntityDictionary` class declares two type parameters: `TKey` and `TValue`. The `TKey` type parameter has two interface type constraints, and the `TValue` type parameter has one class type constraint.

LISTING 11.25: Specifying Multiple Constraints

```
public class EntityDictionary<TKey, TValue>
    : Dictionary<TKey, TValue>
    where TKey : IComparable<TKey>, IFormattable
    where TValue : EntityBase
{
  ...
}
```

In this case, there are multiple constraints on `TKey` itself and an additional constraint on `TValue`. When specifying multiple constraints on one type parameter, an AND relationship is assumed. If a type `C` is supplied as the type argument for `TKey`, `C` must implement `IComparable<C>` and `IFormattable`, for example. 2.0

Notice there is no comma between each `where` clause.

Constructor Constraints

In some cases, it is desirable to create an instance of the type argument's type inside the generic class. In Listing 11.26, for example, the `MakeValue()` method for the `EntityDictionary<TKey, TValue>` class must create an instance of the type argument corresponding to type parameter `TValue`.

Listing 11.26: Requiring a Default Constructor Constraint

```
public class EntityBase<TKey>
{
    public TKey Key { get; set; }
}

public class EntityDictionary<TKey, TValue> :
    Dictionary<TKey, TValue>
    where TKey: IComparable<TKey>, IFormattable
    where TValue : EntityBase<TKey>, new()
{
    // ...

    public TValue MakeValue(TKey key)
    {
        TValue newEntity = new TValue();
        newEntity.Key = key;
        Add(newEntity.Key, newEntity);
        return newEntity;
    }

    // ...
}
```

Because not all objects are guaranteed to have public default constructors, the compiler does not allow you to call the default constructor on an unconstrained type parameter. To override this compiler restriction, you can add the text `new()` after all other constraints are specified. This text is a **constructor constraint,** and it requires the type argument corresponding to the constrained type parameter to have a public default constructor. Only the default constructor constraint is available. You cannot specify a constraint that ensures that the type argument supplied provides a constructor that takes formal parameters.

2.0

Constraint Inheritance

Neither generic type parameters nor their constraints are inherited by a derived class, because generic type parameters are not members. (Remember, class inheritance is the property that the derived class has all of the members of the base class.) It is a common practice to make new generic types that inherit from other generic types. In such a case, because the type parameters of the derived generic type become the type arguments of the generic base class, the type parameters must have equal (or stronger) constraints as those on the base class. Confused? Consider Listing 11.27.

LISTING 11.27: Inherited Constraints Specified Explicitly

```
class EntityBase<T> where T : IComparable<T>
{
  // ...
}
```

```
// ERROR:
// The type 'U' must be convertible to
// 'System.IComparable<U>' to use it as parameter
// 'T' in the generic type or method.
// class Entity<U> : EntityBase<U>
// {
//     ...
// }
```

In Listing 11.27, `EntityBase<T>` requires that the type argument `U` supplied for `T` by the base class specifier `EntityBase<U>` implement `IComparable<U>`. Therefore, the `Entity<U>` class needs to require the same constraint on `U`. Failure to do so will result in a compile-time error. This pattern increases a programmer's awareness of the base class's type constraint in the derived class, avoiding the confusion that might otherwise occur when the programmer uses the derived class and discovers the constraint but does not understand where it comes from.

We have not covered generic methods yet; we'll get to them later in this chapter. For now, simply recognize that methods may also be generic and may also place constraints on the type arguments supplied for their type parameters. How, then, are constraints handled when a virtual generic method is inherited and overridden? In contrast to the situation with type parameters declared on a generic class, constraints on overriding virtual generic methods (or explicit interface) methods are inherited implicitly and may not be restated (see Listing 11.28). 2.0

LISTING 11.28: Repeating Inherited Constraints on Virtual Members Is Prohibited

```
class EntityBase
{
  public virtual void Method<T>(T t)
```

```
        where T : IComparable<T>
    {
        // ...
    }
}
```

```
class Order : EntityBase
{
    public override void Method<T>(T t)
    //    Constraints may not be repeated on overriding
    //    members
    //    where T : IComparable<T>
    {
        // ...
    }
}
```

In the generic class inheritance case, the type parameter on the derived class can be further constrained by adding not only the constraints on the base class (required), but also other constraints. However, overriding virtual generic methods need to conform exactly to the constraints defined by the base class method. Additional constraints could break polymorphism, so they are not allowed and the type parameter constraints on the overriding method are implied.

ADVANCED TOPIC

Constraint Limitations

Constraints are appropriately limited to avoid nonsensical code. For example, you cannot combine a class type constraint with a `struct` or `class` constraint. Also, you cannot specify constraints to restrict inheritance to special types such as `object`, arrays, `System.ValueType`, `System.Enum` (`enum`), `System.Delegate`, or `System.MulticastDelegate`.

In some cases, constraint limitations are perhaps more desirable, but they still are not supported. The following subsections provide some additional
2.0 examples of constraints that are not allowed.

Operator Constraints Are Not Allowed

You cannot constrain a type parameter to a type that implements a particular method or operator, except via interface type constraints (for methods) or class type constraints (for methods and operators). Because of this, the generic `Add()` in Listing 11.29 does not work.

LISTING 11.29: Constraint Expressions Cannot Require Operators

```
public abstract class MathEx<T>
{
    public static T Add(T first, T second)
    {
        // Error: Operator '+' cannot be applied to
        // operands of type 'T' and 'T'.
        // return first + second;
    }
}
```

In this case, the method assumes that the + operator is available on all types that could be supplied as type arguments for `T`. But there is no constraint that prevents you from supplying a type argument that does not have an associated addition operator, so an error occurs. Unfortunately, there is no way to specify that an addition operator is required within a constraint, aside from using a class type constraint where the class type implements an addition operator.

More generally, there is no way to constrain a type to have a static method.

OR Criteria Are Not Supported

If you supply multiple interfaces or class constraints for a type parameter, the compiler always assumes an AND relationship between constraints. For example, `where T : IComparable<T>, IFormattable` requires that both `IComparable<T>` and `IFormattable` are supported. There is no way to specify an OR relationship between constraints. Hence, an equivalent of Listing 11.30 is not supported.

LISTING 11.30: Combining Constraints Using an OR Relationship Is Not Allowed

```
public class BinaryTree<T>
    // Error: OR is not supported.
    // where T: System.IComparable<T> || System.IFormattable
{
    ...
}
```

2.0

Supporting this functionality would prevent the compiler from resolving which method to call at compile time.

Constraints of Type Delegate and Enum Are Not Valid

Delegate types, array types, and enumerated types may not be used as class type constraints, because they are all effectively "sealed" types. (If you are not familiar with delegate types, see Chapter 12.) Their base types—`System.Delegate`, `System.MultiCastDelegate`, `System.Array`, and `System.Enum`—may also not be used as constraints. For example, the compiler will generate an error when it encounters the class declaration in Listing 11.31.

Listing 11.31: Inheritance Constraints Cannot Be of Type `System.Delegate`

```
// Error:  Constraint cannot be special class 'System.Delegate'
public class Publisher<T>
    where T : System.Delegate
{
    public event T Event;
    public void Publish()
    {
        if (Event != null)
        {
            Event(this, new EventArgs());
        }
    }
}
```

All delegate types are considered special classes that cannot be specified as type parameters. Doing so would prevent compile-time validation of the call to `Event()` because the signature of the event firing is unknown with the data types `System.Delegate` and `System.MulticastDelegate`. The same restriction applies to any enum type.

Constructor Constraints Are Allowed Only for Default Constructors

Listing 11.26 includes a constructor constraint that forces the type argument supplied for `TValue` to provide a public parameterless constructor. There is no constraint to force the type argument to provide a constructor that takes other formal parameters. For example, you might want to constrain `TValue` so that the type argument provided for it must provide a
2.0 constructor that takes the type argument provided for `TKey`, but this is not possible. Listing 11.32 demonstrates the invalid code.

Listing 11.32: Constructor Constraints Can Be Specified Only for Default Constructors

```
    public TValue New(TKey key)
    {
```

```
            // Error: 'TValue': Cannot provide arguments
            // when creating an instance of a variable type.
            TValue newEntity = null;
            // newEntity = new TValue(key);
            Add(newEntity.Key, newEntity);
            return newEntity;
        }
```

One way to circumvent this restriction is to supply a factory interface that includes a method for instantiating the type. The factory implementing the interface takes responsibility for instantiating the entity rather than the `EntityDictionary` itself (see Listing 11.33).

LISTING 11.33: Using a Factory Interface in Place of a Constructor Constraint

```
public class EntityBase<TKey>
{
  public EntityBase(TKey key)
  {
      Key = key;
  }
  public TKey Key { get; set; }
}

public class EntityDictionary<TKey, TValue, TFactory> :
      Dictionary<TKey, TValue>
  where TKey : IComparable<TKey>, IFormattable
  where TValue : EntityBase<TKey>
  where TFactory : IEntityFactory<TKey, TValue>, new()
{
  ...
  public TValue New(TKey key)
  {
      TFactory factory = new TFactory();
      TValue newEntity = factory.CreateNew(key);
      Add(newEntity.Key, newEntity);
      return newEntity;
  }
  ...
}

public interface IEntityFactory<TKey, TValue>
{
    TValue CreateNew(TKey key);
}
...
```

2.0

A declaration such as this allows you to pass the new `key` to a `TValue` factory method that takes parameters, rather than forcing you to rely on the default constructor. It no longer uses the constructor constraint on `TValue` because `TFactory` is responsible for instantiating value. (One modification to the code in Listing 11.33 would be to cache a reference to the factory method—possibly leveraging `Lazy<T>` if multithreaded support was needed. This would enable you to reuse the factory method instead of reinstantiating it every time.)

A declaration for a variable of type `EntityDictionary<TKey, TValue, TFactory>` would result in an entity declaration similar to the `Order` entity in Listing 11.34.

LISTING 11.34: Declaring an Entity to Be Used in EntityDictionary<...>

```
public class Order : EntityBase<Guid>
{
  public Order(Guid key) :
      base(key)
  {
      // ...
  }
}

public class OrderFactory : IEntityFactory<Guid, Order>
{
  public Order CreateNew(Guid key)
  {
      return new Order(key);
  }
}
```

Generic Methods

Earlier, you saw that it is a relatively simple matter to add a method to a type when the type is generic; such a method can use the generic type parameters declared by the type. You did this, for example, in the generic class examples we have seen so far.

Generic methods use generic type parameters, much as generic types do. They can be declared in generic or nongeneric types. If declared in a
2.0 generic type, their type parameters are distinct from those of their containing generic type. To declare a generic method, you specify the generic type parameters the same way you do for generic types: Add the type parameter declaration syntax immediately following the method name, as shown in the `MathEx.Max<T>` and `MathEx.Min<T>` examples in Listing 11.35.

LISTING 11.35: Defining Generic Methods

```
public static class MathEx
{
  public static T Max<T>(T first, params T[] values)
      where T : IComparable<T>
  {
      T maximum = first;
      foreach (T item in values)
      {
          if (item.CompareTo(maximum) > 0)
          {
              maximum = item;
          }
      }
      return maximum;
  }

  public static T Min<T>(T first, params T[] values)
      where T : IComparable<T>
  {
      T minimum = first;

        foreach (T item in values)
        {
            if (item.CompareTo(minimum) < 0)
            {
                minimum = item;
            }
        }
      return minimum;
  }
}
```

In this example, the method is static, although C# does not require this.

Generic methods, like generic types, can include more than one type parameter. The arity (the number of type parameters) is an additional distinguishing characteristic of a method signature. That is, it is legal to have two methods that are identical in their names and formal parameter types, as long as they differ in method type parameter arity.

Generic Method Type Inference

2.0

Just as type arguments are provided after the type name when using a generic type, so the method type arguments are provided after the method type name. The code used to call the `Min<T>` and `Max<T>` methods looks like that shown in Listing 11.36.

Listing 11.36: Specifying the Type Parameter Explicitly

```
Console.WriteLine(
    MathEx.Max<int>(7, 490));
Console.WriteLine(
    MathEx.Min<string>("R.O.U.S.", "Fireswamp"));
```

The output to Listing 11.36 appears in Output 11.4.

Output 11.4

```
490
Fireswamp
```

Not surprisingly, the type arguments, `int` and `string`, correspond to the actual types used in the generic method calls. However, specifying the type arguments is redundant because the compiler can infer the type parameters from the formal parameters passed to the method. Clearly, the caller of `Max` in Listing 11.36 intends the type argument to be `int` because both of the method arguments are of type `int`. To avoid redundancy, you can exclude the type parameters from the call in all cases when the compiler is able to logically infer which type arguments you must have intended. An example of this practice, which is known as **method type inference,** appears in Listing 11.37. The output appears in Output 11.5.

Listing 11.37: Inferring the Type Argument from the Arguments

```
Console.WriteLine(
    MathEx.Max(7, 490)); // No type arguments!
Console.WriteLine(
    MathEx.Min("R.O.U.S'", "Fireswamp"));
```

Output 11.5

```
490
Fireswamp
```

2.0

For method type inference to succeed, the types of the arguments must be "matched" with the formal parameters of the generic method in such a way that the desired type arguments can be inferred. An interesting question to consider is what happens when contradictory inferences are made. For example, when you call the `Max<T>` method using `MathEx.Max(7.0, 490)`, the compiler could deduce from the first argument that the type argument should be `double`, and it could deduce from the second argument that the type argument is `int`, a contradiction. In C# 2.0, this would have produced an error. A more sophisticated analysis would notice that the contradiction can be resolved because every `int` can be converted to `double`, so `double` is the best choice for the type argument. C# 3.0 and C# 4.0 both included improvements to the method type inferencing algorithm that permit the compiler to make these more sophisticated analyses.

In cases where method type inference is still not sophisticated enough to deduce the type arguments, you can resolve the error either by inserting casts on the arguments that clarify to the compiler the argument types that should be used in the inferences, or by giving up on type inferencing and including the type arguments explicitly.

Notice that the method type inference algorithm, when making its inferences, considers only the arguments, the arguments' types, and the formal parameter types of the generic method. Other factors that could, in practice, be used in the analysis—such as the return type of the generic method, the type of the variable that the method's returned value is being assigned to, or the constraints on the method's generic type parameters—are not considered at all by the method type inference algorithm.

Specifying Constraints

Type parameters of generic methods may be constrained in exactly the same way that type parameters of generic types are constrained. For example, you can restrict a method's type parameter to implement an interface or to be convertible to a class type. The constraints are specified between the argument list and the method body, as shown in Listing 11.38.

Listing 11.38: Specifying Constraints on Generic Methods

```
public class ConsoleTreeControl
{
    // Generic method Show<T>
    public static void Show<T>(BinaryTree<T> tree, int indent)
        where T :  IComparable<T>
    {
        Console.WriteLine("\n{0}{1}",
            "+ --".PadLeft(5*indent, ' '),
            tree.Item.ToString());
        if (tree.SubItems.First != null)
            Show(tree.SubItems.First, indent+1);
```

2.0

```
            if (tree.SubItems.Second != null)
                Show(tree.SubItems.Second, indent+1);
        }
    }
```

Here, the `Show<T>` implementation itself does not directly use any member of the `IComparable<T>` interface, so you might wonder why the constraint is required. Recall, however, that the `BinaryTree<T>` class did require this constraint (see Listing 11.39).

Listing 11.39: `BinaryTree<T>` Requiring `IComparable<T>` Type Parameters

```
public class BinaryTree<T>
    where T: System.IComparable<T>
{
    ...
}
```

Because the `BinaryTree<T>` class requires this constraint on its `T`, and because `Show<T>` uses its `T` as a type argument corresponding to a constrained type parameter, `Show<T>` needs to ensure that the constraint on the class's type parameter is met on its method type argument.

ADVANCED TOPIC

Casting inside a Generic Method

Sometimes you should be wary of using generics—for instance, when using them specifically to bury a cast operation. Consider the following method, which converts a stream into an object of a given type:

```
public static T Deserialize<T>(
    Stream stream, IFormatter formatter)
{
    return (T)formatter.Deserialize(stream);
}
```

2.0 The `formatter` is responsible for removing data from the stream and converting it to an object. The `Deserialize()` call on the formatter returns data of type `object`. A call to use the generic version of `Deserialize()` looks something like this:

```
string greeting =
    Deserialization.Deserialize<string>(stream, formatter);
```

The problem with this code is that to the caller of the method, `Deserialize<T>()` appears to be type-safe. However, a cast operation is still performed on behalf of the caller, as in the case of the nongeneric equivalent shown here:

```
string greeting =
    (string)Deserialization.Deserialize(stream, formatter);
```

The cast could fail at runtime; the method might not be as type-safe as it appears. The `Deserialize<T>` method is generic solely so that it can hide the existence of the cast from the caller, which seems dangerously deceptive. It might be better for the method to be nongeneric and return `object`, making the caller aware that it is not type-safe. Developers should use care when casting in generic methods if there are no constraints to verify cast validity.

Guidelines

AVOID misleading the caller with generic methods that are not as type-safe as they appear.

Covariance and Contravariance

A question often asked by new users of generic types is why an expression of type `List<string>` may not be assigned to a variable of type `List<object>`—if a `string` may be converted to type `object`, surely a list of strings is similarly compatible with a list of objects. But this is not, generally speaking, either type-safe or legal. If you declare two variables with different type parameters using the same generic class, the variables are not type-compatible even if they are assigning from a more specific type to a more generic type—in other words, they are not **covariant.**

Covariant is a technical term from category theory, but its underlying idea is straightforward: Suppose two types `X` and `Y` have a special relationship—namely, that every value of the type `X` may be converted to the type `Y`. If the types `I<X>` and `I<Y>` always also have that same special relationship, we say, "`I<T>` is covariant in `T`." When dealing with simple generic types with only one type parameter, the type parameter can be understood and we simply say, "`I<T>` is covariant." The conversion from `I<X>` to `I<Y>` is called a **covariant conversion.** 2.0

For example, instances of a generic class, `Pair<Contact>` and `Pair<PdaItem>`, are not type-compatible even when the type arguments are themselves compatible. In other words, the compiler prevents the conversion (implicit or explicit) of `Pair<Contact>` to `Pair<PdaItem>`, even though `Contact` derives from `PdaItem`. Similarly, converting `Pair<Contact>` to the interface type `IPair<PdaItem>` will also fail. See Listing 11.40 for an example.

LISTING 11.40: Conversion between Generics with Different Type Parameters

```
// ...
// Error: Cannot convert type ...
Pair<PdaItem> pair = (Pair<PdaItem>) new Pair<Contact>();
IPair<PdaItem> duple = (IPair<PdaItem>) new Pair<Contact>();
```

But why is this not legal? Why are `List<T>` and `Pair<T>` not covariant? Listing 11.41 shows what would happen if the C# language allowed unrestricted generic covariance.

LISTING 11.41: Preventing Covariance Maintains Homogeneity

```
//...
Contact contact1 = new Contact("Princess Buttercup"),
Contact contact2 = new Contact("Inigo Montoya");
Pair<Contact> contacts = new Pair<Contact>(contact1, contact2);

// This gives an error: Cannot convert type ...
// But suppose it did not.
// IPair<PdaItem> pdaPair = (IPair<PdaItem>) contacts;
// This is perfectly legal, but not type-safe.
// pdaPair.First = new Address("123 Sesame Street");
...
```

An `IPair<PdaItem>` can contain an address, but the object is really a `Pair<Contact>` that can contain only contacts, not addresses. Type safety is completely violated if unrestricted generic covariance is allowed.

Now it should also be clear why a list of strings may not be used as a list of objects. You cannot insert an integer into a list of strings, but you can insert an integer into a list of objects; thus it must be illegal to cast a list of strings to a list of objects, an error the compiler can enforce.

2.0

Begin 4.0

Enabling Covariance with the out Type Parameter Modifier in C# 4.0

You might have noticed that both of the problems described earlier as consequences of unrestricted covariance arise because the generic pair and the generic list allow their contents to be written. Suppose we eliminated this possibility by making a read-only `IReadOnlyPair<T>` interface that exposes `T` only as coming "out" of the interface (that is, used as the return type of a method or read-only property) and never going "into" it (that is, used as a formal parameter or writeable property type). If we restricted ourselves to an "out only" interface with respect to `T`, the covariance problem just described would not occur (see Listing 11.42).

LISTING 11.42: Potentially Possible Covariance

```
interface IReadOnlyPair<T>
{
  T First { get; }
  T Second { get; }
}

interface IPair<T>
{
  T First { get; set; }
  T Second { get; set; }
}

public struct Pair<T> : IPair<T>, IReadOnlyPair<T>
{
  // ...
}

class Program
{
  static void Main()
  {
      // Error: Only theoretically possible without
      // the out type parameter modifier
      Pair<Contact> contacts =
          new Pair<Contact>(
              new Contact("Princess Buttercupt"),
              new Contact("Inigo Montoya") );
      IReadOnlyPair<PdaItem> pair = contacts;
      PdaItem pdaItem1 = pair.First;
      PdaItem pdaItem2 = pair.Second;
  }
}
```

4.0

2.0

When we restrict the generic type declaration to expose data only as it comes out of the interface, there is no reason for the compiler to prevent covariance. All operations on an `IReadOnlyPair<PdaItem>` instance would convert `Contacts` (from the original `Pair<Contact>` object) up to the base class `PdaItem`—a perfectly valid conversion. There is no way to "write" an address into the object that is really a pair of contacts, because the interface does not expose any writeable properties.

The code in Listing 11.42 still does not compile. However, support for safe covariance was added to C# 4. To indicate that a generic interface is intended to be covariant in one of its type parameters, you can declare the type parameter with the `out` type parameter modifier. Listing 11.43 shows how to modify the interface declaration to indicate that it should be allowed to be covariant.

LISTING 11.43: Covariance Using the out Type Parameter Modifier

```
...
interface IReadOnlyPair<out T>
{
  T First { get; }
  T Second { get; }
}
```

4.0

Modifying the type parameter on the `IReadOnlyPair<out T>` interface with `out` will cause the compiler to verify that `T` is, indeed, used only for "outputs"—method return types and read-only property return types—and never for formal parameters or property setters. From then on, the compiler will allow any covariant conversions involving the interface to succeed. When this modification is made to the code in Listing 11.42, it will compile and execute successfully.

A number of important restrictions are placed on covariant conversions:

- Only generic interfaces and generic delegates (described in Chapter 12) may be covariant. Generic classes and structs are never covariant.
- The varying type arguments of both the "source" and "target" generic types must be reference types, not value types. That is, an `IReadOnlyPair<string>` may be converted covariantly to `IReadOnlyPair<object>` because both `string` and `IReadOnlyPair<object>` are reference types. An `IReadOnlyPair<int>` may not be converted to `IReadOnlyPair<object>` because `int` is not a reference type.
- The interface or delegate must be declared as supporting covariance, and the compiler must be able to verify that the annotated type parameters are, in fact, used in only "output" positions.

2.0

Enabling Contravariance with the `in` Type Parameter Modifier in C# 4.0

Covariance that "goes backward" is called **contravariance.** Again, suppose two types `X` and `Y` are related such that every value of the type `X` may be converted to the type `Y`. If the types `I<X>` and `I<Y>` always have that same special relationship "backward"—that is, every value of the type `I<Y>` can be converted to the type `I<X>`—we say, "`I<T>` is contravariant in `T`."

Most people find that contravariance is much harder to comprehend than covariance is. The canonical example of contravariance is a comparer. Suppose you have a derived type, `Apple`, and a base type, `Fruit`. Clearly, they have the special relationship: Every value of type `Apple` may be converted to `Fruit`.

Now suppose you have an interface `ICompareThings<T>` that has a method `bool FirstIsBetter(T t1, T t2)` that takes two `T`s, and returns a `bool` saying whether the first one is better than the second one.

What happens when we provide type arguments? An `ICompareThings<Apple>` has a method that takes two `Apple`s and compares them. An `ICompareThings<Fruit>` has a method that takes two `Fruit`s and compares them. But since every `Apple` is a `Fruit`, clearly a value of type `ICompareThings<Fruit>` can be safely used anywhere that an `ICompareThings<Apple>` is needed. The "direction" of the convertibility has been "reversed"; hence the term "contra-variance."

4.0

Perhaps unsurprisingly, the opposite of the restrictions on a covariant interface are necessary to ensure safe contravariance. An interface that is contravariant in one of its type parameters must use that type parameter only in "input" positions such as formal parameters (or in the types of write-only properties, which are extremely rare). You can mark an interface as being contravariant by declaring the type parameter with the `in` modifier, as shown in Listing 11.44.

LISTING 11.44: Contravariance Using the `in` Type Parameter Modifier

```
class Fruit {}
class Apple : Fruit {}
class Orange : Fruit {}
```

2.0

```
interface ICompareThings<in T>
{
```

```
    bool FirstIsBetter(T t1, T t2);
  }
```

```
  class Program
  {
    class FruitComparer : ICompareThings<Fruit>
    { ... }
    static void Main()
    {
        // Allowed in C# 4.0
        ICompareThings<Fruit> fc = new FruitComparer();
        Apple apple1 = new Apple();
        Apple apple2 = new Apple();
        Orange orange = new Orange();
        // A fruit comparer can compare apples and oranges:
        bool b1 = fc.FirstIsBetter(apple1, orange);
        // or apples and apples:
        bool b2 = fc.FirstIsBetter(apple1, apple2);
        // This is legal because the interface is
        // contravariant.
        ICompareThings<Apple> ac = fc;
        // This is really a fruit comparer, so it can
        // still compare two apples.
        bool b3 = ac.FirstIsBetter(apple1, apple2);
    }
  }
```

4.0

Similar to covariance support, contravariance uses a type parameter modifier: `in`, which appears in the interface's type parameter declaration. This instructs the compiler to check that `T` never appears on a property getter or as the return type of a method, thereby enabling contravariant conversions for this interface.

Contravariant conversions have all the analogous restrictions as described earlier for covariant conversions: They are valid only for generic interface and delegate types, the varying type arguments must be reference types, and the compiler must be able to verify that the interface is safe for the contravariant conversions.

2.0

An interface can be covariant in one type parameter and contravariant in another, but this seldom arises in practice except with delegates. The `Func<A1, A2, …, R>` family of delegates, for example, are covariant in the return type, `R`, and contravariant in all of the argument types.

Lastly, note that the compiler will check the validity of the covariance and contravariance type parameter modifiers throughout the source. Consider the `PairInitializer<in T>` interface in Listing 11.45.

LISTING 11.45: Compiler Validation of Variance

```
// ERROR:  Invalid variance; the type parameter 'T' is not
//         invariantly valid
interface IPairInitializer<in T>
{
  void Initialize(IPair<T> pair);
}
```

```
// Suppose the code above were legal, and see what goes
// wrong:
class FruitPairInitializer : IPairInitializer<Fruit>
{
  // Let's initiaize our pair of fruit with an
  // apple and an orange:
  public void Initialize(IPair<Fruit> pair)
  {
    pair.First = new Orange();
    pair.Second = new Apple();
  }
}
```

```
  // ... later ...
  var f = new FruitPairInitializer();
  // This would be legal if contravariance were legal:
  IPairInitializer<Apple> a = f;
  // And now we write an orange into a pair of apples:
  a.Initialize(new Pair<Apple>());
```

4.0

A casual observer might be tempted to think that since `IPair<T>` is used only as an "input" formal parameter, the contravariant `in` modifier on `IPairInitializer` is valid. However, the `IPair<T>` interface cannot safely vary, so it cannot be constructed with a type argument that can vary. As you can see, this would not be type-safe and, in turn, the compiler disallows the `IPairInitializer<T>` interface from being declared as contravariant in the first place.

Support for Unsafe Covariance in Arrays

2.0

So far we have described covariance and contravariance as being properties of generic types. Of all the nongeneric types, arrays are most like generics; that is, just as we think of a generic "list of T" or a generic "pair of T," so we can think of an "array of T" as being the same sort of pattern. Since arrays clearly support both reading and writing, given what you know about covariance and contravariance, you probably would suppose that arrays may be neither safely contravariant nor covariant. That is, you might imagine that an array can be safely covariant only if it is never written to, and safely contravariant only if it is never read from—though neither seems like a realistic restriction.

Unfortunately, C# does support array covariance, even though doing so is not type-safe. For example, `Fruit[] fruits = new Apple[10];` is perfectly legal in C#. If you then include the expression `fruits[0] = new Orange();`, the runtime will issue a type safety violation in the form of an exception. It is deeply disturbing that it is not always legal to assign an `Orange` into an array of `Fruit` because it might really be an array of `Apple`s, but that is the situation in not just C#, but all CLR languages that use the runtime's implementation of arrays.

Try to avoid using unsafe array covariance. Every array is convertible to the read-only (and therefore safely covariant) interface `IEnumerable<T>`; that is, `IEnumerable<Fruit> fruits = new Apple[10]` is both safe and legal because there is no way to insert an `Orange` into the array if all you have is the read-only interface.

Guidelines

AVOID unsafe array covariance. Instead, **CONSIDER** converting the array to the read-only interface `IEnumerable<T>`, which can be safely converted via covariant conversions.

End 4.0

Generic Internals

Given the discussions in earlier chapters about the prevalence of objects within the CLI type system, it should come as no surprise to learn that generics are also objects. In fact, the type parameter on a generic class becomes metadata that the runtime uses to build appropriate classes when needed. Generics, therefore, support inheritance, polymorphism, and encapsulation. With generics, you can define methods, properties, fields, classes, interfaces, and delegates.

2.0

To achieve this, generics require support from the underlying runtime. In turn, the addition of generics to the C# language is a feature of both the compiler and the platform. To avoid boxing, for example, the implementation of generics is different for value-based type parameters than for generics with reference type parameters.

ADVANCED TOPIC

CIL Representation of Generics

When a generic class is compiled, it is not significantly different from a nongeneric class. The result of the compilation is nothing but metadata and CIL. The CIL is parameterized to accept a user-supplied type somewhere in code. As an example, suppose you had a simple `Stack` class declared as shown in Listing 11.46.

LISTING 11.46: `Stack<T>` Declaration

```
public class Stack<T> where T : IComparable
{
    T[] items;
    // rest of the class here
}
```

When you compile the class, the generated CIL is parameterized and looks something like Listing 11.47.

LISTING 11.47: CIL Code for `Stack<T>`

```
.class private auto ansi beforefieldinit
    Stack'1<([mscorlib]System.IComparable)T>
    extends [mscorlib]System.Object
{
  ...
}
```

The first notable item is the `'1` that appears following `Stack` on the second line. That number is the arity. It declares the number of type parameters that the generic class will require type arguments for. A declaration such as `EntityDictionary<TKey, TValue>` would have an arity of 2.

The second line of the generated CIL shows the constraints imposed upon the class. The `T` type parameter is decorated with an interface declaration for the `IComparable` constraint.

If you continue looking through the CIL, you will find that the item's array declaration of type `T` is altered to contain a type parameter using "exclamation point notation," which is featured in the generics-capable version of the CIL. The exclamation point denotes the presence of the first type parameter specified for the class, as shown in Listing 11.48. 2.0

Listing 11.48: CIL with "Exclamation Point Notation" to Support Generics

```
.class public auto ansi beforefieldinit
     'Stack'1'<([mscorlib]System.IComparable) T>
     extends [mscorlib]System.Object
{
    .field private !0[ ] items
    ...
}
```

Beyond the inclusion of the arity and type parameter in the class header and the type parameter denoted with exclamation points in code, there is little difference between the CIL generated for a generic class and the CIL generated for a nongeneric class.

ADVANCED TOPIC

Instantiating Generics Based on Value Types

When a generic type is first constructed with a value type as a type parameter, the runtime creates a specialized generic type with the supplied type parameter(s) placed appropriately in the CIL. Therefore, the runtime creates new specialized generic types for each new parameter value type.

For example, suppose some code declared a `Stack` constructed of integers, as shown in Listing 11.49.

Listing 11.49: `Stack<int>` Definition

```
Stack<int> stack;
```

When using this type, `Stack<int>`, for the first time, the runtime generates a specialized version of the `Stack` class with the type argument `int` substituted for its type parameter. From then on, whenever the code uses a `Stack<int>`, the runtime reuses the generated specialized `Stack<int>` class. In Listing 11.50, you declare two instances of a `Stack<int>`, both using the
2.0 code already generated by the runtime for a `Stack<int>`.

Listing 11.50: Declaring Variables of Type `Stack<T>`

```
Stack<int> stackOne = new Stack<int>();
Stack<int> stackTwo = new Stack<int>();
```

If later in the code, you create another `Stack` with a different value type substituted for the type parameter (such as a `long` or a user-defined `struct`) the runtime will generate another version of the generic type. The benefit of specialized value type classes is better performance. Furthermore, the code is able to avoid conversions and boxing because each specialized generic class "natively" contains the value type.

ADVANCED TOPIC

Instantiating Generics Based on Reference Types

Generics work slightly differently for reference types. The first time a generic type is constructed with a reference type, the runtime creates a specialized generic type with `object` references substituted for type parameters in the CIL, not a specialized generic type based on the type argument. Each subsequent time a constructed type is instantiated with a reference type parameter, the runtime reuses the previously generated version of the generic type, even if the reference type is different from the first reference type.

For example, suppose you have two reference types: a `Customer` class and an `Order` class. Next, you create an `EntityDictionary` of `Customer` types:

```
EntityDictionary<Guid, Customer> customers;
```

Prior to accessing this class, the runtime generates a specialized version of the `EntityDictionary` class that, instead of storing `Customer` as the specified data type, stores `object` references. Suppose the next line of code creates an `EntityDictionary` of another reference type, called `Order`:

```
EntityDictionary<Guid, Order> orders =
    new EntityDictionary<Guid, Order>();
```

Unlike with value types, no new specialized version of the `EntityDictionary` class is created for the `EntityDictionary` that uses the `Order` type. Instead, an instance of the version of `EntityDictionary` that uses `object` references is instantiated and the `orders` variable is set to reference it.

To still gain the advantage of type safety, for each object reference substituted in place of the type parameter, an area of memory for an `Order` type is specifically allocated and the pointer is set to that memory reference.

2.0

Suppose you then encountered a line of code to instantiate an `EntityDictionary` of a `Customer` type as follows:

```
customers = new EntityDictionary<Guid, Customer>();
```

As with the previous use of the `EntityDictionary` class created with the `Order` type, another instance of the specialized `EntityDictionary` class (the one based on `object` references) is instantiated and the pointers contained therein are set to reference a `Customer` type specifically. This implementation of generics greatly reduces code bloat by reducing to one the number of specialized classes created by the compiler for generic classes of reference types.

Even though the runtime uses the same internal generic type definition when the type parameter on a generic reference type varies, this behavior is superseded if the type parameter is a value type. `Dictionary<int, Customer>`, `Dictionary<Guid, Order>`, and `Dictionary<long, Order>` will require new internal type definitions, for example.

Language Contrast: Java—Generics

The implementation of generics in Java occurs entirely within the compiler, not within the Java Virtual Machine. Sun adopted this approach to ensure that no updated Java Virtual Machine would need to be distributed because generics were used.

The Java implementation uses syntax similar to the templates in C++ and the generics in C#, including type parameters and constraints. Because it does not treat value types differently from reference types, however, the unmodified Java Virtual Machine cannot support generics for value types. As such, generics in Java do not offer the same gains in execution efficiency as they do in C#. Indeed, whenever the Java compiler needs to return data, it injects automatic downcasts from the specified constraint, if one is declared, or the base `Object` type, if it is not declared. Further, the Java compiler generates a single specialized type at compile time, which it then uses to instantiate any constructed type. Finally, because the Java Virtual Machine does not support generics natively, there is no way to ascertain the type parameter for an instance of a generic type at execution time, and other uses of reflection are severely limited.

2.0

SUMMARY

The addition of generic types and methods to C# 2.0 fundamentally transformed the coding style of C# developers. In almost all cases in which programmers used `object` within C# 1.0 code, generics became a better choice in C# 2.0. In modern C# programs, using `object` (particularly in the context of any collection type) should make you consider whether the problem would be better solved with generics. The increased type safety enabled by elimination of casts, the elimination of the boxing performance penalty, and reduction of repeated code are all significant improvements.

Chapter 16 looks at one of the most pervasive generic namespaces, `System.Collections.Generic`. As its name implies, this namespace is composed almost exclusively of generic types. It provides clear examples of how some types that originally used objects were then converted to use generics. However, before we tackle these topics, we will investigate expressions, which provide a significant C# 3.0 (and later) improvement for working with collections.

End 2.0

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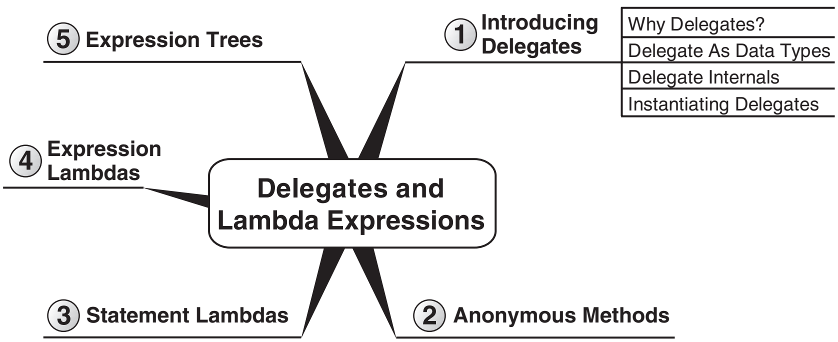
12

Delegates and Lambda Expressions

PREVIOUS CHAPTERS DISCUSSED EXTENSIVELY HOW to create classes to encapsulate data and operations on data. As you create more and more classes, you will see common patterns in the relationships among them. One common pattern is to pass an object to a method solely so that the method can, in turn, call a method on the object. For example, if you pass to a method a reference to `IComparer<int>`, odds are good that the called method will itself call the `Compare()` method on the object you provided. In this case, the interface is nothing more than a way to pass a reference to a single method that can be invoked. It seems unnecessary to have to define a new interface every time you want to pass a method around. In this chapter we describe how to create and use a special kind of class called a *delegate* that enables you to treat references to methods as you would any other data. We then show how to create custom delegates quickly and easily with *lambda expressions*.

Lambda expressions were added to the language in C# 3.0; the previous version, C# 2.0, supported a less elegant syntax for custom delegate creation called anonymous methods. Every version of C# after C# 2.0 supports anonymous methods for backward compatibility, but in new code they should be deprecated in favor of using lambda expressions. This chapter includes Advanced Topic blocks that describe how to use anonymous methods should you need to work with legacy C# 2.0 code; you can largely ignore these sections if you are working only with newer code.

We conclude the chapter with a discussion of expression trees, which enable you to use the compiler's analysis of a lambda expression at execution time.



Introducing Delegates

Veteran C and C++ programmers have long used "function pointers" as a mechanism for passing a reference to one method as an argument to another method. C# achieves similar functionality by using **delegates.** Delegates allow you to capture a reference to a method and pass it around like any other object, and to call the captured method like any other method. Let's consider an example illustrating how this technique might be useful.

Defining the Scenario

Although it is not very efficient, one of the simplest sort routines is the bubble sort. Listing 12.1 shows the `BubbleSort()` method.

Listing 12.1: `BubbleSort()` Method

```
static class SimpleSort1
{
  public static void BubbleSort(int[] items)
  {
      int i;
      int j;
      int temp;
```

```
        if(items==null)
        {
          return;
        }

        for (i = items.Length - 1; i >= 0; i--)
        {
            for (j = 1; j <= i; j++)
            {
                if (items[j - 1] > items[j])
                {
                    temp = items[j - 1];
                    items[j - 1] = items[j];
                    items[j] = temp;
                }
            }
        }
    }
    // ...
  }
```

This method will sort an array of integers in ascending order.

Suppose you need to sort the integers in Listing 12.1 in either ascending or descending order. You could duplicate the code and replace the greater-than operator with a less-than operator, but it seems like a bad idea to replicate several dozen lines of code merely to change a single operator. As a less verbose alternative, you could pass in an additional parameter indicating how to perform the sort, as shown in Listing 12.2.

LISTING 12.2: `BubbleSort()` Method, Ascending or Descending

```
  class SimpleSort2
  {
    public enum SortType
    {
        Ascending,
        Descending
    }

    public static void BubbleSort(int[] items, SortType sortOrder)
    {
        int i;
        int j;
        int temp;

        if(items==null)
        {
          return;
        }
```

```
        for (i = items.Length - 1; i >= 0; i--)
        {
            for (j = 1; j <= i; j++)
            {
                bool swap = false;
                switch (sortOrder)
                {
                    case SortType.Ascending :
                        swap = items[j - 1] > items[j];
                        break;

                    case SortType.Descending :
                        swap = items[j - 1] < items[j];
                        break;
                }
                if (swap)
                {
                    temp = items[j - 1];
                    items[j - 1] = items[j];
                    items[j] = temp;
                }
            }
        }
    }
    // ...
}
```

However, this code handles only two of the possible sort orders. If you wanted to sort them lexicographically (that is, 1, 10, 11, 12, 2, 20, …), or order them via some other criterion, it would not take long before the number of SortType values and the corresponding switch cases would become cumbersome.

Delegate Data Types

To increase flexibility and reduce code duplication in the previous code listings, you can make the comparison method a parameter to the BubbleSort() method. To pass a method as an argument, a data type is required to represent that method; this data type is called a delegate because it "delegates" the call to the method referred to by the object. Listing 12.3 includes a modification to the BubbleSort() method that takes a delegate parameter. In this case, the delegate data type is ComparisonHandler.

LISTING 12.3: BubbleSort() with Delegate Parameter

```
class DelegateSample
{
```

```
    // ...

    public static void BubbleSort(
        int[] items, ComparisonHandler comparisonMethod)
    {
        int i;
        int j;
        int temp;

        if(comparisonMethod == null)
        {
            throw new ArgumentNullException("comparisonMethod");
        }

        if(items==null)
        {
          return;
        }

        for (i = items.Length - 1; i >= 0; i--)
        {
            for (j = 1; j <= i; j++)
            {
                if (comparisonMethod(items[j - 1], items[j]))
                {
                  temp = items[j - 1];
                  items[j - 1] = items[j];
                  items[j] = temp;
                }
            }
        }
    }
    // ...
}
```

The delegate type `ComparisonHandler` represents a method that compares two integers. Within the `BubbleSort()` method, you then use the instance of the `ComparisonHandler`, referred to by the `comparisonMethod` parameter, to determine which integer is greater. Since `comparisonMethod` represents a method, the syntax to invoke the method is identical to calling any other method. In this case, the `ComparisonHandler` delegate takes two integer parameters and returns a Boolean value that indicates whether the first integer is greater than the second one.

Note that the `ComparisonHandler` delegate is strongly typed to represent a method that returns a `bool` and accepts exactly two integer parameters. Just as with any other method call, the call to a delegate is strongly typed, and if the data types for the arguments are not compatible with the parameters, the C# compiler reports an error.

Declaring a Delegate Type

You just saw how to define a method that uses a delegate, and you learned how to invoke a call to the delegate simply by treating the delegate variable as a method. However, you have yet to learn how to declare a delegate type. To declare a delegate type, you use the `delegate` keyword and follow it with what looks like a method declaration. The signature of that method is the signature of the method that the delegate can refer to, and the name of the delegate type appears where the name of the method would appear in a method declaration. Listing 12.4 shows how to declare the `ComparisonHandler` delegate type to require two integers and return a Boolean value.

Listing 12.4: Declaring a Delegate Type

```
public delegate bool ComparisonHandler (
  int first, int second);
```

Just as classes can be nested in other classes, so delegates can also be nested in classes. If the delegate declaration appeared within another class, the delegate type would be a nested type, as shown in Listing 12.5.

Listing 12.5: Declaring a Nested Delegate Type

```
class DelegateSample
{
  public delegate bool ComparisonHandler (
    int first, int second);
}
```

In this case, the data type would be `DelegateSample.ComparisonHandler` because it is defined as a nested type within `DelegateSample`.

Instantiating a Delegate

In this final step of implementing the `BubbleSort()` method with a delegate, you will learn how to call the method and pass a delegate instance—specifically, an instance of type `ComparisonHandler`. To instantiate a delegate, you need a method with parameters and a return type that matches the signature of the delegate type itself. In the case of `ComparisonHandler`, that method takes two integers and returns a `bool`. The name of the method need not match the name of the delegate, but the rest of the method signature must be compatible with the delegate signature. Listing 12.6 shows the code for a greater-than method compatible with the delegate type.

Listing 12.6: Declaring a `ComparisonHandler`-Compatible Method

```
public delegate bool ComparisonHandler (
  int first, int second);

class DelegateSample
{
  public static void BubbleSort(
    int[] items, ComparisonHandler comparisonMethod)
  {
      // ...
  }

  public static bool GreaterThan(int first, int second)
  {
    return first > second;
  }
  // ...
}
```

With this method defined, you can call `BubbleSort()` and supply as the argument the name of the method that is to be captured by the delegate, as shown in Listing 12.7.

Listing 12.7: Using a Method Name As an Argument

```
public delegate bool ComparisonHandler (
   int first, int second);

class DelegateSample
{
  public static void BubbleSort(
      int[] items, ComparisonHandler comparisonMethod)
  {
       // ...
  }

  public static bool GreaterThan(int first, int second)
  {
      return first > second;
  }

  static void Main()
```

```
    {
        int i;
        int[] items = new int[5];

        for (i=0; i < items.Length; i++)
        {
            Console.Write("Enter an integer: ");
            items[i] = int.Parse(Console.ReadLine());
        }

        BubbleSort(items, GreaterThan);

        for (int i = 0; i < items.Length; i++)
        {
            Console.WriteLine(items[i]);
        }
    }

}
```

Note that the `ComparisonHandler` delegate is a reference type, but you do not necessarily use `new` to instantiate it. The conversion from the **method group**—the expression that names the method—to the delegate type automatically creates a new delegate object in C# 2.0 and later.

ADVANCED TOPIC

Delegate Instantiation in C# 1.0

In Listing 12.7, the delegate was instantiated by simply passing the name of the desired method, `GreaterThan`, as an argument to the call to the `BubbleSort()` method. The first version of C# required instantiation of the delegate, using the more verbose syntax shown in Listing 12.8.

Listing 12.8: Passing a Delegate As a Parameter in C# 1.0

```
        BubbleSort(items,
            new ComparisonHandler(GreaterThan));
```

Later versions support both syntaxes; throughout the remainder of the book we will show only the modern, concise syntax.

ADVANCED TOPIC

Delegate Internals

A delegate is actually a special kind of class. Although the C# standard does not specify exactly what the class hierarchy is, a delegate must always derive directly or indirectly from `System.Delegate`. In fact, in .NET, delegate types always derive from `System.MulticastDelegate`, which in turn derives from `System.Delegate`, as shown in Figure 12.1.

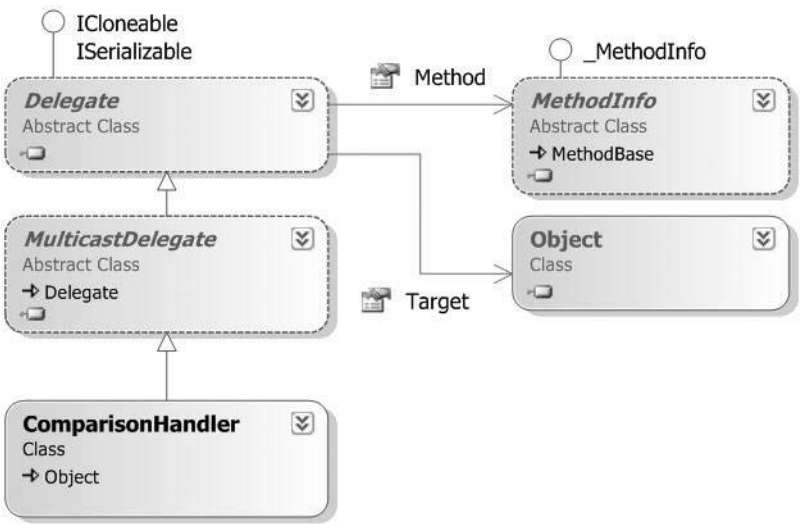


FIGURE 12.1: Delegate Types Object Model

The first property is of type `System.Reflection.MethodInfo`, which we cover in Chapter 17. `MethodInfo` describes the signature of a particular method, including its name, parameters, and return type. In addition to `MethodInfo`, a delegate needs the instance of the object containing the method to invoke. This is the purpose of the second property, `Target`. In the case of a static method, `Target` corresponds to the type itself. The purpose of the `MulticastDelegate` class is the topic of the next chapter.

Note that all delegates are immutable; that is, you cannot change a delegate once you have created it. If you have a variable that contains a reference to a delegate and you want it to refer to a different method, you must create a new delegate and assign it to the variable.

Although all delegate data types derive indirectly from `System.Delegate`, the C# compiler does not allow you to declare a class that derives directly or indirectly from `System.Delegate` or `System.MulticastDelegate`. As a consequence, the code shown in Listing 12.9 is not valid.

LISTING 12.9: `System.Delegate` Cannot Explicitly Be a Base Class

```
// ERROR: 'ComparisonHandler' cannot
// inherit from special class 'System.Delegate'
public class ComparisonHandler: System.Delegate
{
  // ...
}
```

Passing the delegate to specify the sort order is a significantly more flexible strategy than using the approach described at the beginning of this chapter. By passing a delegate you can change the sort order to be alphabetical simply by adding an alternative delegate to convert integers to strings as part of the comparison. Listing 12.10 shows a full listing that demonstrates alphabetical sorting, and Output 12.1 shows the results.

LISTING 12.10: Using a Different `ComparisonHandler`-Compatible Method

```
using System;
class DelegateSample
{

  public delegate bool ComparisonHandler(int first, int second);

  public static void BubbleSort(
      int[] items, ComparisonHandler comparisonMethod)
  {
      int i;
      int j;
      int temp;

      for (i = items.Length - 1; i >= 0; i--)
      {
          for (j = 1; j <= i; j++)
          {
              if (comparisonMethod(items[j - 1], items[j]))
              {
                  temp = items[j - 1];
                  items[j - 1] = items[j];
                  items[j] = temp;
              }
          }
```

```
        }
    }

    public static bool GreaterThan(int first, int second)
    {
        return first > second;
    }

    public static bool AlphabeticalGreaterThan(
        int first, int second)
    {
        int comparison;
        comparison = (first.ToString().CompareTo(
            second.ToString()));

        return comparison > 0;
    }

    static void Main(string[] args)
    {
        int i;
        int[] items = new int[5];

        for (i=0; i<items.Length; i++)
        {
            Console.Write("Enter an integer: ");
            items[i] = int.Parse(Console.ReadLine());
        }

        BubbleSort(items, AlphabeticalGreaterThan);

        for (i = 0; i < items.Length; i++)
        {
            Console.WriteLine(items[i]);
        }
    }
}
```

OUTPUT 12.1

```
Enter an integer: 1
Enter an integer: 12
Enter an integer: 13
Enter an integer: 5
Enter an integer: 4
1
12
13
4
5
```

The alphabetic order is different from the numeric order. Even so, notice how simple it was to add this additional sort mechanism compared to the process used at the beginning of the chapter. The only changes to create the alphabetical sort order were the addition of the `AlphabeticalGreaterThan` method and then passing that method into the call to `BubbleSort()`.

Begin 3.0

Lambda Expressions

In Listings 12.7 and 12.10, we saw that you can convert the expressions `GreaterThan` and `AlphabeticalGreaterThan` to a delegate type that is compatible with the parameter types and the return type of the named method. You might have noticed that the declaration of the `GreaterThan` method—the code that says it is a public, static, `bool`-returning method with two parameters of type `int` named `first` and `second`—was considerably larger than the body of the method, which simply compared its two parameters and returned the result. It is unfortunate that so much "ceremony" has to surround such a simple method merely so that it can be converted to a delegate type.

To address this concern, C# 2.0 introduced a far more compact syntax for creating a delegate, and C# 3.0 introduced several even more compact syntaxes than C# 2.0's syntax. The C# 2.0 feature is called **anonymous methods,** while the C# 3.0 feature is called **lambda expressions.** When referring generally to either syntax, we'll refer to them as **anonymous functions.** Both syntaxes are still legal, but for new code the lambda expression syntax is preferred over the anonymous method syntax. Throughout this book we will generally use the lambda expression syntax except when specifically describing C# 2.0 anonymous methods.

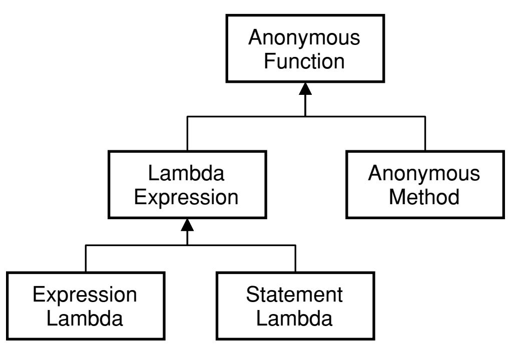


FIGURE 12.2: Anonymous Function Terminology

Lambda expressions are themselves divided into two types: **statement lambdas** and **expression lambdas.** Figure 12.2 shows the hierarchical relationship between these terms.

Statement Lambdas

The purpose of a lambda expression is to eliminate the hassle of declaring an entirely new member when you need to make a delegate from a very simple method. Several different forms of lambda expressions exist. A statement lambda, for example, consists of a formal parameter list, followed by the lambda operator `=>`, followed by a code block.

Listing 12.11 shows equivalent functionality to the call to `BubbleSort` from Listing 12.7, except that Listing 12.11 uses a statement lambda to represent the comparison method, rather than creating a `GreaterThan` method. As you can see, much of the information that appeared in the `GreaterThan` method declaration is included in the statement lambda; the formal parameter declarations and the block are the same, but the method name and its modifiers are missing.

LISTING 12.11: Creating a Delegate with a Statement Lambda

```
// ...

    BubbleSort(items,
        (int first, int second) =>
        {
            return first < second;
        }
    );

// ...
```

3.0

When reading code that includes a lambda operator, you would replace the lambda operator with the words *go/goes to.* For example, in Listing 12.11, you would read the second `BubbleSort()` parameter as "integers `first` and `second` go to returning the result of `first` less than `second`."

As readers will observe, the syntax in Listing 12.11 is almost identical to that in Listing 12.7, apart from the fact that the comparison method is now found lexically where it is converted to the delegate type, rather than being found elsewhere and looked up by name. The name of the method is missing, which explains why such methods are called "anonymous functions."

The return type is missing, but the compiler can see that the lambda expression is being converted to a delegate whose signature requires the return type `bool`. The compiler verifies that the expressions of every `return` statement in the statement lambda's block would be legal in a `bool`-returning method. The `public` modifier is missing; given that the method is no longer an accessible member of the containing class, there is no need to describe its accessibility. Similarly, the `static` modifier is no longer necessary. The amount of "ceremony" around the method is already greatly reduced.

The syntax is still needlessly verbose, however. We have deduced from the delegate type that the lambda expression must be `bool`-returning; we can similarly deduce that both parameters must be of type `int`, as shown in Listing 12.12.

LISTING 12.12: Omitting Parameter Types from Statement Lambdas

```
    // ...

        BubbleSort(items,
            (first, second) =>
            {
                return first < second;
            }
        );

    // ...
```

3.0 In general, explicitly declared parameter types are optional in all lambda expressions if the compiler can infer the types from the delegate that the lambda expression is being converted to. For situations when specifying the type makes code more readable, however, C# enables you to do so. In cases where inference is not possible, the C# language requires that the lambda parameter types be stated explicitly. If one lambda parameter type is specified explicitly, then all of them must be specified explicitly, and they must all match the delegate parameter types exactly.

Guidelines

CONSIDER omitting the types from lambda formal parameter lists when the types are obvious to the reader, or when they are an insignificant detail.

One other means of reducing the syntax is possible, as shown in Listing 12.13: A lambda expression that has exactly one parameter whose type is inferred may omit the parentheses around the parameter list. If there are zero parameters or more than one parameter, or if the single parameter is explicitly typed, the lambda must have parentheses around the parameter list.

LISTING 12.13: Statement Lambdas with a Single Input Parameter

```
using System.Collections.Generic;
using System.Diagnostics;
using System.Linq;
  // ...
  IEnumerable<Process> processes = Process.GetProcesses().Where(
      process => { return process.WorkingSet64 > 1000000000; });
  // ...
```

In Listing 12.13, the `Where()` method returns a query for processes that have a physical memory utilization greater than 1 billion bytes. Contrast this with Listing 12.14, which has a parameterless statement lambda. The empty parameter list requires parentheses. Note also that in Listing 12.14, the body of the statement lambda includes multiple statements inside the statement block (via curly braces). Although a statement lambda can contain any number of statements, typically a statement lambda uses only two or three statements in its statement block. (The use of the generic `Func` delegate type is described in the section "General-Purpose Delegates: `System.Func` and `System.Action`" later in this chapter.)

3.0

LISTING 12.14: Parameterless Statement Lambdas

```
using System;
  // ...
  Func<string> getUserInput =
      () =>
      {
          string input;
          do
          {
              input = Console.ReadLine();
          }
          while(input.Trim().Length == 0);
          return input;
      };
  // ...
```

Expression Lambdas

The statement lambda syntax is already much less verbose than the corresponding method declaration; as we've seen, it need not declare the method's name, accessibility, return type, or parameter types. Nevertheless, we can get even less verbose by using an expression lambda. In Listings 12.12, 12.13, and 12.14, we saw statement lambdas whose blocks consisted of a single return statement. What if we eliminated the "ceremony" around that? The only relevant information in such a lambda block is the expression that is returned. An expression lambda contains only that returned expression, with no statement block at all. Listing 12.15 is the same as Listing 12.11, except that it uses an expression lambda rather than a statement lambda.

LISTING 12.15: Passing a Delegate with an Expression Lambda

```
    // ...
    BubbleSort(items, (first, second) => first < second );
    // ...
```

Generally, you would read the lambda operator `=>` in an expression lambda the same way as you would a statement lambda: as *goes to*, or *becomes*. When a lambda is used to return a `bool`, as it is in our `BubbleSort()` example, the lambda is called a **predicate.** In those cases it is common to read the lambda operator as *such that* or *where*. You might read the lambda in Listing 12.15 as "`first` and `second` such that `first` is less than `second`."

3.0 Like the `null` literal, an anonymous function does not have any type associated with it; rather, its type is determined by the type it is being converted to. In other words, the lambda expressions we've seen so far are not intrinsically of the `ComparisonHandler` type, but they are compatible with that type and may be converted to it. As a result, you cannot use the `typeof()` operator (see Chapter 17) on an anonymous method, and calling `GetType()` is possible only after you convert the anonymous method to a particular type.

Table 12.1 provides additional lambda expression characteristics.

TABLE 12.1: Lambda Expression Notes and Examples

<table>
<tr><th>Statement</th><th>Example</th></tr>
<tr><td>Lambda expressions themselves do not have a type. Therefore, there are no members that can be accessed directly from a lambda expression, not even the methods of <code>object</code>.</td><td><pre>// ERROR: Operator '.' cannot be applied to
// operand of type 'lambda expression'
string s = ((int x) => x).ToString();</pre></td></tr>
<tr><td>Lambda expressions do not have a type and so cannot appear to the left of an <code>is</code> operator.</td><td><pre>// ERROR: The first operand of an 'is' or 'as'
// operator may not be a lambda expression or
// anonymous method
bool b = ((int x) => x) is Func<int, int>;</pre></td></tr>
<tr><td>A lambda expression can be converted only to a compatible delegate type; here an <code>int</code>-returning lambda may not be converted to a delegate type that represents a <code>bool</code>-returning method.</td><td><pre>// ERROR: Lambda expression is not compatible
// with Func<int, bool> type.
Func<int, bool> f = (int x) => x;</pre></td></tr>
<tr><td>A lambda expression does not have a type, so it cannot be used to infer the type of a local variable.</td><td><pre>// ERROR: Cannot assign lambda expression to
// an implicitly typed local variable
var v = x => x;</pre></td></tr>
<tr><td>Jump statements (<code>break</code>, <code>goto</code>, <code>continue</code>) inside lambda expressions cannot be used to jump to locations outside the lambda expression, and vice versa. Here the <code>break</code> statement inside the lambda would jump to the end of the <code>switch</code> statement outside the lambda.</td><td><pre>// ERROR: Control cannot leave the body of an
// anonymous method or lambda expression
string[] args;
Func<string> f;
switch(args[0])
{
  case "/File":
      f = () =>
      {
          if (!File.Exists(args[1]))
              break;
          return args[1];
      };
      // ...
}</pre></td></tr>
<tr><td>Parameters and locals introduced by a lambda expression are in scope only within the lambda body.</td><td><pre>// ERROR: The name 'first' does not
// exist in the current context
Func<int, int, bool> expression =
    (first, second) => first > second;
first++;</pre></td></tr>
</table>

3.0

continues

TABLE 12.1: Lambda Expression Notes and Examples (*continued*)

Statement	Example

The compiler's definite assignment analysis is unable to detect initialization of "outer" local variables in lambda expressions.	`int number;`
	`Func<string, bool> f =`
	`  text => int.TryParse(text, out number);`
	`if (f("1"))`
	`{`
	`  // ERROR: Use of unassigned local variable`
	`  System.Console.Write(number);`
	`}`

	`int number;`
	`Func<int, bool> isFortyTwo =`
	`  x => 42 == (number = x);`
	`if (isFortyTwo(42))`
	`{`
	`    // ERROR: Use of unassigned local variable`
	`    System.Console.Write(number);`
	`}`

End 3.0

Begin 2.0

Anonymous Methods

Lambda expressions are not supported in C# 2.0. Instead, C# 2.0 uses a syntax called anonymous methods. An anonymous method is like a statement lambda, but without many of the features that make lambdas so compact. An anonymous method must explicitly type every parameter, and must have a statement block. Rather than using the lambda operator => between the parameter list and the code block, an anonymous method puts the keyword `delegate` before the parameter list, emphasizing that the anonymous method must be converted to a delegate type. Listing 12.16 shows the code from Listings 12.7, 12.12, and 12.15 rewritten to use an anonymous method.

LISTING 12.16: Passing an Anonymous Method in C# 2.0

```
        // ...
        BubbleSort(items,
            delegate(int first, int second)
            {
                return first < second;
            }
        );
        // ...
```

It is unfortunate that there are two very similar ways to define an anonymous function in C# 3.0 and later.

Guidelines

AVOID the anonymous method syntax in new code; prefer the more compact lambda expression syntax.

There is, however, one small feature that is supported in anonymous methods that is not supported in lambda expressions: Anonymous methods may omit their parameter list entirely in some circumstances.

ADVANCED TOPIC

Parameterless Anonymous Methods

Unlike lambda expressions, anonymous methods may omit the parameter list entirely provided that the anonymous method body does not use any parameter and the delegate type requires only "value" parameters (that is, it does not require the parameters to be marked as `out` or `ref`). For example, the anonymous method expression `delegate { return Console.ReadLine() != ""; }` is convertible to any delegate type that requires a return type of `bool` regardless of the number of parameters the delegate requires. This feature is not used frequently, but you might encounter it when reading legacy code. End 2.0

ADVANCED TOPIC

Why "Lambda" Expressions?

It is fairly obvious why anonymous methods are called "anonymous methods": They look very similar to method declarations but do not have a declared name associated with them. But where did the "lambda" in "lambda expressions" come from?

The idea of lambda expressions comes from the work of the logician Alonzo Church, who in the 1930s invented a technique for studying functions called the "lambda calculus." In Church's notation, a function that takes a parameter *x* and results in an expression *y* is notated by prefixing the entire expression with a small Greek letter lambda, and separating the parameter from the value with a dot. The C# lambda expression `x=>y` would be notated `λx.y` in Church's notation. Because it is inconvenient to use Greek letters in C# programs and because the dot already has many meanings in C#, the designers of C# chose to use the "fat arrow" notation rather than the original notation. The name "lambda expression" indicates that the theoretical underpinnings of the idea of anonymous functions are based on the lambda calculus, even though no letter lambda actually appears in the text.

Begin 3.0

Begin 4.0

General-Purpose Delegates: System.Func and System.Action

To reduce the need to define your own custom delegate types, the .NET 3.5 runtime library (which corresponds to C# 3.0) included a set of general-purpose delegates, most of them generic. The `System.Func` family of delegates is for referring to methods that return a value; the `System.Action` family of delegates is for referring to `void`-returning methods. The signatures for these delegates are shown in Listing 12.17 (although the `in`/`out` type modifiers were not added until C# 4.0, as discussed shortly).

Listing 12.17: Func and Action Delegate Declarations

```
public delegate void Action ();
public delegate void Action<in T>(T arg)
public delegate void Action<in T1, in T2>(
    in T1 arg1, in T2 arg2)
public delegate void Action<in T1, in T2, in T3>(
    T1 arg1, T2 arg2, T3 arg3)
public delegate void Action<in T1, in T2, in T3, in T4(
    T1 arg1, T2 arg2, T3 arg3, T4 arg4)
...
public delegate void Action<
    in T1, in T2, in T3, in T4, in T5, in T6, in T7, in T8,
    in T9, in T10, in T11, in T12, in T13, in T14, in T16(
        T1 arg1, T2 arg2, T3 arg3, T4 arg4,
        T5 arg5, T6 arg6, T7 arg7, T8 arg8,
        T9 arg9, T10 arg10, T11 arg11, T12 arg12,
        T13 arg13, T14 arg14, T15 arg15, T16 arg16)

public delegate TResult Func<out TResult>();
```

```
public delegate TResult Func<in T, out TResult>(T arg)
public delegate TResult Func<in T1, in T2, out TResult>(
    in T1 arg1, in T2 arg2)
public delegate TResult Func<in T1, in T2, in T3, out TResult>(
    T1 arg1, T2 arg2, T3 arg3)
public delegate TResult Func<in T1, in T2, in T3, in T4,
    out TResult>(T1 arg1, T2 arg2, T3 arg3, T4 arg4)
...
public delegate TResult Func<
    in T1, in T2, in T3, in T4, in T5, in T6, in T7, in T8,
    in T9, in T10, in T11, in T12, in T13, in T14, in T16,
    out TResult>(
        T1 arg1, T2 arg2, T3 arg3, T4 arg4,
        T5 arg5, T6 arg6, T7 arg7, T8 arg8,
        T9 arg9, T10 arg10, T11 arg11, T12 arg12,
        T13 arg13, T14 arg14, T15 arg15, T16 arg16)
```

Because the delegate definitions in Listing 12.17 are generic, it is possible to use them instead of defining a custom delegate. The last type parameter of a `Func` delegate is always the return type of the delegate. The other type parameters correspond in sequence to the types of the delegate parameters. The `BubbleSort` method in Listing 12.3, for example, requires a delegate that returns `bool` and takes two `int` parameters. Thus, rather than declaring the `ComparisonHandler` delegate type and using it, we could have declared the `BubbleSort` method as follows: 4.0

```
void BubbleSort(int[] items,
      Func<int, int, bool> comparisonMethod) { ... }
```

In many cases, the inclusion of `Func` and `Action` delegates in the .NET Framework 3.5 entirely eliminates the need to define your own delegate types. However, you should consider declaring your own delegate types when doing so significantly increases the readability of the code. A delegate named `ComparisonHandler` provides an explicit indication of what the delegate is used for, whereas using `Func<int, int, bool>` provides a more explicit indication of the delegate's formal parameters and return type. 3.0

Guidelines

CONSIDER whether the readability benefit of defining your own delegate type outweighs the convenience of using a predefined generic delegate type.

Delegates Do Not Have Structural Equality

Delegate types in .NET do not exhibit **structural equality.** That is, you cannot convert a reference to an object of one delegate type to an unrelated delegate type, even if the formal parameters and return types of both delegates are identical. For example, you cannot assign a reference to a `ComparisonHandler` to a variable of type `Func<int, int, bool>` even though both delegate types represent methods that take two `int` parameters and return a `bool`. Unfortunately, the only way to use a delegate of a given type when a delegate of a structurally identical but unrelated delegate type is needed is to create a new delegate that refers to the `Invoke` method of the old delegate. For example, if you have a variable `c` of type `ComparisonHandler`, and you need to assign its value to a variable `f` of type `Func<int, int, bool>`, you can say `f = c.Invoke;`.

However, thanks to the variance support added in C# 4.0, it is possible to make reference conversions between some delegate types. Consider the following contravariant example: Because `void Action<in T>(T arg)` has the `in` type parameter modifier, it is possible to assign a reference to a delegate of type `Action<object>` to a variable of type `Action<string>`.

4.0

Many people find delegate contravariance confusing; just remember that an action that can act on every object can be used as an action that acts on any string. But the opposite is not true: An action that can act only on strings cannot act on every object. Similarly, every type in the `Func` family of delegates is covariant in its return type, as indicated by the `out` type parameter modifier on `TResult`. Therefore it is possible to assign a reference to a delegate of type `Func<string>` to a variable of type `Func<object>`.

3.0

Listing 12.18 shows examples of delegate covariance and contravariance.

Listing 12.18: Using Variance for Delegates

```
// Contravariance
Action<object> broadAction =
  (object data) =>
  {
      Console.WriteLine(data);
  };
Action<string> narrowAction = broadAction;

// Covariance
Func<string> narrowFunction =
  () =>Console.ReadLine();
Func<object> broadFunction = narrowFunction;
```

```
// Contravariance and covariance combined
Func<object, string> func1 =
  (object data) => data.ToString();
Func<string, object> func2 = func1;
```

The last part of the listing combines both variance concepts into a single example, demonstrating how they can occur simultaneously if both `in` and `out` type parameters are involved.

Allowing reference conversions on generic delegate types was a key motivating scenario for adding covariant and contravariant conversions to C# 4.0. (The other was support for covariance to `IEnumerable<out T>`.)

End 4.0

ADVANCED TOPIC

Lambda Expression and Anonymous Method Internals

Lambda expressions (and anonymous methods) are not intrinsically "built in" to the CLR. Rather, when the compiler encounters an anonymous function, it translates it into special hidden classes, fields, and methods that implement the desired semantics. The C# compiler generates the implementation code for this pattern so that developers do not have to code this themselves. When given the code in Listing 12.11, 12.12, 12.15, or 12.16, the C# compiler generates CIL code that is similar to the code shown in Listing 12.19.

LISTING 12.19: C# Equivalent of CIL Generated by the Compiler for Lambda Expressions

3.0

```
class DelegateSample
{
  // ...
  static void Main(string[] args)
  {
      int i;
      int[] items = new int[5];

      for (i=0; i<items.Length; i++)
      {
          Console.Write("Enter an integer:");
          items[i] = int.Parse(Console.ReadLine());
      }


      BubbleSort(items,
```

```
            DelegateSample.__AnonymousMethod_00000000);

        for (i = 0; i < items.Length; i++)
        {
            Console.WriteLine(items[i]);
        }

    }

    private static bool __AnonymousMethod_00000000(
        int first, int second)
    {
        return first < second;
    }

}
```

In this example, the compiler transforms an anonymous function into a separately declared static method, which is then instantiated as a delegate and passed as a parameter. Unsurprisingly, the compiler generates code that looks remarkably like the original code in Listing 12.7, which the anonymous function syntax was intended to streamline. However, the code transformation performed by the compiler can be considerably more complex than merely rewriting the anonymous function as a static method if "outer variables" are involved.

Outer Variables

3.0

Local variables declared outside a lambda expression (including parameters of the containing method) are called the **outer variables** of that lambda. (The `this` reference, though technically not a variable, is also considered to be an outer variable.) When a lambda body uses an outer variable, the variable is said to be **captured** (or, equivalently, **closed over**) by the lambda. In Listing 12.20, we use an outer variable to count how many times `BubbleSort()` performs a comparison. Output 12.2 shows the results of this listing.

Listing 12.20: Using an Outer Variable in a Lambda Expression

```
class DelegateSample
{

  // ...
```

```
    static void Main(string[] args)
    {

        int i;
        int[] items = new int[5];
        int comparisonCount=0;

        for (i=0; i<items.Length; i++)
        {
            Console.Write("Enter an integer:");
            items[i] = int.Parse(Console.ReadLine());
        }

        BubbleSort(items,
            (int first, int second) =>
            {
                comparisonCount++;
                return first < second;
            }
        );

        for (i = 0; i < items.Length; i++)
        {
            Console.WriteLine(items[i]);
        }

        Console.WriteLine("Items were compared {0} times.",
                          comparisonCount);
    }
}
```

Output 12.2

```
Enter an integer:5
Enter an integer:1
Enter an integer:4
Enter an integer:2
Enter an integer:3
5
4
3
2
1
Items were compared 10 times.
```

3.0

Note that `comparisonCount` appears outside the lambda expression and is incremented inside it. After calling the `BubbleSort()` method, `comparisonCount` is printed out to the console.

Normally the lifetime of a local variable is tied to its scope; when control leaves the scope, the storage location associated with the variable is no longer valid. But a delegate created from a lambda that captures an outer variable might have a longer (or shorter) lifetime than the local variable normally would, and the delegate must be able to safely access the outer variable every time the delegate is invoked. Therefore, the lifetime of a captured variable is extended; it is guaranteed to live at least as long as the longest-lived delegate object capturing it. (And it may live even longer than that—precisely how the compiler generates code that ensures outer variable lifetimes are extended is an implementation detail and subject to change.)

The C# compiler takes care of generating CIL code that shares `comparisonCount` between the anonymous method and the method that declares it.

ADVANCED TOPIC

Outer Variable CIL Implementation

The CIL code generated by the C# compiler for anonymous functions that capture outer variables is more complex than the code for a simple anonymous function that captures nothing. Listing 12.21 shows the C# equivalent of the CIL code used to implement outer variables for the code in Listing 12.20.

3.0

LISTING 12.21: C# Equivalent of CIL Code Generated by Compiler for Outer Variables

```
class DelegateSample
{
  // ...
  private sealed class __LocalsDisplayClass_00000001
  {
      public int comparisonCount;
      public bool __AnonymousMethod_00000000(
          int first, int second)
      {
              comparisonCount++;
              return first < second;
      }
  }
  // ...
  static void Main(string[] args)
  {
      int i;
      __LocalsDisplayClass_00000001 locals =
          new __LocalsDisplayClass_00000001();
```

```
        locals.comparisonCount=0;
        int[] items = new int[5];

        for (i=0; i<items.Length; i++)
        {
            Console.Write("Enter an integer:");
            items[i] = int.Parse(Console.ReadLine());
        }

        BubbleSort(items, locals.__AnonymousMethod_00000000);
        for (i = 0; i < items.Length; i++)
        {
            Console.WriteLine(items[i]);
        }

        Console.WriteLine("Items were compared {0} times.",
                          locals.comparisonCount);
    }
  }
```

Notice that the captured local variable is never "passed" anywhere and is never "copied" anywhere. Rather, the captured local variable (`comparisonCount`) is a single variable whose lifetime the compiler has extended by implementing it as an instance field rather than as a local variable. All usages of the local variable are rewritten to be usages of the field.

The generated class, `__LocalsDisplayClass`, is a **closure**—a data structure (class in C#) that contains an expression and the variables (public fields in C#) necessary to evaluate the expression.

3.0

Begin 5.0

ADVANCED TOPIC

Accidentally Capturing Loop Variables

What do you think the output of Listing 12.22 should be?

Listing 12.22: Capturing Loop Variables in C# 5.0

```
class CaptureLoop
{
  static void Main()
  {
      var items = new string[] { "Moe", "Larry", "Curly" };
      var actions = new List<Action>();
      foreach (string item in items)
      {
          actions.Add( ()=> { Console.WriteLine(item); } );
```

```
        }
        foreach (Action action in actions)
        {
            action();
        }
    }
}
```

Most people expect that the output will be as shown in Output 12.3, and in C# 5.0 it is. In previous versions of C#, however, the output is as shown in Output 12.4.

5.0

OUTPUT 12.3: C# 5.0 OUTPUT

```
Moe
Larry
Curly
```

OUTPUT 12.4: C# 4.0 OUTPUT

```
Curly
Curly
Curly
```

A lambda expression captures a variable and always uses the latest value of the variable; it does not capture and preserve the value that the variable had when the delegate was created. This is normally what you want—after all, the whole point of capturing `comparisonCount` in Listing 12.20 was to ensure that its latest value would be used when it was incremented. Loop variables are no different; when you capture a loop variable, every delegate captures the same loop variable. When the loop variable changes, every delegate that captured this loop variable sees the change. The C# 4.0 behavior is therefore justified, but is almost never what the author of the code wants.

3.0

In C# 5.0, the C# language was changed so that the loop variable of a `foreach` loop is now considered to be a "fresh" variable every time the loop iterates; therefore, each delegate creation captures a different variable, rather than all iterations sharing the same variable. This change was not applied to the `for` loop, however: If you write similar code using a `for` loop, any loop variable declared in the header of the `for` statement will be considered a single outer variable when captured. If you need to write code that works the same in both C# 5.0 and previous C# versions, use the pattern shown in Listing 12.23.

Listing 12.23: Loop Variable Capture Workaround before C# 5.0

```
class DoNotCaptureLoop
{
  static void Main()
  {
      var items = new string[] { "Moe", "Larry", "Curly" };
      var actions = new List<Action>();
      foreach (string item in items)
      {
          string _item = item;
          actions.Add(
              ()=> { Console.WriteLine(_item); } );
      }
      foreach (Action action in actions)
      {
          action();
      }
  }
}
```

Now there is clearly one fresh variable per loop iteration; each delegate is, in turn, closed over a different variable.

End 5.0

3.0

Guidelines

AVOID capturing loop variables in anonymous functions.

Expression Trees

Thus far we've seen that lambda expressions are a succinct syntax for declaring an "inline" method that can be converted to a delegate type. Expression lambdas (but not statement lambdas or anonymous methods) can also be converted to **expression trees.** A delegate is an object that enables you to pass around a method like any other object and invoke it at any time. An expression tree is an object that enables you to pass around the compiler's analysis of the lambda body. But why would you ever need that capability? Obviously, the compiler's analysis is useful to the compiler when generating the CIL, but why is it useful to the developer to have an object representing that analysis at execution time? Let's take a look at an example.

Using Lambda Expressions As Data

Consider the lambda expression in the following code:

```
persons.Where(
    person => person.Name.ToUpper() == "INIGO MONTOYA");
```

Suppose that `persons` is an array of `Persons`, and the formal parameter of the `Where` method that corresponds to the lambda expression argument is of delegate type `Func<Person, bool>`. The compiler emits a method that contains the code in the body of the lambda. It generates code that creates a delegate to the emitted method and passes the delegate to the `Where` method. The `Where` method returns a query object that, when executed, applies the delegate to each member of the array to determine the query results.

Now suppose that `persons` is not of type `Person[]`, but rather is an object that represents a remote database table containing data on millions of people. Information about each row in the table can be streamed from the server to the client, and the client can then create a `Person` object corresponding to that row. The call to `Where` returns an object that represents the query. When the results of that query are requested on the client, how are the results determined?

One technique would be to transmit several million rows of data from
3.0 the server to the client. You could create a `Person` object from each row, create a delegate from the lambda, and execute the delegate on every `Person`. This is conceptually no different from the array scenario, but it is far, far more expensive.

A second, much better technique is to somehow send the meaning of the lambda ("filter out every row that names a person other than Inigo Montoya") to the server. Database servers are optimized to rapidly perform this sort of filtering. The server can then choose to stream only the tiny number of matching rows to the client; instead of creating millions of `Person` objects and rejecting almost all of them, the client creates only those objects that already match the query, as determined by the server. But how does the meaning of the lambda get sent to the server?

This scenario is the motivation for adding expression trees to the language. Lambda expressions converted to expression trees become objects that represent data that describes the lambda expression, rather than compiled code that implements an anonymous function. Since the expression tree represents data rather than compiled code, it is possible to analyze the lambda at execution time and use that information to construct a query that executes on a database, for example. The expression tree received by `Where()` might be converted into a SQL query that is passed to a database, as shown in Listing 12.24.

Listing 12.24: Converting an Expression Tree to a SQL `where` Clause

```
persons.Where( person => person.Name.ToUpper() == "INIGO MONTOYA");


select * from Person where upper(Name) = 'INIGO MONTOYA';
```

The expression tree passed to the `Where()` call says that the lambda argument consists of the following elements:

- A read of the `Name` property of a `Person` object
- A call to a `string` method called `ToUpper()`
- A constant value, `"INIGO MONTOYA"`
- An equality operator, `==`

The `Where()` method takes this data and converts it to the SQL `where` clause by examining the data and building a SQL query string. However, SQL is just one possibility; you can build an expression tree evaluator that converts expressions to any query language.

3.0

Expression Trees Are Object Graphs

At execution time, a lambda converted to an expression tree becomes an object graph containing objects from the `System.Linq.Expressions` namespace. The "root" object in the graph represents the lambda itself. This object refers to objects representing the parameters, a return type, and body expression, as shown in Figure 12.3. The object graph contains all the information that the compiler deduced about the lambda. That information can then be used at execution time to create a query. Alternatively, the root lambda expression has a method, `Compile`, that generates CIL "on the fly" and creates a delegate that implements the described lambda.

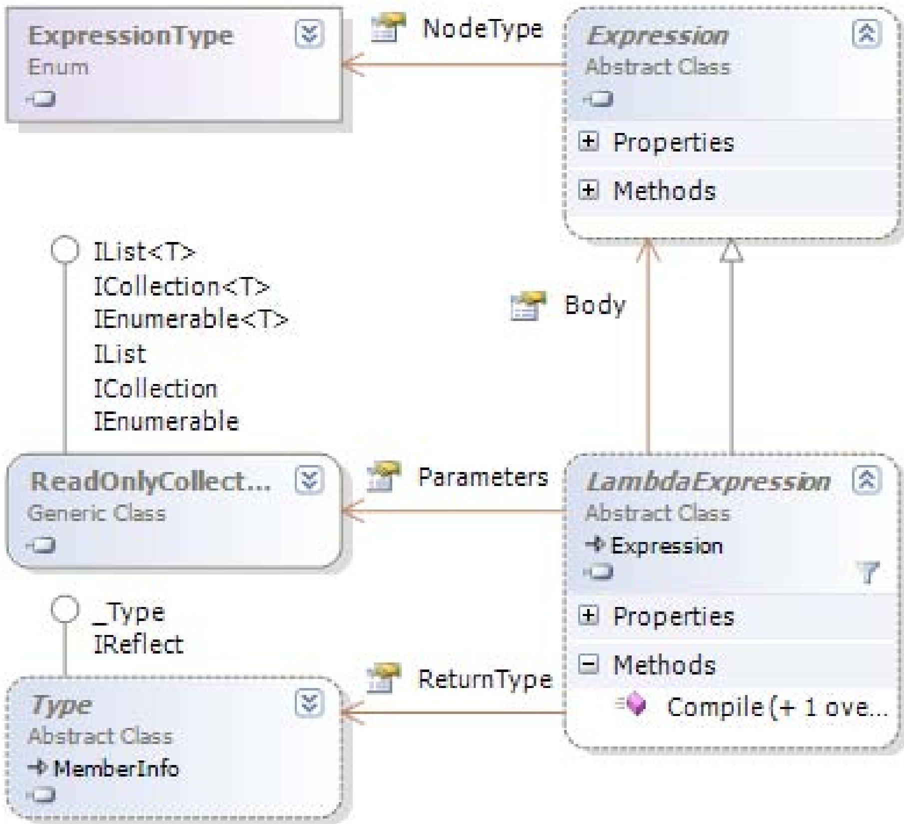


FIGURE 12.3: The Lambda Expression Tree Type

3.0

Figure 12.4 shows the types found in object graphs for a unary and binary expression in the body of a lambda.

A `UnaryExpression` represents an expression such as `-count`. It has a single child `Operand` of type `Expression`. A `BinaryExpression` has two child expressions, `Left` and `Right`. Both types have a `NodeType` property that identifies the specific operator, and both inherit from the base class `Expression`. There are another 30 or so expression types, such as `NewExpression`, `ParameterExpression`, `MethodCallExpression`, and `LoopExpression`, to represent (almost) every possible expression in C# and Visual Basic.

Delegates versus Expression Trees

The validity of a lambda expression is verified at compile time with a full semantic analysis, whether it is converted to a delegate or an expression

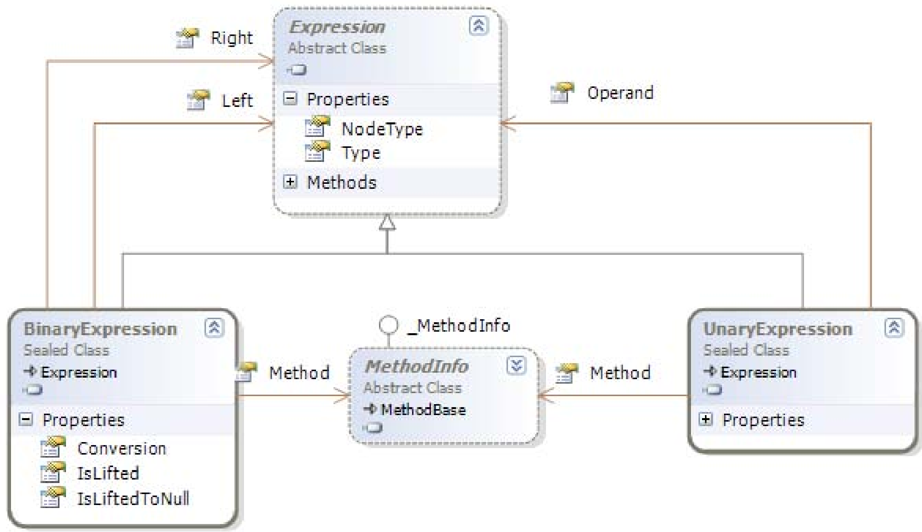


FIGURE 12.4: Unary and Binary Expression Tree Types

tree. A lambda that is converted to a delegate causes the compiler to emit the lambda as a method, and generates code that creates a delegate to that method at execution time. A lambda that is converted to an expression tree causes the compiler to generate code that creates an instance of `LambdaExpression` at execution time. But when using the Language Integrated Query (LINQ) API, how does the compiler know whether to generate a delegate, to execute a query locally, or to generate an expression tree so that information about the query can be sent to the remote database server? 3.0

The methods used to build LINQ queries, such as `Where()`, are extension methods. The versions of those methods that extend the `IEnumerable<T>` interface take delegate parameters; the methods that extend the `IQueryable<T>` interface take expression tree parameters. The compiler, therefore, can use the type of the collection that is being queried to determine whether to create delegates or expression trees from lambdas supplied as arguments.

Consider, for example, the `Where()` method in the following code:

```
persons.Where( person => person.Name.ToUpper() ==
    "INIGO MONTOYA");
```

The extension method signature declared in the `System.Linq.Enumerable` class is

```
public IEnumerable<TSource> Where<TSource>(
    this IEnumerable<TSource> collection,
    Func<TSource, bool> predicate);
```

The extension method signature declared in the System.Linq.Queryable class is

```
public IQueryable<TSource> Where<TSource>(
    this IQueryable<TSource> collection,
    Expression<Func<TSource, bool>> predicate);
```

The compiler decides which extension method to use based on the compile-time type of persons; if it is a type convertible to IQueryable<Person>, the method from System.Linq.Queryable is chosen. It converts the lambda to an expression tree. At execution time, the object referred to by persons receives the expression tree data and might use that data to build a SQL query, which is then passed to the database when the results of the query are requested. The result of the call to Where is an object that, when asked for query results, sends the query to the database and produces the results.

If persons cannot be converted implicitly to IQueryable<Person> but can be converted implicitly to IEnumerable<Person>, the method from System.Linq.Enumerable is chosen, and the lambda is converted to a delegate. The result of the call to Where is an object that, when asked for query results, applies the generated delegate as a predicate to every member of the collection and produces the results that match the predicate.

Examining an Expression Tree

3.0 As we've seen, converting a lambda expression to an Expression<TDelegate> creates an expression tree rather than a delegate. We have seen previously in this chapter how to convert a lambda such as (x,y)=>x>y to a delegate type such as Func<int, int, bool>. To turn this same lambda into an expression tree, we simply convert it to Expression<Func<int, int, bool>>, as shown in Listing 12.25. We can then examine the generated object and display information about its structure, as well as that of a more complex expression tree.

Note that passing an instance of expression tree to Console.WriteLine() automatically converts the expression tree to a descriptive string form; the objects generated for expression trees all override ToString() so that you can see at a glance what the contents of an expression tree are when debugging.

Listing 12.25: Examining an Expression Tree

```
using System;
using System.Linq.Expressions;

public class Program
{
    public static void Main()
    {
        Expression<Func<int, int, bool>> expression;
        expression = (x, y) => x > y;
        Console.WriteLine("------------- {0} -------------",
            expression);
        PrintNode(expression.Body, 0);
        Console.WriteLine();
        Console.WriteLine();
        expression = (x, y) => x * y > x + y;
        Console.WriteLine("------------- {0} -------------",
            expression);
        PrintNode(expression.Body, 0);
    }
    public static void PrintNode(Expression expression,
        int indent)
    {
        if (expression is BinaryExpression)
            PrintNode(expression as BinaryExpression, indent);
        else
            PrintSingle(expression, indent);
    }
    private static void PrintNode(BinaryExpression expression,
      int indent)
    {
        PrintNode(expression.Left, indent + 1);
        PrintSingle(expression, indent);
        PrintNode(expression.Right, indent + 1);
    }
    private static void PrintSingle(
        Expression expression, int indent)
    {
        Console.WriteLine("{0," + indent * 5 + "}{1}",
          "", NodeToString(expression));
    }
    private static string NodeToString(Expression expression)
    {
        switch (expression.NodeType)
        {
            case ExpressionType.Multiply:
                return "*";
            case ExpressionType.Add:
                return "+";
            case ExpressionType.Divide:
                return "/";
            case ExpressionType.Subtract:
```

3.0

```
                    return "-";
                case ExpressionType.GreaterThan:
                    return ">";
                case ExpressionType.LessThan:
                    return "<";
                default:
                    return expression.ToString() +
                        " (" + expression.NodeType.ToString() + ")";
            }
        }
    }
```

In Output 12.5, we see that the `Console.WriteLine()` statements within `Main()` print out the body of the expression trees as text.

Output 12.5

```
------------- (x, y) => (x > y) -------------
     x (Parameter)
>
     y (Parameter)


------------- (x, y) => ((x * y) > (x + y)) -------------
          x (Parameter)
     *
          y (Parameter)
>
          x (Parameter)
     +
          y (Parameter)
```

3.0 The important point to note is that an expression tree is a collection of data, and by iterating over the data, it is possible to convert the data to another format; in this case we convert the expression tree to descriptive strings, but it could also be converted to expressions in another query language.

Using recursion, the `PrintNode()` function demonstrates that nodes in an expression tree are themselves trees containing zero or more child expression trees. The "root" tree that represents the lambda refers to the expression that is the body of the lambda with its `Body` property. Every expression tree node includes a `NodeType` property of enumerated type `ExpressionType` that describes what kind of expression it is. Numerous types of expressions exist: `BinaryExpression`, `ConditionalExpression`, `LambdaExpression`, `MethodCallExpression`, `ParameterExpression`, and `ConstantExpression` are examples. Each type derives from `Expression`.

Note that, although the expression tree library now contains objects to represent most of the statements of C# and Visual Basic, neither language supports the conversion of statement lambdas to expression trees. Only expression lambdas can be converted to expression trees.

SUMMARY

This chapter began with a discussion of delegates and their use as references to methods or callbacks. This powerful concept enables you to pass a set of instructions to call in a different location, rather than immediately, when coding the instructions.

The concept of lambda expressions is a syntax that supersedes (but does not eliminate) the C# 2.0 anonymous method syntax. These constructs allow programmers to assign a set of instructions to a variable directly, without defining an explicit method that contains the instructions. This construct provides significant flexibility for programming instructions dynamically within the method—a powerful concept that greatly simplifies the programming of collections through the LINQ API.

The chapter ended with a discussion of the concept of expression trees, and a consideration of how they compile into objects that represent the semantic analysis of a lambda expression, rather than the delegate implementation itself. This important feature supports such libraries as the Entity Framework and LINQ to XML—that is, libraries that interpret the expression tree and use it within contexts other than CIL.

Lambda expressions encompass both *statement lambdas* and *expression lambdas*. In other words, both statement lambdas and expression lambdas are types of lambda expressions. 3.0

One thing that the chapter mentioned but did not elaborate on was multicast delegates. The next chapter investigates multicast delegates in detail and explains how they enable the publish–subscribe pattern with events.

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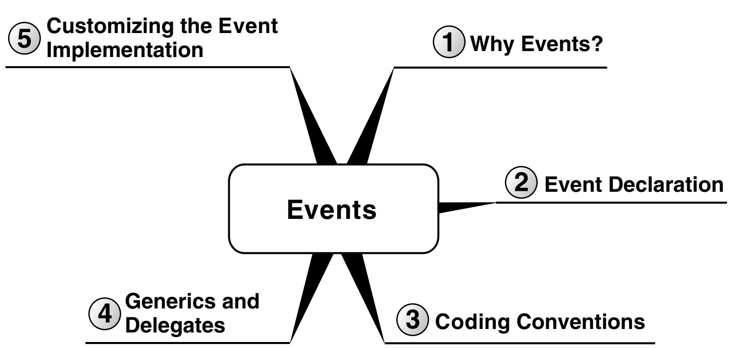
13

Events

Begin 2.0

IN THE PRECEDING CHAPTER, YOU saw how to reference a method with an instance of a delegate type and invoke that method via the delegate. Delegates are the building blocks of a larger pattern called publish–subscribe. The use of delegates for the publish–subscribe pattern is the focus of this chapter. Almost everything described within this chapter can be done using delegates alone. However, the event constructs that this chapter highlights provide additional encapsulation, making the publish–subscribe pattern easier to implement and less error-prone.

In the preceding chapter, all delegates referenced a single method. More broadly, a single delegate value can reference a whole collection of methods to be called in sequence; such a delegate is called a **multicast delegate.** Its application enables scenarios where notifications of single events, such as a change in object state, are published to multiple subscribers.



Although events existed in C# 1.0, the introduction of generics in C# 2.0 significantly changed the coding conventions because using a generic delegate data type meant that it was no longer necessary to declare a delegate for every possible event signature. For this reason, the chapter assumes a minimum of C# 2.0 throughout. Readers still living in the world of C# 1.0 can also use events, but they will have to declare their own delegate data types (as discussed in Chapter 12).

Coding the Observer Pattern with Multicast Delegates

Consider a temperature control, where a heater and a cooler are hooked up to the same thermostat. For the unit to turn on and off appropriately, you must notify the unit of changes in temperature. One thermostat publishes temperature changes to multiple subscribers—the heating and cooling units. The next section investigates the code.[1]

Defining Subscriber Methods

Begin by defining the `Heater` and `Cooler` objects (see Listing 13.1).

LISTING 13.1: `Heater` and `Cooler` Event Subscriber Implementations

2.0

```
class Cooler
{
  public Cooler(float temperature)
  {
      Temperature = temperature;
  }

  public float Temperature { get; set; }

  public void OnTemperatureChanged(float newTemperature)
  {
      if (newTemperature > Temperature)
      {
          System.Console.WriteLine("Cooler: On");
      }
      else
      {
          System.Console.WriteLine("Cooler: Off");
      }
  }
}
```

1. In this example, we use the term *thermostat* because people more commonly think of it in the context of heating and cooling systems. Technically, *thermometer* would be more appropriate.

```
class Heater
{
  public Heater(float temperature)
  {
      Temperature = temperature;
  }

  public float Temperature { get; set; }

  public void OnTemperatureChanged(float newTemperature)
  {
      if (newTemperature < Temperature)
      {
          System.Console.WriteLine("Heater: On");
      }
      else
      {
          System.Console.WriteLine("Heater: Off");
      }
  }
}
```

The two classes are essentially identical, with the exception of the temperature comparison. (In fact, you could eliminate one of the classes if you used a delegate to a comparison method within the `OnTemperatureChanged` method.) Each class stores the temperature at which the unit should be turned on. In addition, both classes provide an `OnTemperatureChanged()` method. Calling the `OnTemperatureChanged()` method is the means to indicate to the `Heater` and `Cooler` classes that the temperature has changed. The method implementation uses `newTemperature` to compare against the stored trigger temperature to determine whether to turn on the device.

The `OnTemperatureChanged()` methods are the subscriber methods. They must have the parameters and a return type that matches the delegate from the `Thermostat` class, which we discuss next.

Defining the Publisher

The `Thermostat` class is responsible for reporting temperature changes to the `heater` and `cooler` object instances. The `Thermostat` class code appears in Listing 13.2. 2.0

LISTING 13.2: Defining the Event Publisher, `Thermostat`

```
public class Thermostat
{
  // Define the event publisher
```

```
  public Action<float> OnTemperatureChange { get; set; }

  public float CurrentTemperature { get; set; }
}
```

The Thermostat includes a property called OnTemperatureChange that is of the Action<float> delegate type. OnTemperatureChange stores a list of subscribers. Notice that only one delegate field is required to store all the subscribers. In other words, both the Cooler and the Heater classes will receive notifications of a change in the temperature from this single publisher.

The last member of Thermostat is the CurrentTemperature property. This property sets and retrieves the value of the current temperature reported by the Thermostat class.

Hooking up the Publisher and Subscribers

Finally, we put all these pieces together in a Main() method. Listing 13.3 shows a sample of what Main() could look like.

LISTING 13.3: Connecting the Publisher and Subscribers

```
class Program
{
  public static void Main()
  {
      Thermostat thermostat = new Thermostat();
      Heater heater = new Heater(60);
      Cooler cooler = new Cooler(80);
      string temperature;

      thermostat.OnTemperatureChange +=
          heater.OnTemperatureChanged;
      thermostat.OnTemperatureChange +=
          cooler.OnTemperatureChanged;

      Console.Write("Enter temperature: ");
      temperature = Console.ReadLine();
      thermostat.CurrentTemperature = int.Parse(temperature);
  }
}
```

2.0

The code in this listing has registered two subscribers (heater.OnTemperatureChanged and cooler.OnTemperatureChanged) to the OnTemperatureChange delegate by directly assigning them using the += operator.

By taking the temperature value the user has entered as input, you can set the CurrentTemperature of thermostat. However, you have not yet written any code to publish the change temperature event to subscribers.

Invoking a Delegate

Every time the CurrentTemperature property on the Thermostat class changes, you want to **invoke the delegate** to notify the subscribers (heater and cooler) of the change in temperature. To achieve this goal, you must modify the CurrentTemperature property to save the new value and publish a notification to each subscriber. The code modification appears in Listing 13.4.

LISTING 13.4: Invoking a Delegate without Checking for null

```
public class Thermostat
{
  ...
  public float CurrentTemperature
  {
      get { return _CurrentTemperature; }
      set
      {
          if (value != CurrentTemperature)
          {
              _CurrentTemperature = value;

              // INCOMPLETE:  Check for null needed
              // Call subscribers
              OnTemperatureChange(value);
          }
      }
  }
  private float _CurrentTemperature;
}
```

Now the assignment of CurrentTemperature includes some special logic to notify subscribers of changes in CurrentTemperature. The call to notify all subscribers is simply the single C# statement, OnTemperatureChange(value). This single statement publishes the temperature change to both the cooler and heater objects. Here, you see in practice that the ability to notify multiple subscribers using a single call is why delegates are more specifically known as multicast delegates. 2.0

Begin 6.0

Check for null

One important part of event publishing code is missing from Listing 13.4. If no subscriber has registered to receive the notification, `OnTemperatureChange` would be `null` and executing the `OnTemperatureChange(value)` statement would throw a `NullReferenceException`. To avoid this scenario, it is necessary to check for `null` before firing the event. Listing 13.5 demonstrates how to do this using C# 6.0's null conditional operator before calling `Invoke()`.

Listing 13.5: Invoking a Delegate

```
public class Thermostat
{
  ...
  public float CurrentTemperature
  {
      get { return _CurrentTemperature; }
      set
      {
          if (value != CurrentTemperature)
          {
              _CurrentTemperature = value;
              // If there are any subscribers,
              // notify them of changes in temperature
              // by invoking said subscribers
              OnTemperatureChange?.Invoke(value);  // C# 6.0
          }
      }
  }
  private float _CurrentTemperature;
}
```

Notice the call to the `Invoke()` method that follows the null conditional. Although this method may be called using only a dot operator, there is little point since that is the equivalent of calling the delegate directly (see `OnTemperatureChange(value)` in Listing 13.4). The important advantage underlying null conditional operator is special logic to ensure that after checking for `null`, there is no possibility that a subscriber might unsubscribe, leaving the delegate `null` again.

End 6.0

2.0

Unfortunately, no such special uninterruptable null-checking logic exists prior to C# 6.0. As such, the implementation is significantly more verbose in earlier C# versions, as shown in Listing 13.6.

LISTING 13.6: Invoking a Delegate with Null Check Prior to C# 6.0

```
public class Thermostat
{
  ...
  public float CurrentTemperature
  {
      get{return _CurrentTemperature;}
      set
      {
          if (value != CurrentTemperature)
          {
              _CurrentTemperature = value;
              // If there are any subscribers,
              // notify them of changes in temperature
              // by invoking said subscribers
              Action<float> localOnChange =
                  OnTemperatureChange;
              if(localOnChange != null)
              {
                  // Call subscribers
                  localOnChange(value);
              }
          }
      }
  }
  private float _CurrentTemperature;
}
```

Instead of checking for `null` directly, this code first assigns `OnTemperatureChange` to a second delegate variable, `localOnChange`. This simple modification ensures that if all `OnTemperatureChange` subscribers are removed (by a different thread) between checking for `null` and sending the notification, you will not raise a `NullReferenceException`.

For the remainder of the book all samples will rely on the C# 6.0 null conditional operator for delegate invocation.

Guidelines

DO check that the value of a delegate is not `null` before invoking it.

DO use the null conditional operator prior to calling `Invoke()` starting in C# 6.0.

2.0

ADVANCED TOPIC

-= Operator for a Delegate Returns a New Instance

Given that a delegate is a reference type, it is perhaps somewhat surprising that assigning a local variable and then using that local variable is sufficient for making the `null` check thread-safe. Since `localOnChange` points at the same location as `OnTemperatureChange` does, you might imagine that any changes in `OnTemperatureChange` would be reflected in `localOnChange` as well.

This is not the case because, effectively, any calls to `OnTemperatureChange -= <listener>` will not simply remove a delegate from `OnTemperatureChange` so that it contains one less delegate than before. Rather, such a call will assign an entirely new multicast delegate without having any effect on the original multicast delegate to which `localOnChange` also points.

ADVANCED TOPIC

Thread-Safe Delegate Invocation

If subscribers can be added and removed from the delegate on different threads, it is wise (as noted earlier) to copy the delegate reference into a local variable before checking it for `null`. Although this approach prevents the invocation of a null delegate, it does not avoid all possible race conditions. For example, one thread could make the copy, and then another thread could reset the delegate to `null`, and then the original thread could invoke the previous value of the delegate, thereby notifying a subscriber that is no longer on the list of subscribers. Subscribers in multithreaded programs should ensure that their code remains robust in this scenario; it is always possible that a "stale" subscriber will be invoked.

Delegate Operators

2.0 To combine the two subscribers in the `Thermostat` example, you used the `+=` operator. This operator takes the first delegate and adds the second delegate to the chain. Now, after the first delegate's method returns, the second delegate is called. To remove delegates from a delegate chain, use the `-=` operator, as shown in Listing 13.7.

Listing 13.7: Using the += and -= Delegate Operators

```
// ...
Thermostat thermostat = new Thermostat();
Heater heater = new Heater(60);
Cooler cooler = new Cooler(80);

Action<float> delegate1;
Action<float> delegate2;
Action<float> delegate3;

delegate1 = heater.OnTemperatureChanged;
delegate2 = cooler.OnTemperatureChanged;

Console.WriteLine("Invoke both delegates:");
delegate3 = delegate1;
delegate3 += delegate2;
delegate3(90);

Console.WriteLine("Invoke only delegate2");
delegate3 -= delegate1;
delegate3(30);
// ...
```

The results of Listing 13.7 appear in Output 13.1.

Output 13.1

```
Invoke both delegates:
Heater: Off
Cooler: On
Invoke only delegate2
Cooler: Off
```

Furthermore, you can also use the + and – operators to combine delegates, as Listing 13.8 shows.

Listing 13.8: Using the + and - Delegate Operators

```
// ...
Thermostat thermostat = new Thermostat();
Heater heater = new Heater(60);
Cooler cooler = new Cooler(80);

Action<float> delegate1;
Action<float> delegate2;
Action<float> delegate3;

// Note: Use new Action (cooler.OnTemperatureChanged)
// for C# 1.0 syntax.
```

2.0

```
    delegate1 = heater.OnTemperatureChanged;
    delegate2 = cooler.OnTemperatureChanged;

    Console.WriteLine("Combine delegates using + operator:");
    delegate3 = delegate1 + delegate2;
    delegate3(60);

    Console.WriteLine("Uncombine delegates using - operator:");
    delegate3 = delegate3 - delegate2;
    delegate3(60);
    // ...
```

Use of the assignment operator clears out all previous subscribers and allows you to replace them with new subscribers. This is an unfortunate characteristic of a delegate. It is simply too easy to mistakenly code an assignment when, in fact, the `+=` operator is intended. The solution, called events, appears in the "Events" section later in this chapter.

Both the `+` and `-` operators and their assignment equivalents, `+=` and `-=`, are implemented internally using the static methods `System.Delegate.Combine()` and `System.Delegate.Remove()`. These methods take two parameters of type `delegate`. The first method, `Combine()`, joins the two parameters so that the first parameter points to the second within the list of delegates. The second, `Remove()`, searches through the chain of delegates specified in the first parameter and then removes the delegate specified by the second parameter.

One interesting thing to note about the `Combine()` method is that either or both of its parameters can be `null`. If one of them is `null`, `Combine()` returns the non-`null` parameter. If both are `null`, `Combine()` returns `null`. This explains why you can call `thermostat.OnTemperatureChange += heater.OnTemperatureChanged;` and not throw an exception, even if the value of `thermostat.OnTemperatureChange` is still `null`.

Sequential Invocation

Figure 13.1 highlights the sequential notification of both `heater` and `cooler`.

2.0

Although you coded only a single call to `OnTemperatureChange()`, the call is broadcast to both subscribers. Thus, with just one call, both `cooler` and `heater` are notified of the change in temperature. If you added more subscribers, they, too, would be notified by `OnTemperatureChange()`.

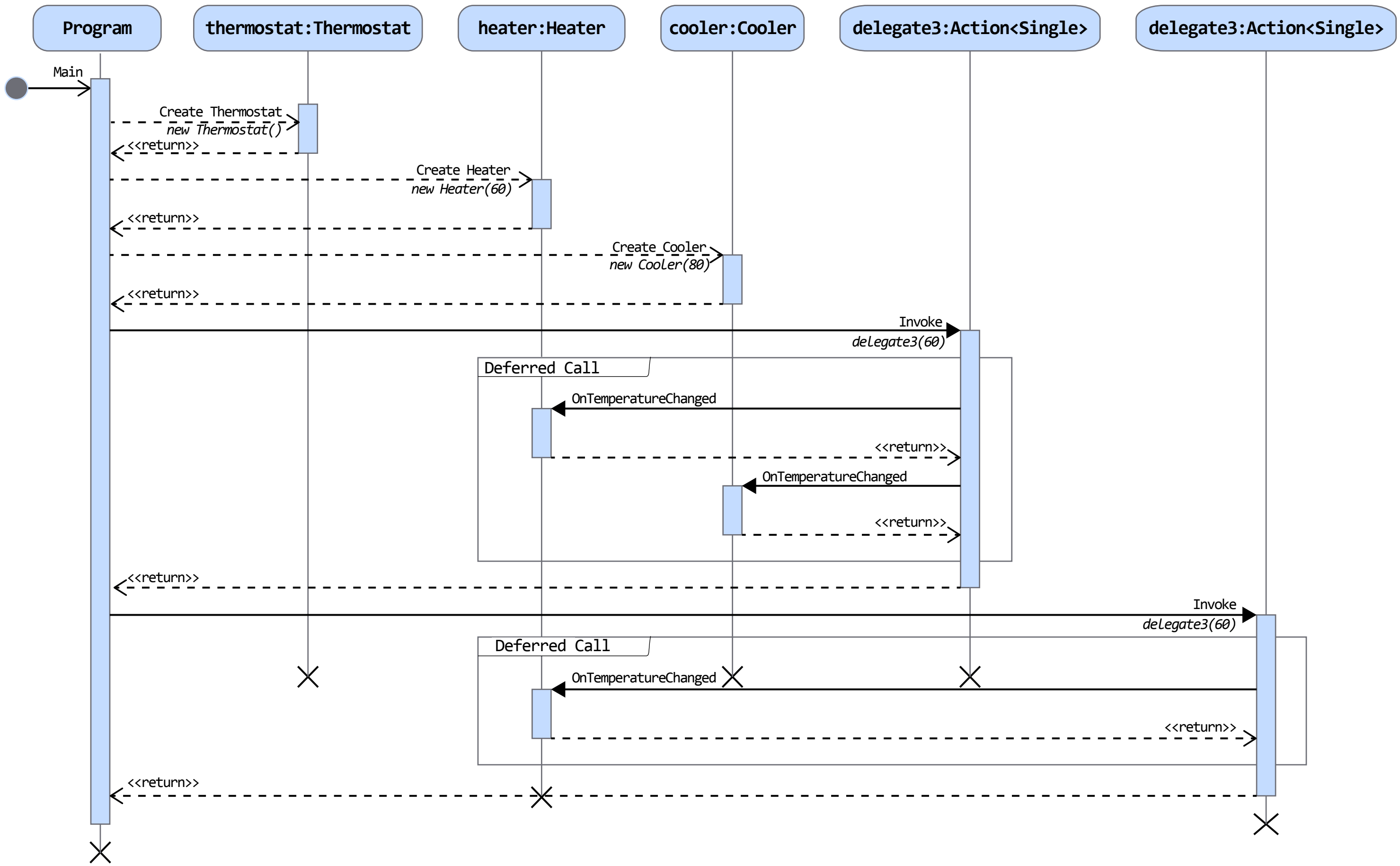


FIGURE 13.1: Delegate Invocation Sequence Diagram

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Although a single call, `OnTemperatureChange()`, caused the notification of each subscriber, the subscribers are still called sequentially, not simultaneously, because they are all called on the same thread of execution.

ADVANCED TOPIC

Multicast Delegate Internals

To understand how events work, you need to revisit the first examination of the `System.Delegate` type internals. Recall that the `delegate` keyword is an alias for a type derived from `System.MulticastDelegate`. In turn, `System.MulticastDelegate` is derived from `System.Delegate`, which, for its part, is composed of an object reference (needed for nonstatic methods) and a method reference. When you create a delegate, the compiler automatically employs the `System.MulticastDelegate` type rather than the `System.Delegate` type. The `MulticastDelegate` class includes an object reference and a method reference, just like its `Delegate` base class, but it also contains a reference to another `System.MulticastDelegate` object.

When you add a method to a multicast delegate, the `MulticastDelegate` class creates a new instance of the delegate type, stores the object reference and the method reference for the added method into the new instance, and adds the new delegate instance as the next item in a list of delegate instances. In effect, the `MulticastDelegate` class maintains a linked list of `Delegate` objects. Conceptually, you can represent the thermostat example as shown in Figure 13.2 on the facing page (denoted as a continuation of this advanced topic).

When invoking a multicast delegate, each delegate instance in the linked list is called sequentially. Generally, delegates are called in the order they were added, but this behavior is not specified within the CLI specification. Furthermore, it can be overridden. Therefore, programmers should not depend on an invocation order.

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Error Handling

Error handling makes awareness of the sequential notification critical. If one subscriber throws an exception, later subscribers in the chain do not receive the notification. Consider, for example, what would happen if you changed the `Heater`'s `OnTemperatureChanged()` method so that it threw an exception, as shown in Listing 13.9.

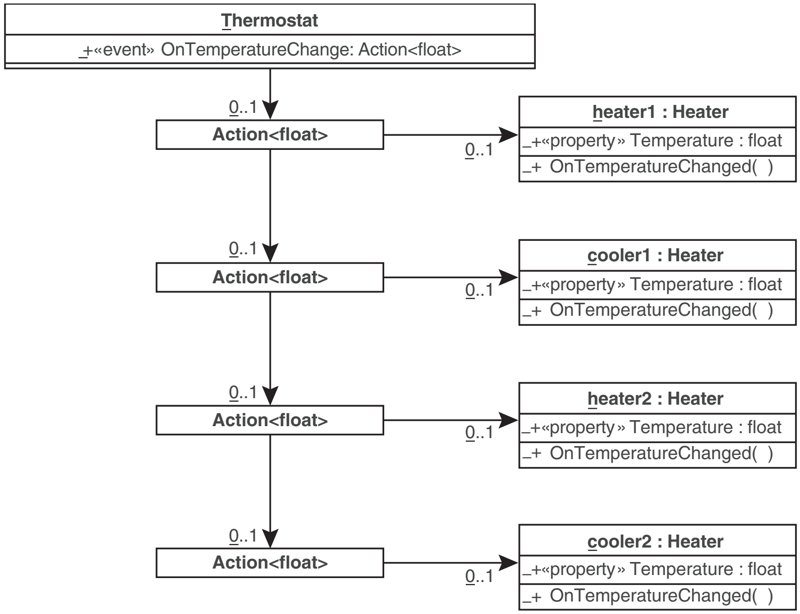

FIGURE 13.2: Multicast Delegates Chained Together

LISTING 13.9: `OnTemperatureChanged()` Throwing an Exception

```
class Program
{
  public static void Main()
  {
      Thermostat thermostat = new Thermostat();
      Heater heater = new Heater(60);
      Cooler cooler = new Cooler(80);
      string temperature;

      thermostat.OnTemperatureChange +=
          heater.OnTemperatureChanged;
      // Using C# 3.0. Change to anonymous method
      // if using C# 2.0.
      thermostat.OnTemperatureChange +=
          (newTemperature) =>
              {
                  throw new InvalidOperationException();
              };
      thermostat.OnTemperatureChange +=
          cooler.OnTemperatureChanged;

      Console.Write("Enter temperature: ");
      temperature = Console.ReadLine();
      thermostat.CurrentTemperature = int.Parse(temperature);
  }
}
```

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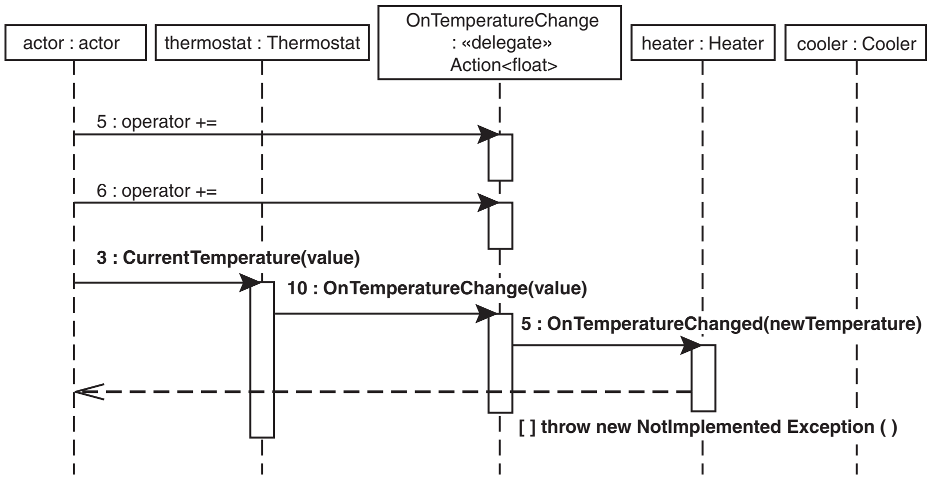

FIGURE 13.3: Delegate Invocation with Exception Sequence Diagram

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Figure 13.3 shows an updated sequence diagram. Even though `cooler` and `heater` subscribed to receive messages, the lambda expression exception terminates the chain and prevents the `cooler` object from receiving notification.

To avoid this problem so that all subscribers receive notification, regardless of the behavior of earlier subscribers, you must manually enumerate through the list of subscribers and call them individually. Listing 13.10 shows the updates required in the `CurrentTemperature` property. The results appear in Output 13.2.

LISTING 13.10: Handling Exceptions from Subscribers

2.0

```
public class Thermostat
{
  // Define the event publisher
  public Action<float> OnTemperatureChange;

  public float CurrentTemperature
  {
      get { return _CurrentTemperature; }
      set
      {
          if (value != CurrentTemperature)
          {
              _CurrentTemperature = value;
              Action<float> onTemperatureChange = OnTemperatureChange;
              if(onTemperatureChange != null)
              {
```

```
                    List<Exception> exceptionCollection =
                        new List<Exception>();
                    foreach (
                        Action<float> handler in
                        onTemperatureChange.GetInvocationList())
                    {
                        try
                        {
                            handler(value);
                        }
                        catch (Exception exception)
                        {
                            exceptionCollection.Add(exception);
                        }
                    }
                    if (exceptionCollection.Count > 0)
                    {
                        throw new AggregateException(
                            "There were exceptions thrown by
  OnTemperatureChange Event subscribers.",
                            exceptionCollection);
                    }
                  }
            }
        }
    }
    private float _CurrentTemperature;
  }
```

OUTPUT 13.2

```
Enter temperature: 45
Heater: On
Error in the application
Cooler: Off
```

This listing demonstrates that you can retrieve a list of subscribers from a delegate's `GetInvocationList()` method. Enumerating over each item in this list returns the individual subscribers. If you then place each invocation of a subscriber within a try/catch block, you can handle any error conditions before continuing with the enumeration loop. In this example, even though the delegate listener throws an exception, `cooler` still receives notification of the temperature change. After all notifications have been sent, Listing 13.10 reports any exceptions by throwing an `AggregateException`, which wraps a collection of exceptions that are accessible by the `InnerExceptions`

2.0

property. In this way, all exceptions are still reported and, at the same time, all subscribers are notified.

Parenthetically, no null conditional was used in this example because of the if condition that verified `onTemperatureChange` was not null.

Method Returns and Pass-by-Reference

There is another scenario in which it is useful to iterate over the delegate invocation list instead of simply activating a notification directly. This scenario relates to delegates that either do not return `void` or have `ref` or `out` parameters. In the thermostat example, the `OnTemperatureChange` delegate is of type `Action<float>`, which returns `void` and has no `out` or `ref` parameters. As a result, no data is returned to the publisher. This consideration is important, because an invocation of a delegate potentially triggers notification to multiple subscribers. If each of the subscribers returns a value, it is ambiguous as to which subscriber's return value would be used.

If you changed `OnTemperatureChange` to return an enumeration value, indicating whether the device was on because of the temperature change, the new delegate would be of type `Func<float, Status>`, where `Status` was an enum with elements `On` and `Off`. All subscriber methods would have to use the same method signature as the delegate and, therefore, each would be required to return a status value. Also, since `OnTemperatureChange` might potentially correspond to a chain of delegates, it is necessary to follow the same pattern that you used for error handling. In other words, you must iterate through each delegate invocation list, using the `GetInvocationList()` method, to retrieve each individual return value. Similarly, delegate types that use `ref` and `out` parameters need special consideration. However, although it is possible to use this approach in exceptional circumstances, the guideline is to avoid this scenario entirely by returning `void`.

2.0

Events

There are two key problems with the delegates as you have used them so far in this chapter. To overcome these issues, C# uses the keyword `event`. In this section, you will see why you would use events, and how they work.

Why Events?

This chapter and the preceding one covered all you need to know about how delegates work. Unfortunately, weaknesses in the delegate structure may inadvertently allow the programmer to introduce a bug. These issues relate to encapsulation that neither the subscription nor the publication of events can sufficiently control.

Encapsulating the Subscription

As demonstrated earlier, it is possible to assign one delegate to another using the assignment operator. Unfortunately, this capability introduces a common source for bugs. Consider Listing 13.11.

LISTING 13.11: Using the Assignment Operator = Rather Than +=

```
class Program
{
  public static void Main()
  {
      Thermostat thermostat = new Thermostat();
      Heater heater = new Heater(60);
      Cooler cooler = new Cooler(80);
      string temperature;

      // Note: Use new Action (cooler.OnTemperatureChanged)
      // if C# 1.0
      thermostat.OnTemperatureChange =
          heater.OnTemperatureChanged;

      // Bug: Assignment operator overrides
      // previous assignment.
      thermostat.OnTemperatureChange =
          cooler.OnTemperatureChanged;

      Console.Write("Enter temperature: ");
      temperature = Console.ReadLine();
      thermostat.CurrentTemperature = int.Parse(temperature);
  }
}
```

Listing 13.11 is almost identical to Listing 13.7, except that instead of using the += operator, you use a simple assignment operator. As a result, when code assigns `cooler.OnTemperatureChanged` to `OnTemperatureChange`, `heater.OnTemperatureChanged` is cleared out because an entirely new chain is assigned to replace the previous one. The potential for mistakenly using an assignment operator, when actually the += assignment was intended, is 2.0

so high that it would be preferable if the assignment operator were not even supported for objects except within the containing class. The `event` keyword provides this additional encapsulation so that you cannot inadvertently cancel other subscribers.

Encapsulating the Publication

The second important difference between delegates and events is that events ensure that only the containing class can trigger an event notification. Consider Listing 13.12.

LISTING 13.12: Firing the Event from Outside the Events Container

```
class Program
{
  public static void Main()
  {
      Thermostat thermostat = new Thermostat();
      Heater heater = new Heater(60);
      Cooler cooler = new Cooler(80);
      string temperature;

      // Note: Use new Action (cooler.OnTemperatureChanged)
      // if C# 1.0.
      thermostat.OnTemperatureChange +=
          heater.OnTemperatureChanged;

      thermostat.OnTemperatureChange +=
          cooler.OnTemperatureChanged;

      thermostat.OnTemperatureChange(42);
  }
}
```

In Listing 13.12, `Program` is able to invoke the `OnTemperatureChange` delegate even though the `CurrentTemperature` on `thermostat` did not change. `Program`, therefore, triggers a notification to all `thermostat` subscribers that the temperature changed, even though there was actually no change in the `thermostat` temperature. As before, the problem with the delegate is that there is insufficient encapsulation. `Thermostat` should prevent any other class from being able to invoke the `OnTemperatureChange` delegate.

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Declaring an Event

C# provides the `event` keyword to deal with both of these problems. Although seemingly like a field modifier, `event` defines a new type of member (see Listing 13.13).

Listing 13.13: Using the event Keyword with the Event-Coding Pattern

```
public class Thermostat
{
    public class TemperatureArgs: System.EventArgs
  {
      public TemperatureArgs( float newTemperature )
      {
          NewTemperature = newTemperature;
      }

      public float NewTemperature { get; set; }
  }

  // Define the event publisher
  public event EventHandler<TemperatureArgs> OnTemperatureChange =
      delegate { };

  public float CurrentTemperature
  {
      ...
  }
  private float _CurrentTemperature;
}
```

The new `Thermostat` class has four changes relative to the original class. First, the `OnTemperatureChange` property has been removed, and `OnTemperatureChange` has instead been declared as a public field. This seems contrary to solving the earlier encapsulation problem. It would make more sense to increase the encapsulation, not decrease it by making a field public. However, the second change was to add the `event` keyword immediately before the field declaration. This simple change provides all the encapsulation needed. By adding the `event` keyword, you prevent use of the assignment operator on a public delegate field (for example, `thermostat.OnTemperatureChange = cooler.OnTemperatureChanged`). In addition, only the containing class is able to invoke the delegate that triggers the publication to all subscribers (for example, disallowing `thermostat.OnTemperatureChange(42)` from outside the class). In other words, the `event` keyword provides the needed encapsulation that prevents any external class from publishing an event or unsubscribing previous subscribers it did not add. This resolves the two previously mentioned issues with plain delegates and is one of the key reasons for the inclusion of the `event` keyword in C#. 2.0

Another potential pitfall with plain delegates is that it is all too easy to forget to check for `null` (ideally using a null conditional in C# 6.0 code) before invoking the delegate. This omission may result in an unexpected `NullReferenceException`. Fortunately, the encapsulation that the `event` keyword provides enables an alternative possibility during declaration (or within the constructor), as shown in Listing 13.13. Notice that when declaring the event we assign `delegate { }`—an empty delegate representing a collection of zero listeners. By assigning the empty delegate, we can raise the event without checking whether there are any listeners. (This behavior is similar to assigning an array of zero items to a variable. Doing so allows the invocation of an array member without first checking whether the variable is `null`.) Of course, if there is any chance that the delegate could be reassigned with `null`, a check is still required. However, because the `event` keyword restricts assignment to occur only within the class, any reassignment of the delegate could occur only from within the class. Assuming `null` is never assigned, there will be no need to check for `null` whenever the code invokes the delegate.

Coding Conventions

All you need to do to gain the desired functionality is to change the original delegate variable declaration to a field, and add the `event` keyword. With these two changes, you provide the necessary encapsulation and all other functionality remains the same. However, an additional change occurs in the delegate declaration in the code in Listing 13.13. To follow standard C# coding conventions, you should replace `Action<float>` with a new delegate type: `EventHandler<TemperatureArgs>`, a CLR type whose declaration is shown in Listing 13.14 (new in .NET Framework 2.0).

LISTING 13.14: Declaring a Generic Delegate Type

```
public delegate void EventHandler<TEventArgs>(object sender, TEventArgs e)
   where TEventArgs : EventArgs;
```

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The result is that the single temperature parameter in the `Action<TEventArgs>` delegate type is replaced with two new parameters—one for the sender and a second for the event data. This change is not something that the C# compiler will enforce, but passing two parameters of these types is the norm for a delegate intended for an event.

The first parameter, `sender`, contains an instance of the class that invoked the delegate. This is especially helpful if the same subscriber method registers with multiple events—for example, if the `heater.OnTemperatureChanged` event subscribes to two different `Thermostat` instances. In such a scenario, either `Thermostat` instance can trigger a call to `heater.OnTemperatureChanged`. To determine which instance of `Thermostat` triggered the event, you use the `sender` parameter from inside `Heater.OnTemperatureChanged()`. If the event is static, this option will not be available, so pass `null` for the `sender` argument value.

The second parameter, `TEventArgs e`, is specified as type `Thermostat.TemperatureArgs`. The important part about `TemperatureArgs`, at least as far as the coding convention goes, is that it derives from `System.EventArgs`. (In fact, derivation from `System.EventArgs` is something that the framework forced with a generic constraint until .NET Framework 4.5.) The only significant property on `System.EventArgs` is `Empty`, which is used to indicate that there is no event data. When you derive `TemperatureArgs` from `System.EventArgs`, however, you add an additional property, `NewTemperature`, as a means to pass the temperature from the thermostat to the subscribers.

To summarize the coding convention for events: The first argument, `sender`, is of type `object` and contains a reference to the object that invoked the delegate or `null` if the event is static. The second argument is of type `System.EventArgs` or something that derives from `System.EventArgs` but contains additional data about the event. You invoke the delegate exactly as before, except for the additional parameters. Listing 13.15 shows an example.

LISTING 13.15: Firing the Event Notification

```
public class Thermostat
{
  ...
  public float CurrentTemperature
  {
      get{return _CurrentTemperature;}
      set
      {
          if (value != CurrentTemperature)
          {
              _CurrentTemperature = value;
              // If there are any subscribers,
              // notify them of changes in temperature
              // by invoking said subscribers
              OnTemperatureChange?.Invoke(  // Using C# 6.0
                    this, new TemperatureArgs(value) );
            }
```

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```
            }
        }
    }
    private float _CurrentTemperature;
  }
```

You usually specify the sender using the container class (`this`) because that is the only class that can invoke the delegate for events.

In this example, the subscriber could cast the sender parameter to `Thermostat` and access the current temperature that way, as well as via the `TemperatureArgs` instance. However, the current temperature on the `Thermostat` instance may change via a different thread. In the case of events that occur due to state changes, passing the previous value along with the new value is a pattern frequently used to control which state transitions are allowable.

Guidelines

DO check that the value of a delegate is not `null` before invoking it (possibly by using the null conditional operator in C# 6.0).

DO NOT pass `null` as the value of the sender for nonstatic events, but DO pass `null` as the same value for static events.

DO NOT pass `null` as the value of `eventArgs` argument.

DO use a delegate type of `EventHandler<TEventArgs>` for the events.

DO use `System.EventArgs` or a type that derives from `System.EventArgs` for a `TEventArgs`.

CONSIDER using a subclass of `System.EventArgs` as the event argument type (`TEventArgs`), unless you are absolutely sure the event will never need to carry any data.

Generics and Delegates

2.0 The preceding section discussed that the guideline for defining a type for an event is to use a delegate type of `EventHandler<TEventArgs>`. In theory, any delegate type could be used, but by convention, the first parameter, `sender`, is of type `object` and the second parameter, `e`, should be of a type deriving from `System.EventArgs`. One of the more cumbersome aspects of delegates in C# 1.0 was that you had to declare a new delegate type whenever the parameters on the handler changed. Every creation of a new derivation from `System.EventArgs` (a relatively common occurrence) required the declaration of a new delegate data type that used the new `EventArgs`-derived type. For example, to use `TemperatureArgs` within the event notification code in Listing 13.15, it would be necessary to declare the delegate type `TemperatureChangeHandler` that has `TemperatureArgs` as a parameter (see Listing 13.16).

Listing 13.16: Using a Custom Delegate Type

```
public class Thermostat
{
  public class TemperatureArgs: System.EventArgs
  {
      public TemperatureArgs( float newTemperature )
      {
          NewTemperature = newTemperature;
      }

      public float NewTemperature
      {
          get { return _NewTemperature; }
          set { _NewTemperature = value; }
      }
      private float _NewTemperature;
  }

  public delegate void TemperatureChangeHandler(
      object sender, TemperatureArgs newTemperature);

  public event TemperatureChangeHandler
      OnTemperatureChange;

  public float CurrentTemperature
  {
      ...
  }
  private float _CurrentTemperature;
}
```

Although generally `EventHandler<TEventArgs>` is preferred over creating a custom delegate type such as `TemperatureChangeHandler`, there is one advantage associated with the latter type. Specifically, if a custom type is used, the parameter names can be specific to the event. In Listing 13.16, for example, when invoking the delegate to raise the event, the second parameter name will appear as `newTemperature` rather than as simply `e`. 2.0

Another reason why a custom delegate type might be used concerns parts of the CLR API that were defined prior to C# 2.0. Given that these parts represent a fairly significant percentage of the more common types within the framework, it is not uncommon to encounter specific delegate types rather than the generic form on events coming from the CLR API. Regardless, in the majority of circumstances when using events in C# 2.0 and later, it is not necessary to declare a custom delegate data type.

Guidelines

DO use `System.EventHandler<T>` instead of manually creating new delegate types for event handlers, unless the parameter names of a custom type offer significant clarification.

ADVANCED TOPIC

Event Internals

Events restrict external classes from doing anything other than adding subscribing methods to the publisher via the `+=` operator and then unsubscribing using the `-=` operator. In addition, they restrict classes, other than the containing class, from invoking the event. To do so, the C# compiler takes the public delegate variable with its `event` keyword modifier and declares the delegate as private. In addition, it adds a couple of methods and two special event blocks. Essentially, the `event` keyword is a C# shortcut for generating the appropriate encapsulation logic. Consider the example in the event declaration shown in Listing 13.17.

LISTING 13.17: Declaring the `OnTemperatureChange` Event

2.0

```
public class Thermostat
{
  public event EventHandler<TemperatureArgs> OnTemperatureChange;

  ...
}
```

When the C# compiler encounters the `event` keyword, it generates CIL code equivalent to the C# code shown in Listing 13.18.

Listing 13.18: C# Conceptual Equivalent of the Event CIL Code Generated by the Compiler

```
public class Thermostat
{
  // ...
  // Declaring the delegate field to save the
  // list of subscribers.
  private EventHandler<TemperatureArgs> _OnTemperatureChange;

  public void add_OnTemperatureChange(
      EventHandler<TemperatureArgs> handler)
  {
      System.Delegate.Combine(_OnTemperatureChange, handler);
  }

  public void remove_OnTemperatureChange(
      EventHandler<TemperatureArgs> handler)
  {
      System.Delegate.Remove(_OnTemperatureChange, handler);
  }

  public event EventHandler<TemperatureArgs> OnTemperatureChange
  {
      add
      {
          add_OnTemperatureChange(value)
      }
      remove
      {
          remove_OnTemperatureChange(value)
      }
  }
}
```

In other words, the code shown in Listing 13.17 is (conceptually) the C# shorthand that the compiler uses to trigger the code expansion shown in Listing 13.18. (The "conceptually" qualifier is needed because some details regarding thread synchronization have been eliminated for the purpose of elucidation.)

The C# compiler first takes the original event definition and defines a private delegate variable in its place. As a result, the delegate becomes unavailable to any external class—even to classes derived from it.

2.0

Next, the C# compiler defines two methods, `add_OnTemperatureChange()` and `remove_OnTemperatureChange()`, in which the `OnTemperatureChange` suffix is taken from the original name of the event. These methods are responsible for implementing the `+=` and `-=` assignment operators, respectively.

As Listing 13.18 shows, these methods are implemented using the static `System.Delegate.Combine()` and `System.Delegate.Remove()` methods, discussed earlier in the chapter. The first parameter passed to each of these methods is the private `EventHandler<TemperatureArgs>` delegate instance, `OnTemperatureChange`.

Perhaps the most curious part of the code generated from the `event` keyword is the last segment. The syntax is very similar to that of a property's getter and setter methods, except that the methods are called `add` and `remove`. The `add` block takes care of handling the `+=` operator on the event by passing the call to `add_OnTemperatureChange()`. In a similar manner, the `remove` block operator handles the `-=` operator by passing the call on to `remove_OnTemperatureChange`.

Take careful note of the similarities between this code and the code generated for a property. Readers will recall that the C# implementation of a property is to create `get_<propertyname>` and `set_<propertyname>`, and then to pass calls to the `get` and `set` blocks on to these methods. Clearly, the event syntax in such cases is very similar.

Another important characteristic to note about the generated CIL code is that the CIL equivalent of the `event` keyword remains in the CIL. In other words, an event is something that the CIL code recognizes explicitly; it is not just a C# construct. By keeping an equivalent `event` keyword in the CIL code, all languages and editors are able to provide special functionality because they can recognize the event as a special class member.

Customizing the Event Implementation

You can customize the code for `+=` and `-=` that the compiler generates. Consider, for example, changing the scope of the `OnTemperatureChange` delegate so that it is protected rather than private. This, of course, would allow classes derived from `Thermostat` to access the delegate directly instead of being limited to the same restrictions as external classes. To enable this behavior, C# allows the same property as the syntax shown in Listing 13.16. In other words, C# allows you to define custom `add` and `remove` blocks to provide a unique implementation for each aspect of the event encapsulation. Listing 13.19 provides an example.

2.0

Listing 13.19: Custom add and remove Handlers

```
public class Thermostat
{
  public class TemperatureArgs: System.EventArgs
  {
      ...
  }

    // Define the event publisher
  public event EventHandler<TemperatureArgs> OnTemperatureChange
  {
      add
      {
          System.Delegate.Combine(value, _OnTemperatureChange);
      }
      remove
      {
          System.Delegate.Remove(_OnTemperatureChange, value);
      }
  }
  protected EventHandler<TemperatureArgs> _OnTemperatureChange;

  public float CurrentTemperature
  {
      ...
  }
  private float _CurrentTemperature;
}
```

In this case, the delegate that stores each subscriber, `_OnTemperatureChange`, was changed to `protected`. In addition, implementation of the `add` block switches around the delegate storage so that the last delegate added to the chain is the first delegate to receive a notification.

SUMMARY

Now that we have described events, it is worth mentioning that in general, method references are the only cases where it is advisable to work with a delegate variable outside the context of an event. In other words, given the additional encapsulation features of an event and the ability to customize the implementation when necessary, the best practice is always to use events for the observer pattern.

It may take a little practice before you can code events from scratch without referring to sample code. However, events are a critical foundation for the asynchronous, multithreaded coding of later chapters.

End 2.0

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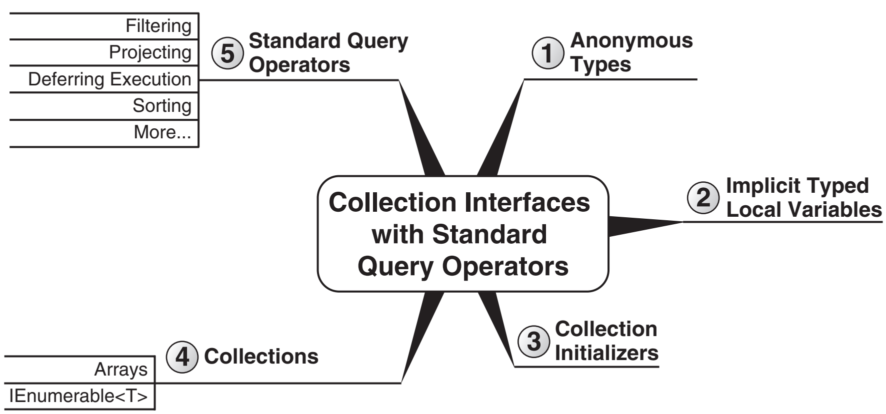
14

Collection Interfaces with Standard Query Operators

The most significant features added in C# 3.0 were in the area of collections. Extension methods and lambda expressions enabled a far superior API for working with collections. In fact, in earlier editions of this book, the chapter on collections came immediately after the chapter on generics and just before the one on delegates. However, lambda expressions make such a significant impact on collection APIs that it is no longer possible to cover collections without first covering delegates (the basis of lambda expressions). Now that you have a solid foundation in lambda expressions from the preceding chapter, we can delve into the details of collections—a topic that spans three chapters.



To begin, this chapter introduces anonymous types and collection initializers—topics that we covered only briefly in a few Advanced Topic sections in Chapter 5. Next, this chapter covers the various collection interfaces and explores how they relate to one another. This is the basis for understanding collections, so readers should cover the material with diligence. The section on collection interfaces includes coverage of the `IEnumerable<T>` extension methods that were added in C# 3.0 to implement the standard query operators.

There are two categories of collection-related classes and interfaces: those that support generics and those that don't. This chapter primarily discusses the generic collection interfaces. You should use collection classes that don't support generics only when you are writing components that need to interoperate with earlier versions of the runtime. This is because everything that was available in the nongeneric form has a generic replacement that is strongly typed. Although the concepts still apply to both forms, we will not explicitly discuss the nongeneric versions.[1]

Begin 3.0

Anonymous Types and Implicitly Typed Local Variables

C# 3.0 significantly improved support for handling collections of items. What is amazing is that to support this advanced API, fewer than nine new language enhancements were made. However, these enhancements are critical to why C# 3.0 was such a marvelous improvement to the language. Two such enhancements were anonymous types and implicit local variables.

Anonymous Types

Anonymous types are data types that are declared by the compiler, rather than through the explicit class definitions of Chapter 5. As with anonymous functions, when the compiler sees an anonymous type, it does the work to make that class for you and then lets you use it as though you had declared it explicitly. Listing 14.1 shows such a declaration.

LISTING 14.1: Implicit Local Variables with Anonymous Types

```
using System;

class Program
{
  static void Main()
```

1. In fact, in WinRT, the nongeneric collections have been removed.

```
    {
        var patent1 =
            new
            {
                Title = "Bifocals",
                YearOfPublication = "1784"
            };
        var patent2 =
            new
            {
                Title = "Phonograph",
                YearOfPublication = "1877"
            };
        var patent3 =
            new
            {
                patent1.Title,
                // Renamed to show property naming.
                Year = patent1.YearOfPublication
            };

        Console.WriteLine(
            $"{ patent1.Title } ({ patent1.YearOfPublication })");
        Console.WriteLine(
            $"{ patent2.Title } ({ patent2.YearOfPublication })");

        Console.WriteLine();
        Console.WriteLine(patent1);
        Console.WriteLine(patent2);

        Console.WriteLine();
        Console.WriteLine(patent3);
    }
  }
```

3.0

The corresponding output is shown in Output 14.1.

Output 14.1

```
Bifocals (1784)
Phonograph (1784)

{ Title = Bifocals, YearOfPublication = 1784 }
{ Title = Phonograph, YearOfPublication = 1877 }

{ Title = Bifocals, Year = 1784 }
```

Anonymous types are purely a C# feature, not a new kind of type in the runtime. When the compiler encounters the anonymous type syntax, it generates a CIL class with properties corresponding to the named values and data types in the anonymous type declaration.

Implicitly Typed Local Variables (var)

Because an anonymous type by definition has no name, it is not possible to declare a local variable as explicitly being of an anonymous type. Rather, the local variable's type is replaced with `var`. However, by no means does this indicate that implicitly typed variables are untyped. On the contrary, they are fully typed to the data type of the value they are assigned. If an implicitly typed variable is assigned an anonymous type, the underlying CIL code for the local variable declaration will be of the type generated by the compiler. Similarly, if the implicitly typed variable is assigned a `string`, its data type in the underlying CIL will be a `string`. In fact, there is no difference in the resultant CIL code for implicitly typed variables whose assignment is not an anonymous type (such as `string`) and those that are declared as type `string`. If the declaration statement is `string text = "This is a test of the..."`, the resultant CIL code will be identical to an implicitly typed declaration, `var text = "This is a test of the..."`. The compiler determines the data type of the implicitly typed variable from the expression assigned. In an explicitly typed local variable with an initializer (`string s = "hello";`), the compiler first determines the type of `s` from the declared type on the left-hand side, then analyzes the right-hand side and verifies that the expression on the right-hand side is assignable to that type. In an implicitly typed local variable, the process is in some sense reversed. First the right-hand side is analyzed to determine its type, and then the "var" is logically replaced with that type.

3.0

Although C# does not include a name for the anonymous type, it is still strongly typed as well. For example, the properties of the type are fully accessible. In Listing 14.1, `patent1.Title` and `patent2.YearOfPublication` are called within the `Console.WriteLine` statement. Any attempts to call nonexistent members will result in compiler errors. Even IntelliSense in IDEs such as Visual Studio works with the anonymous type.

You should use implicitly typed variable declarations sparingly. Obviously, for anonymous types, it is not possible to specify the data type, and the use of `var` is required. However, for cases where the data type is not an anonymous type, it is frequently preferable to use the explicit data type. As is the case generally, you should focus on making the semantics of the code more readable while at the same time using the compiler to verify that the resultant variable is of the type you expect. To accomplish this with implicitly typed local variables, use them only when the type assigned to the implicitly typed variable is entirely obvious. For example, in `var items = new Dictionary<string, List<Account>>();`, the resultant code is more succinct and readable. In contrast, when the type is not obvious, such as when a method return is assigned, developers should favor an explicit variable type declaration such as the following:

```
Dictionary<string, List<Account>> dictionary = GetAccounts();
```

> **NOTE**
>
> Implicitly typed variables should generally be reserved for anonymous type declaration rather than used indiscriminately when the data type is known at compile time, unless the type assigned to the variable is entirely obvious.

Language Contrast: C++/Visual Basic/JavaScript—void*, Variant, and var

An implicitly typed variable is not the equivalent of `void*` in C++, a `Variant` in Visual Basic, or `var` in JavaScript. In each of these cases, the variable declaration is not very restrictive because the variable may be assigned a value of any type, just as you could in C# with a variable declaration of type `object`. In contrast, `var` is definitively typed by the compiler; once established at declaration, the type may not change, and type checks and member calls are verified at compile time.

3.0

More about Anonymous Types and Implicit Local Variables

In Listing 14.1, member names on the anonymous types are explicitly identified using the assignment of the value to the name for `patent1` and `patent2` (for example, `Title = "Phonograph"`). However, if the value assigned is a property or field call, the name may default to the name of the field or property rather than explicitly specifying the value. `patent3`, for example, is defined using a property named "Title" rather than an assignment to an explicit name. As Output 14.1 shows, the resultant property name is determined, by the compiler, to match the property from where the value was retrieved.

`patent1` and `patent2` both have the same property names with the same data types. Therefore, the C# compiler generates only one data type for these two anonymous declarations. `patent3`, however, forces the compiler to create a second anonymous type because the property name for the patent year is different from what it was in `patent1` and `patent2`. Furthermore, if the order of the properties were switched between `patent1` and `patent2`, these two anonymous types would also not be type-compatible. In other words, the requirements for two anonymous types to be type-compatible within the same assembly are a match in property names, data types, and order of properties. If these criteria are met, the types are compatible even if they appear in different methods or classes. Listing 14.2 demonstrates the type incompatibilities.

LISTING 14.2: Type Safety and Immutability of Anonymous Types

3.0

```
class Program
{
  static void Main()
  {
      var patent1 =
          new
          {
              Title = "Bifocals",
              YearOfPublication = "1784"
          };

      var patent2 =
          new
          {
              YearOfPublication = "1877",
              Title = "Phonograph"
          };

      var patent3 =
          new
          {
              patent1.Title,
```

```
                Year = patent1.YearOfPublication
            };

        // ERROR: Cannot implicitly convert type
        //        'AnonymousType#1' to 'AnonymousType#2'
        patent1 = patent2;
        // ERROR: Cannot implicitly convert type
        //        'AnonymousType#3' to 'AnonymousType#2'
        patent1 = patent3;

        // ERROR: Property or indexer 'AnonymousType#1.Title'
        //        cannot be assigned to -- it is read-only
        patent1.Title = "Swiss Cheese";
    }
  }
```

The resultant first two compiler errors assert the fact that the types are not compatible, so they will not successfully convert from one to the other.

The third compiler error is caused by the reassignment of the `Title` property. Anonymous types are immutable, so it is a compiler error to change a property on an anonymous type once it has been instantiated.

Although not shown in Listing 14.2, it is not possible to declare a method with an implicit data type parameter (`var`). Therefore, instances of anonymous types can be passed outside the method in which they are created in only two ways. First, if the method parameter is of type `object`, the anonymous type instance may be passed outside the method because the anonymous type will convert implicitly. A second way is to use method type inference, whereby the anonymous type instance is passed as a method type parameter that the compiler can successfully infer. Calling `void Method<T>(T parameter)` using `Function(patent1)`, therefore, would succeed, although the available operations on `parameter` within `Function()` are limited to those supported by `object`. 3.0

In spite of the fact that C# allows anonymous types such as the ones shown in Listing 14.1, it is generally not recommended that you define them in this way. Anonymous types provide critical functionality with C# 3.0 support for projections, such as joining/associating collections, as we discuss later in the chapter. However, generally you should reserve anonymous type definitions for circumstances where they are required, such as aggregation of data from multiple types.

ADVANCED TOPIC

Anonymous Type Generation

Even though `Console.WriteLine()`'s implementation is to call `ToString()`, notice in Listing 14.1 that the output from `Console.WriteLine()` is not the default `ToString()`, which writes out the fully qualified data type name. Rather, the output is a list of `PropertyName = value` pairs, one for each property on the anonymous type. This occurs because the compiler overrides `ToString()` in the anonymous type code generation, so as to format the `ToString()` output as shown. Similarly, the generated type includes overriding implementations for `Equals()` and `GetHashCode()`.

The implementation of `ToString()` on its own is an important reason that variation in the order of properties causes a new data type to be generated. If two separate anonymous types, possibly in entirely separate types and even namespaces, were unified and then the order of properties changed, changes in the order of properties on one implementation would have noticeable and possibly unacceptable effects on the other's `ToString()` results. Furthermore, at execution time it is possible to reflect back on a type and examine the members on a type—even to call one of these members dynamically (determining at runtime which member to call). A variation in the order of members on two seemingly identical types could then trigger unexpected results. To avoid this problem, the C# designers decided to generate two different types.

3.0

Collection Initializers

Another feature added to C# in version 3.0 was **collection initializers.** A collection initializer allows programmers to construct a collection with an initial set of members at instantiation time in a manner similar to array declaration. Before collection initialization was available, elements had to be explicitly added to a collection after the collection was instantiated—using something like `System.Collections.Generic.ICollection<T>`'s `Add()` method. With collection initialization, the `Add()` calls are generated by the C# compiler rather than explicitly coded by the developer. Listing 14.3 shows how to initialize the collection using a collection initializer.

LISTING 14.3: Collection Initialization

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      List<string> sevenWorldBlunders;
      sevenWorldBlunders = new List<string>()
      {
          // Quotes from Ghandi
          "Wealth without work",
          "Pleasure without conscience",
          "Knowledge without character",
          "Commerce without morality",
          "Science without humanity",
          "Worship without sacrifice",
          "Politics without principle"
      };

      Print(sevenWorldBlunders);

  }

  private static void Print<T>(IEnumerable<T> items)
  {
      foreach (T item in items)
      {
          Console.WriteLine(item);
      }
  }
}
```

The syntax is similar not only to the array initialization, but also to an object initializer with the curly braces following the constructor. If no parameters are passed in the constructor, the parentheses following the data type are optional (as they are with object initializers). 3.0

A few basic requirements are needed for a collection initializer to compile successfully. Ideally, the collection type to which a collection initializer is applied would be of a type that implements `System.Collections.Generic.ICollection<T>`. This ensures that the collection includes an `Add()` that the compiler-generated code can invoke. However, a relaxed version of the requirement also exists and simply demands that one or more `Add()` methods exist either as an extension method (C# 6.0) or as an instance method on a type that implements `IEnumerable<T>`—even if the collection doesn't implement `ICollection<T>`. The `Add()` methods need to Begin 6.0

take parameters that are compatible with the values specified in the collection initializer.

For dictionaries, the collection initializer syntax is slightly more complex, because each element in the dictionary requires both the key and the value. This syntax is shown in Listing 14.4.

Listing 14.4: Initializing Anonymous Type Arrays

```
using System;
using System.Collections.Generic;
#if !PRECSHARP6
  // C# 6.0 or later
  Dictionary<string, ConsoleColor> colorMap =
      new Dictionary<string, ConsoleColor>
      {
          ["Error"] = ConsoleColor.Red,
          ["Warning"] = ConsoleColor.Yellow,
          ["Information"] = ConsoleColor.Green,
          ["Verbose"] = ConsoleColor.White
      };
#else
  // Before C# 6.0
  Dictionary<string, ConsoleColor> colorMap =
      new Dictionary<string, ConsoleColor>
      {
          { "Error", ConsoleColor.Red },
          { "Warning", ConsoleColor.Yellow },
          { "Information", ConsoleColor.Green },
          { "Verbose", ConsoleColor.White}
        };
#endif
```

3.0

This listing actually includes two different versions of the initialization. The first demonstrates a new syntax introduced in C# 6.0, which expresses the intent of a name/value pair by allowing the assignment operator to express which value is associated with which key. The second syntax (which still works with C# 6.0 or later) pairs the name and the value together using curly brackets.

End 6.0

Allowing initializers on collections that don't support `ICollection<T>` was important for two reasons. First, the majority of collections (types that implement `IEnumerable<T>`) do not also implement `ICollection<T>`, which significantly reduces the usefulness of collection initializers. Second, matching on the method name and signature compatibility with the collection initializer items enables greater diversity in the items initialized into the collection. For example, the initializer now can support `new DataStore(){ a, {b, c}}` as long as there is one `Add()` method whose signature is compatible with parameter `a`, and a second `Add()` method whose signature is compatible with `b, c`.

Note that you cannot have a collection initializer for an anonymous type since the collection initializer requires a constructor call, and it is impossible to name the constructor. The workaround is to define a method such as `static List<T> CreateList<T>(T t) { return new List<T>(); }`. Method type inference allows the type parameter to be implied rather than specified explicitly, so this workaround successfully allows for the creation of a collection of anonymous types.

Another approach to initializing a collection of anonymous types is to use an array initializer. As it is not possible to specify the data type in the constructor, array initialization syntax allows for anonymous array initializers using `new[]` (see Listing 14.5).

LISTING 14.5: Initializing Anonymous Type Arrays

```
using System;
using System.Collections.Generic;
using System.Linq;

class Program
{
  static void Main()
  {
      var worldCup2006Finalists = new[]
      {
          new
          {
              TeamName = "France",
              Players = new string[]
              {
                  "Fabien Barthez", "Gregory Coupet",
                  "Mickael Landreau", "Eric Abidal",
                  // ...
              }
          },
          new
          {
              TeamName = "Italy",
              Players = new string[]
              {
                  "Gianluigi Buffon", "Angelo Peruzzi",
                  "Marco Amelia", "Cristian Zaccardo",
                  // ...
              }
          }
      };
```

3.0

```
        Print(worldCup2006Finalists);
    }

    private static void Print<T>(IEnumerable<T> items)
    {
        foreach (T item in items)
        {
            Console.WriteLine(item);
        }
    }
}
```

End 3.0

The resultant variable is an array of the anonymous type items, which must be homogeneous because it is an array.

What Makes a Class a Collection: IEnumerable<T>

By definition, a collection within .NET is a class that, at a minimum, implements `IEnumerable<T>` (or the nongeneric type `IEnumerable`). This interface is critical because implementing the methods of `IEnumerable<T>` is the minimum needed to support iterating over the collection.

Chapter 3 showed how to use a `foreach` statement to iterate over an array of elements. This syntax is simple and avoids the complication of having to know how many elements there are. The runtime does not directly support the `foreach` statement, however. Instead, the C# compiler transforms the code as described in this section.

foreach with Arrays

Listing 14.6 demonstrates a simple `foreach` loop iterating over an array of integers and then printing out each integer to the console.

Listing 14.6: foreach with Arrays

```
int[] array = new int[]{1, 2, 3, 4, 5, 6};

foreach (int item in array)
{
    Console.WriteLine(item);
}
```

From this code, the C# compiler creates a CIL equivalent of the `for` loop, as shown in Listing 14.7.

Listing 14.7: Compiled Implementation of foreach with Arrays

```
int[] tempArray;
int[] array = new int[]{1, 2, 3, 4, 5, 6};

tempArray = array;
for (int counter = 0; (counter < tempArray.Length); counter++)
{
  int item = tempArray[counter];

  Console.WriteLine(item);
}
```

In this example, note that `foreach` relies on support for the `Length` property and the index operator (`[]`). With the `Length` property, the C# compiler can use the `for` statement to iterate through each element in the array.

foreach with IEnumerable<T>

Although the code shown in Listing 14.7 works well on arrays where the length is fixed and the index operator is always supported, not all types of collections have a known number of elements. Furthermore, many of the collection classes, including the `Stack<T>`, `Queue<T>`, and `Dictionary<Tkey, Tvalue>` classes, do not support retrieving elements by index. Therefore, a more general approach of iterating over collections of elements is needed. The iterator pattern provides this capability. Assuming you can determine the first, next, and last elements, knowing the count and supporting retrieval of elements by index is unnecessary.

The `System.Collections.Generic.IEnumerator<T>` and nongeneric `System.Collections.IEnumerator` interfaces (see Listing 14.9) are designed to enable the iterator pattern for iterating over collections of elements, rather than the length–index pattern shown in Listing 14.7. A class diagram of their relationships appears in Figure 14.1.

`IEnumerator`, which `IEnumerator<T>` derives from, includes three members. The first is `bool MoveNext()`. Using this method, you can move from one element within the collection to the next, while at the same time detecting when you have enumerated through every item. The second member, a read-only property called `Current`, returns the element currently in process. `Current` is overloaded in `IEnumerator<T>`, providing a type-specific implementation of it. With these two members on the collection class, it is possible to iterate over the collection simply using a `while` loop, as demonstrated

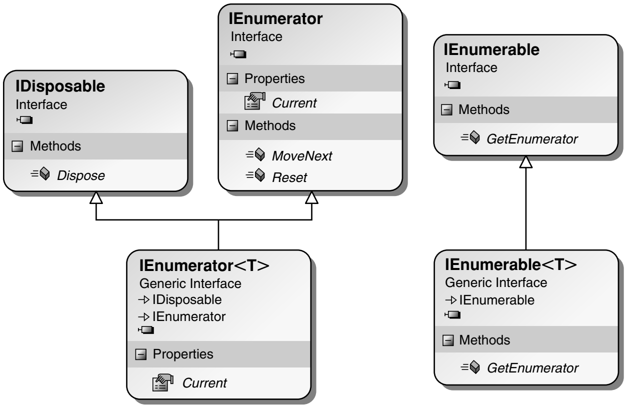


FIGURE 14.1: A Class Diagram of **IEnumerator<T>** and **IEnumerator** Interfaces

in Listing 14.8. (The `Reset()` method usually throws a `NotImplementedException`, so it should never be called. If you need to restart an enumeration, just create a fresh enumerator.)

LISTING 14.8: Iterating over a Collection Using **while**

```
System.Collections.Generic.Stack<int> stack =
  new System.Collections.Generic.Stack<int>();
int number;
// ...

// This code is conceptual, not the actual code.
while (stack.MoveNext())
{
  number = stack.Current;
  Console.WriteLine(number);
}
```

In Listing 14.8, the `MoveNext()` method returns `false` when it moves past the end of the collection. This replaces the need to count elements while looping.

Listing 14.8 uses a `System.Collections.Generic.Stack<T>` as the collection type. Numerous other collection types exist; this is just one example. The key trait of `Stack<T>` is its design as a “last in, first out” (LIFO) collection. Notice that the type parameter `T` identifies the type of all items within the collection. Collecting one particular type of object within a collection is a key characteristic of a generic collection. The programmer must know the data type within the collection when adding, removing, or accessing items within the collection.

The preceding example showed the gist of the C# compiler output, but it doesn't actually compile that way because it omits two important details concerning the implementation: interleaving and error handling.

State Is Shared

The problem with an implementation such as Listing 14.8 is that if two such loops interleaved each other—one `foreach` inside another, both using the same collection—the collection must maintain a state indicator of the current element so that when `MoveNext()` is called, the next element can be determined. In such a case, one interleaving loop can affect the other. (The same is true of loops executed by multiple threads.)

To overcome this problem, the collection classes do not support `IEnumerator<T>` and `IEnumerator` interfaces directly. As shown in Figure 14.1, there is a second interface, called `IEnumerable<T>`, whose only method is `GetEnumerator()`. The purpose of this method is to return an object that supports `IEnumerator<T>`. Instead of the collection class maintaining the state, a different class—usually a nested class, so that it has access to the internals of the collection—will support the `IEnumerator<T>` interface and will keep the state of the iteration loop. The enumerator is like a "cursor" or a "bookmark" in the sequence. You can have multiple bookmarks, and moving each of them enumerates over the collection independently of the other. Using this pattern, the C# equivalent of a `foreach` loop will look like the code shown in Listing 14.9.

LISTING 14.9: A Separate Enumerator Maintaining State during an Iteration

```
System.Collections.Generic.Stack<int> stack =
  new System.Collections.Generic.Stack<int>();
int number;
System.Collections.Generic.Stack<int>.Enumerator
  enumerator;

// ...

// If IEnumerable<T> is implemented explicitly,
// then a cast is required.
// ((IEnumerable<int>)stack).GetEnumerator();
enumerator = stack.GetEnumerator();
while (enumerator.MoveNext())
{
  number = enumerator.Current;
  Console.WriteLine(number);
}
```

ADVANCED TOPIC

Cleaning up Following Iteration

Given that the classes that implement the `IEnumerator<T>` interface maintain the state, sometimes you need to clean up the state after it exits the loop (because either all iterations have completed or an exception is thrown). To achieve this, the `IEnumerator<T>` interface derives from `IDisposable`. Enumerators that implement `IEnumerator` do not necessarily implement `IDisposable`, but if they do, `Dispose()` will be called as well. This enables the calling of `Dispose()` after the `foreach` loop exits. The C# equivalent of the final CIL code, therefore, looks like Listing 14.10.

LISTING 14.10: Compiled Result of `foreach` on Collections

```
System.Collections.Generic.Stack<int> stack =
  new System.Collections.Generic.Stack<int>();
System.Collections.Generic.Stack<int>.Enumerator
  enumerator;
IDisposable disposable;

enumerator = stack.GetEnumerator();
try
{
  int number;
  while (enumerator.MoveNext())
  {
      number = enumerator.Current;
      Console.WriteLine(number);
  }
}
finally
{
  // Explicit cast used for IEnumerator<T>.
  disposable = (IDisposable) enumerator;
  disposable.Dispose();

  // IEnumerator will use the as operator unless IDisposable
  // support is known at compile time.
  // disposable = (enumerator as IDisposable);
  // if (disposable != null)
  // {
  //     disposable.Dispose();
  // }
}
```

Notice that because the `IDisposable` interface is supported by `IEnumerator<T>`, the `using` statement can simplify the code in Listing 14.10 to that shown in Listing 14.11.

Listing 14.11: Error Handling and Resource Cleanup with using

```
System.Collections.Generic.Stack<int> stack =
  new System.Collections.Generic.Stack<int>();
int number;

using(
  System.Collections.Generic.Stack<int>.Enumerator
      enumerator = stack.GetEnumerator())
{
  while (enumerator.MoveNext())
  {
      number = enumerator.Current;
      Console.WriteLine(number);
  }
}
```

However, recall that the CIL does not directly support the `using` keyword. Thus the code in Listing 14.10 is actually a more accurate C# representation of the `foreach` CIL code.

ADVANCED TOPIC

foreach without IEnumerable

C# doesn't require that `IEnumerable`/`IEnumerable<T>` be implemented to iterate over a data type using `foreach`. Rather, the compiler uses a concept known as **duck typing;** it looks for a `GetEnumerator()` method that returns a type with a `Current` property and `MoveNext()` method. Duck typing involves searching by name rather than relying on an interface or explicit method call to the method. (The name "duck typing" comes from the whimsical idea that to be treated as a duck, the object must merely implement a `Quack()` method; it need not implement an `IDuck` interface.) If duck typing fails to find a suitable implementation of the enumerable pattern, the compiler checks whether the collection implements the interfaces.

Do Not Modify Collections during foreach Iteration

Chapter 3 showed that the compiler prevents assignment of the `foreach` variable (`number`). As is demonstrated in Listing 14.10, an assignment to `number` would not be a change to the collection element itself, so the C# compiler prevents such an assignment altogether.

In addition, neither the element count within a collection nor the items themselves can generally be modified during the execution of a `foreach` loop. If, for example, you called `stack.Push(42)` inside the `foreach` loop, it would be ambiguous whether the `iterator` should ignore or incorporate the change to `stack`—in other words, whether `iterator` should iterate over the newly added item or ignore it and assume the same state as when it was instantiated.

Because of this ambiguity, an exception of type `System.InvalidOperationException` is generally thrown upon accessing the enumerator if the collection is modified within a `foreach` loop, reporting that the collection was modified after the enumerator was instantiated.

Begin 3.0

Standard Query Operators

Besides the methods on `System.Object`, any type that implements `IEnumerable<T>` is required to implement only one other method, `GetEnumerator()`. Yet, doing so makes more than 50 methods available to all types implementing `IEnumerable<T>`, not including any overloading—and this happens without needing to explicitly implement any method except the `GetEnumerator()` method. The additional functionality is provided through C# 3.0's extension methods and resides in the class `System.Linq.Enumerable`. Therefore, including the `using` declarative for `System.Linq` is all it takes to make these methods available.

Each method on `IEnumerable<T>` is a **standard query operator;** it provides querying capability over the collection on which it operates. In the following sections, we will examine some of the most prominent of these standard query operators. Many of these examples will depend on an `Inventor` and/or `Patent` class, both of which are defined in Listing 14.12.

Listing 14.12: Sample Classes for Use with Standard Query Operators

```
using System;
using System.Collections.Generic;
using System.Linq;

public class Patent
{
  // Title of the published application
  public string Title { get; set; }

  // The date the application was officially published
  public string YearOfPublication { get; set; }
```

```
    // A unique number assigned to published applications
    public string ApplicationNumber { get; set; }

    public long[] InventorIds { get; set; }

    public override string ToString()
    {
        return $"{ Title } ({ YearOfPublication })";
    }
}

public class Inventor
{
    public long Id { get; set; }
    public string Name { get; set; }
    public string City { get; set; }
    public string State { get; set; }
    public string Country { get; set; }

    public override string ToString()
    {
        return $"{ Name } ({ City }, { State })";
    }
}

class Program
{
    static void Main()
    {
      IEnumerable<Patent> patents = PatentData.Patents;
      Print(patents);

      Console.WriteLine();

      IEnumerable<Inventor> inventors = PatentData.Inventors;
      Print(inventors);
    }

    private static void Print<T>(IEnumerable<T> items)
    {
        foreach (T item in items)
        {
            Console.WriteLine(item);
        }
    }
}

public static class PatentData
{
    public static readonly Inventor[] Inventors = new Inventor[]
        {
            new Inventor(){
                Name="Benjamin Franklin", City="Philadelphia",
                State="PA", Country="USA", Id=1 },
```

3.0

```
            new Inventor(){
                Name="Orville Wright", City="Kitty Hawk",
                State="NC", Country="USA", Id=2},
            new Inventor(){
                Name="Wilbur Wright", City="Kitty Hawk",
                State="NC", Country="USA", Id=3},
            new Inventor(){
                Name="Samuel Morse", City="New York",
                State="NY", Country="USA", Id=4},
            new Inventor(){
                Name="George Stephenson", City="Wylam",
                State="Northumberland", Country="UK", Id=5},
            new Inventor(){
                Name="John Michaelis", City="Chicago",
                State="IL", Country="USA", Id=6},
            new Inventor(){
                Name="Mary Phelps Jacob", City="New York",
                State="NY", Country="USA", Id=7},
        };

    public static readonly Patent[] Patents = new Patent[]
        {
            new Patent(){
                Title="Bifocals", YearOfPublication="1784",
                InventorIds=new long[] {1}},
            new Patent(){
                Title="Phonograph", YearOfPublication="1877",
                InventorIds=new long[] {1}},
            new Patent(){
                Title="Kinetoscope", YearOfPublication="1888",
                InventorIds=new long[] {1}},
            new Patent(){
                Title="Electrical Telegraph",
                YearOfPublication="1837",
                InventorIds=new long[] {4}},
            new Patent(){
                Title="Flying Machine", YearOfPublication="1903",
                InventorIds=new long[] {2,3}},
            new Patent(){
                Title="Steam Locomotive",
                YearOfPublication="1815",
                InventorIds=new long[] {5}},
            new Patent(){
                Title="Droplet Deposition Apparatus",
                YearOfPublication="1989",
                InventorIds=new long[] {6}},
            new Patent(){
                Title="Backless Brassiere",
                YearOfPublication="1914",
                InventorIds=new long[] {7}},
        };
}
```

3.0

Listing 14.12 also provides a selection of sample data. Output 14.2 displays the results of running this code.

Output 14.2

```
Bifocals (1784)
Phonograph (1877)
Kinetoscope (1888)
Electrical Telegraph (1837)
Flying Machine (1903)
Steam Locomotive (1815)
Droplet Deposition Apparatus (1989)
Backless Brassiere (1914)

Benjamin Franklin (Philadelphia, PA)
Orville Wright (Kitty Hawk, NC)
Wilbur Wright (Kitty Hawk, NC)
Samuel Morse (New York, NY)
George Stephenson (Wylam, Northumberland)
John Michaelis (Chicago, IL)
Mary Phelps Jacob (New York, NY)
```

Filtering with `Where()`

To filter out data from a collection, we need to provide a filter method that returns `true` or `false`, indicating whether a particular element should be included or not. A delegate expression that takes an argument and returns a Boolean is called a **predicate,** and a collection's `Where()` method depends on predicates for identifying filter criteria, as shown in Listing 14.13. (Technically, the result of the `Where()` method is a **monad** that encapsulates the operation of filtering a given sequence with a given predicate.) The results appear in Output 14.3.

3.0

Listing 14.13: Filtering with `System.Linq.Enumerable.Where()`

```
using System;
using System.Collections.Generic;
using System.Linq;

class Program
{
  static void Main()
  {
      IEnumerable<Patent> patents = PatentData.Patents;
      patents = patents.Where(
          patent => patent.YearOfPublication.StartsWith("18"));
      Print(patents);
  }

  // ...
}
```

Output 14.3

```
Phonograph (1877)
Kinetoscope (1888)
Electrical Telegraph (1837)
Steam Locomotive (1815)
```

Notice that the code assigns the output of the `Where()` call back to `IEnumerable<T>`. In other words, the output of `IEnumerable<T>.Where()` is a new `IEnumerable<T>` collection. In Listing 14.13, it is `IEnumerable<Patent>`.

Less obvious is that the `Where()` expression argument has not necessarily been executed at assignment time. This is true for many of the standard query operators. In the case of `Where()`, for example, the expression is passed in to the collection and "saved" but not executed. Instead, execution of the expression occurs only when it is necessary to begin iterating over the items within the collection. A `foreach` loop, for example, such as the one in `Print()` (in Listing 14.12), will trigger the expression to be evaluated for each item within the collection. At least conceptually, the `Where()` method should be understood as a means of specifying the query regarding what appears in the collection, not the actual work involved with iterating over to produce a new collection with potentially fewer items.

Projecting with `Select()`

Since the output from the `IEnumerable<T>.Where()` method is a new `IEnumerable<T>` collection, it is possible to again call a standard query operator on the same collection. For example, rather than just filtering
3.0 the data from the original collection, we could transform the data (see Listing 14.14).

Listing 14.14: Projection with `System.Linq.Enumerable.Select()`

```
using System;
using System.Collections.Generic;
using System.Linq;

class Program
{
  static void Main()
  {
      IEnumerable<Patent> patents = PatentData.Patents;
      IEnumerable<Patent> patentsOf1800 = patents.Where(
          patent => patent.YearOfPublication.StartsWith("18"));
      IEnumerable<string> items = patentsOf1800.Select(
          patent => patent.ToString());
```

```
        Print(items);
    }

    // ...
}
```

In Listing 14.14, we create a new `IEnumerable<string>` collection. In this case, it just so happens that adding the `Select()` call doesn't change the output—but this is only because `Print()`'s `Console.WriteLine()` call used `ToString()` anyway. Obviously, a transform still occurred on each item from the `Patent` type of the original collection to the string type of the `items` collection.

Consider the example using `System.IO.FileInfo` in Listing 14.15.

LISTING 14.15: Projection with `System.Linq.Enumerable.Select()` and `new`

```
    // ...
    IEnumerable<string> fileList = Directory.GetFiles(
        rootDirectory, searchPattern);
    IEnumerable<FileInfo> files = fileList.Select(
        file => new FileInfo(file));
    // ...
```

Here `fileList` is of type `IEnumerable<string>`. However, using the projection offered by `Select`, we can transform each item in the collection to a `System.IO.FileInfo` object.

Lastly, capitalizing on anonymous types, we could create a collection, `IEnumerable<T>`, where `T` is an anonymous type (see Listing 14.16 and Output 14.4).

3.0

LISTING 14.16: Projection to an Anonymous Type

```
    // ...
    IEnumerable<string> fileList = Directory.EnumerateFiles(
        rootDirectory, searchPattern);
    var items = fileList.Select(
        file =>
        {
            FileInfo fileInfo = new FileInfo(file);
            return new
            {
                FileName = fileInfo.Name,
                Size = fileInfo.Length
            };
        });
    // ...
```

OUTPUT 14.4

```
{ FileName = AssemblyInfo.cs, Size = 1704 }
{ FileName = CodeAnalysisRules.xml, Size = 735 }
{ FileName = CustomDictionary.xml, Size = 199 }
{ FileName = EssentialCSharp.sln, Size = 40415 }
{ FileName = EssentialCSharp.suo, Size = 454656 }
{ FileName = EssentialCSharp.vsmdi, Size = 499 }
{ FileName = EssentialCSharp.vssscc, Size = 256 }
{ FileName = intelliTechture.ConsoleTester.dll, Size = 24576 }
{ FileName = intelliTechture.ConsoleTester.pdb, Size = 30208 }
{ FileName = LocalTestRun.testrunconfig, Size = 1388 }
```

The output of an anonymous type automatically shows the property names and their values as part of the generated `ToString()` method associated with the anonymous type.

Projection using the `Select()` method is very powerful. We already saw how to filter a collection vertically (reducing the number of items in the collection) using the `Where()` standard query operator. Now, via the `Select()` standard query operator, we can also reduce the collection horizontally (making fewer columns) or transform the data entirely. In combination, `Where()` and `Select()` provide a means for extracting only those pieces of the original collection that are desirable for the current algorithm. These two methods alone provide a powerful collection manipulation API that would otherwise result in significantly more code that is less readable.

Begin 4.0

3.0

ADVANCED TOPIC

Running LINQ Queries in Parallel

With the abundance of computers having multiple processors and multiple cores within those processors, the ability to easily take advantage of the additional processing power becomes far more important. To do so, programs need to be changed to support multiple threads so that work can happen simultaneously on different CPUs within the computer. Listing 14.17 demonstrates one way to do this using Parallel LINQ (PLINQ).

LISTING 14.17: Executing LINQ Queries in Parallel

```
      // ...
      IEnumerable<string> fileList = Directory.EnumerageFiles(
          rootDirectory, searchPattern);
      var items = fileList.AsParallel().Select(
          file =>
```

```
            {
                FileInfo fileInfo = new FileInfo(file);
                return new
                {
                    FileName = fileInfo.Name,
                    Size = fileInfo.Length
                };
            });
        // ...
```

As Listing 14.17 shows, the change in code to enable parallel support is minimal. All that it uses is a .NET Framework 4–introduced standard query operator, `AsParallel()`, on the static class `System.Linq.ParallelEnumerable`. Using this simple extension method, however, the runtime begins executing over the items within the `fileList` collection and returning the resultant objects in parallel. Each parallel operation in this case isn't particularly expensive (although it is relative to the other execution taking place), but consider CPU-intensive operations such as encryption or compression. Running the query in parallel across multiple CPUs can decrease execution time by a factor corresponding to the number of CPUs.

An important caveat to be aware of (and the reason why `AsParallel()` appears as an Advanced Topic rather than in the standard text) is that parallel execution can introduce race conditions, such that an operation on one thread can be intermingled with an operation on a different thread, causing data corruption. To avoid this problem, synchronization mechanisms are required on data with shared access from multiple threads to force the operations to be atomic where necessary. Synchronization itself, however, can introduce deadlocks that freeze the execution, further complicating the effective parallel programming.

More details on this and additional multithreading topics are provided in Chapters 18 and 19.

3.0

End 4.0

Counting Elements with `Count()`

Another query frequently performed on a collection of items is to retrieve the count. To support this type of query, LINQ includes the `Count()` extension method.

Listing 14.18 demonstrates that `Count()` is overloaded to simply count all elements (no parameters) or to take a predicate that counts only items identified by the predicate expression.

Listing 14.18: Counting Items with `Count()`

```
using System;
using System.Collections.Generic;
using System.Linq;

class Program
{
  static void Main()
  {
      IEnumerable<Patent> patents = PatentData.Patents;
      Console.WriteLine($"Patent Count: { patents.Count() }");
      Console.WriteLine($@"Patent Count in 1800s: {
          patents.Count(patent =>
              patent.YearOfPublication.StartsWith("18"))
      }");
  }

  // ...
}
```

In spite of the apparent simplicity of the `Count()` statement, `IEnumerable<T>` has not changed, so the executed code still iterates over all the items in the collection. Whenever a `Count` property is directly available on the collection, it is preferable to use that rather than LINQ's `Count()` method (a subtle difference). Fortunately, `ICollection<T>` includes the `Count` property, so code that calls the `Count()` method on a collection that supports `ICollection<T>` will cast the collection and call `Count` directly. However, if `ICollection<T>` is not supported, `Enumerable.Count()` will proceed to enumerate all the items in the collection rather than call the built-in `Count` mechanism. If the purpose of checking the count is just to see whether it is greater than zero (`if(patents.Count() > 0){...}`), the preferable approach would be to use the `Any()` operator (`if(patents.Any()){...}`). `Any()` attempts to iterate over only one of the items in the collection to return a true result, rather than iterating over the entire sequence.

3.0

Guidelines

DO use `System.Linq.Enumerable.Any()` rather than calling `patents.Count()` when checking if there are more than zero items.

DO use a collection's `Count` property (if available) in favor of calling the `System.Linq.Enumerable.Count()` method.

Deferred Execution

One of the most important concepts to remember when using LINQ is deferred execution. Consider the code in Listing 14.19 and the corresponding output in Output 14.5.

LISTING 14.19: Filtering with `System.Linq.Enumerable.Where()`

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

    IEnumerable<Patent> patents = PatentData.Patents;
    bool result;
    patents = patents.Where(
        patent =>
        {
            if (result =
                patent.YearOfPublication.StartsWith("18"))
            {
                // Side effects like this in a predicate
                // are used here to demonstrate a
                // principle and should generally be
                // avoided.
                Console.WriteLine("\t" + patent);
            }
            return result;
        });

    Console.WriteLine("1. Patents prior to the 1900s are:");
    foreach (Patent patent in patents)
    {
    }

    Console.WriteLine();
    Console.WriteLine(
        "2. A second listing of patents prior to the 1900s:");
    Console.WriteLine(
        $@"   There are { patents.Count()
            } patents prior to 1900.");

    Console.WriteLine();
    Console.WriteLine(
        "3. A third listing of patents prior to the 1900s:");
    patents = patents.ToArray();
    Console.Write("   There are ");
    Console.WriteLine(
        $"{ patents.Count() } patents prior to 1900.");

// ...
```

3.0

OUTPUT 14.5

```
1. Patents prior to the 1900s are:
        Phonograph (1877)
        Kinetoscope (1888)
        Electrical Telegraph (1837)
        Steam Locomotive (1815)

2. A second listing of patents prior to the 1900s:
        Phonograph (1877)
        Kinetoscope (1888)
        Electrical Telegraph (1837)
        Steam Locomotive (1815)
   There are 4 patents prior to 1900.

3. A third listing of patents prior to the 1900s:
        Phonograph (1877)
        Kinetoscope (1888)
        Electrical Telegraph (1837)
        Steam Locomotive (1815)
   There are 4 patents prior to 1900.
```

Notice that `Console.WriteLine("1. Patents prior…)` executes before the lambda expression. This is a very important characteristic to pay attention to because it is not obvious to those who are unaware of its importance. In general, predicates should do exactly one thing—evaluate a condition—and they should not have any side effects (even printing to the console, as in this example).

To understand what is happening, recall that lambda expressions are delegates—references to methods—that can be passed around. In the context of LINQ and standard query operators, each lambda expression forms part of the overall query to be executed.

3.0

At the time of declaration, lambda expressions are not executed. In fact, it isn't until the lambda expressions are invoked that the code within them begins to execute. Figure 14.2 shows the sequence of operations.

As Figure 14.2 shows, three calls in Listing 14.17 trigger the lambda expression, and each time it is fairly implicit. If the lambda expression were expensive (such as a call to a database), it would therefore be important to minimize the lambda expression's execution.

First, the execution is triggered within the `foreach` loop. As we described earlier in the chapter, the `foreach` loop breaks down into a `MoveNext()` call and each call results in the lambda expression's execution for each item in the original collection. While iterating, the runtime invokes the lambda expression for each item to determine whether the item satisfies the predicate.

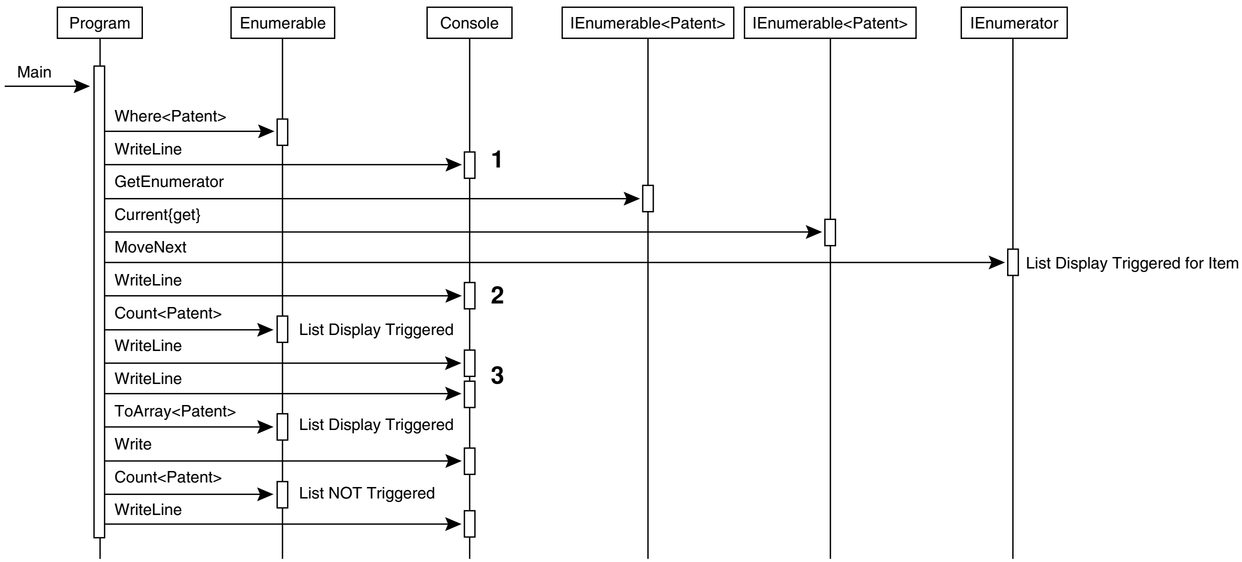


FIGURE 14.2: Sequence of Operations Invoking Lambda Expressions

3.0

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Second, a call to `Enumerable`'s `Count()` (the function) triggers the lambda expression for each item once more. Again, this is very subtle behavior because `Count` (the property) is very common on collections that have not been queried with a standard query operator.

Third, the call to `ToArray()` (or `ToList()`, `ToDictionary()`, or `ToLookup()`) triggers the lambda expression for each item. However, converting the collection with one of these "To" methods is extremely helpful. Doing so returns a collection on which the standard query operator has already executed. In Listing 14.17, the conversion to an array means that when `Length` is called in the final `Console.WriteLine()`, the underlying object pointed to by `patents` is, in fact, an array (which obviously implements `IEnumerable<T>`); in turn, `System.Array`'s implementation of `Length` is called and not `System.Linq.Enumerable`'s implementation. Consequently, following a conversion to one of the collection types returned by a "To" method, it is generally safe to work with the collection (until another standard query operator is called). However, be aware that this will bring the entire result set into memory (it may have been backed by a database or file prior to this step). Furthermore, the "To" method will take a snapshot of the underlying data, such that no fresh results will be returned upon requerying the "To" method result.

NOTE

3.0

To avoid such repeated execution, you must cache the data that the executed query retrieves. To do so, you assign the data to a local collection using one of the "To" method's collection methods. During the assignment call of a "To" method, the query obviously executes. However, iterating over the assigned collection after that point will not involve the query expression any further. In general, if you want the behavior of an in-memory collection snapshot, it is a best practice to assign a query expression to a cached collection to avoid unnecessary iterations.

We strongly encourage readers to review the sequence diagram in Figure 14.2 along with the corresponding code and recognize that the deferred execution of standard query operators can result in extremely subtle triggering of the standard query operators; therefore, developers should use caution and seek to avoid unexpected calls. The query object represents the query, not the results. When you ask the query for the results, the whole query executes (perhaps even again) because the query object doesn't know that the results will be the same as they were during a previous execution (if one existed).

Sorting with OrderBy() and ThenBy()

Another common operation on a collection is to sort it. This involves a call to `System.Linq.Enumerable`'s `OrderBy()`, as shown in Listing 14.20 and Output 14.6.

Listing 14.20: Ordering with `System.Linq.Enumerable.OrderBy()/ThenBy()`

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

      IEnumerable<Patent> items;
      Patent[] patents = PatentData.Patents;
      items = patents.OrderBy(
          patent => patent.YearOfPublication).ThenBy(
          patent => patent.Title);
      Print(items);
      Console.WriteLine();

      items = patents.OrderByDescending(
          patent => patent.YearOfPublication).ThenByDescending(
          patent => patent.Title);
      Print(items);

// ...
```

Output 14.6

3.0

```
Bifocals (1784)
Steam Locomotive (1815)
Electrical Telegraph (1837)
Phonograph (1877)
Kinetoscope (1888)
Flying Machine (1903)
Backless Brassiere (1914)
Droplet Deposition Apparatus (1989)

Droplet Deposition Apparatus (1989)
Backless Brassiere (1914)
Flying Machine (1903)
Kinetoscope (1888)
Phonograph (1877)
Electrical Telegraph (1837)
Steam Locomotive (1815)
Bifocals (1784)
```

The `OrderBy()` call takes a lambda expression that identifies the key on which to sort. In Listing 14.20, the initial sort uses the year that the patent was published.

However, notice that the `OrderBy()` call takes only a single parameter, which uses the name `keySelector`, to sort on. To sort on a second column, it is necessary to use a different method: `ThenBy()`. Similarly, code would use `ThenBy()` for any additional sorting.

`OrderBy()` returns an `IOrderedEnumerable<T>` interface, not an `IEnumerable<T>`. Furthermore, `IOrderedEnumerable<T>` derives from `IEnumerable<T>`, so all the standard query operators (including `OrderBy()`) are available on the `OrderBy()` return. However, repeated calls to `OrderBy()` would undo the work of the previous call such that the end result would sort by only the `keySelector` in the final `OrderBy()` call. For this reason, you should be careful not to call `OrderBy()` on a previous `OrderBy()` call.

Instead, you should specify additional sorting criteria using `ThenBy()`. Although `ThenBy()` is an extension method, it is not an extension of `IEnumerable<T>`, but rather of `IOrderedEnumerable<T>`. The method, also defined on `System.Linq.Extensions.Enumerable`, is declared as follows:

```
public static IOrderedEnumerable<TSource>
  ThenBy<TSource, TKey>(
    this IOrderedEnumerable<TSource> source,
    Func<TSource, TKey> keySelector)
```

In summary, use `OrderBy()` first, followed by zero or more calls to `ThenBy()` to provide additional sorting "columns." The methods `OrderByDescending()` and `ThenByDescending()` provide the same functionality except with descending order. Mixing and matching ascending and descending methods is not a problem, but if sorting further, use a `ThenBy()` call (either ascending or descending).

3.0

Two more important notes about sorting are warranted. First, the actual sort doesn't occur until you begin to access the members in the collection, at which point the entire query is processed. You can't sort unless you have all the items to sort, because you can't determine whether you have the first item. The fact that sorting is delayed until you begin to access the members is due to deferred execution, as we describe earlier in this chapter. Second, each subsequent call to sort the data (`Orderby()` followed by `ThenBy()` followed by `ThenByDescending()`, for example) does involve additional calls to the `keySelector` lambda expression of the earlier sorting calls. In other words, a call to `OrderBy()` will call its corresponding `keySelector` lambda expression once you iterate over the collection. Furthermore, a subsequent call to `ThenBy()` will again make calls to `OrderBy()`'s `keySelector`.

Guidelines

DO not call an `OrderBy()` following a prior `OrderBy()` method call. Use `ThenBy()` to sequence items by more than one value.

BEGINNER TOPIC

Join Operations

Consider two collections of objects as shown in the Venn diagram in Figure 14.3. The left circle in the diagram includes all inventors, and the right circle contains all patents. The intersection includes both inventors and patents, and a line is formed for each case where there is a match of inventors to patents. As the diagram shows, each inventor may have multiple patents and each patent can have one or more inventors. Each patent has an inventor, but in some cases inventors do not yet have patents.

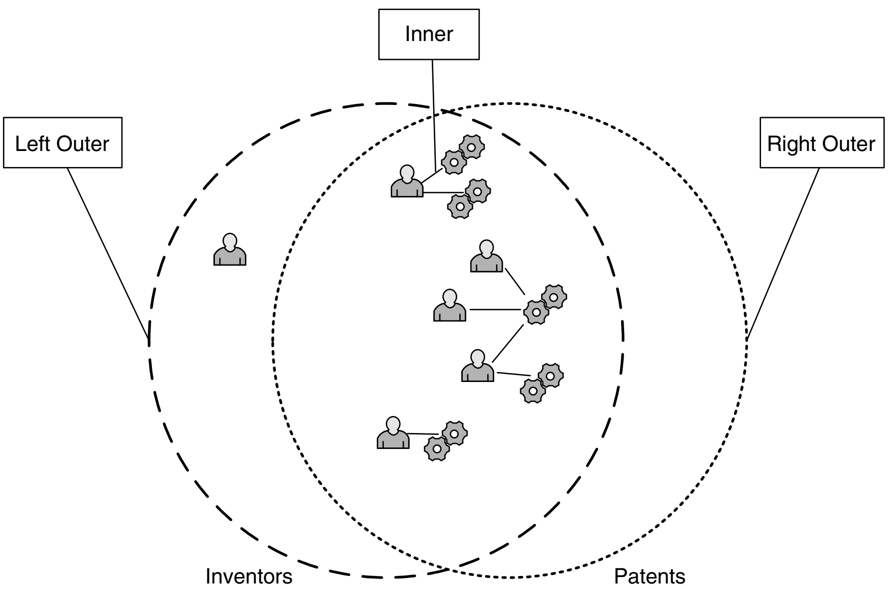

FIGURE 14.3: Venn Diagram of Inventor and Patent Collections

3.0

Matching up inventors within the intersection to patents is an **inner join.** The result is a collection of inventor/patent pairs in which both patents and inventions exist for a pair. A **left outer join** includes all the items within the left circle regardless of whether they have a corresponding patent. In this particular example, a **right outer join** would be the same as an inner join because there are no patents without inventors. Furthermore, the designation of left versus right is arbitrary, so there is really no distinction between left and outer joins. A **full outer join,** however, would include records from both outer sides; it is relatively rare to perform a full outer join.

Another important characteristic in the relationship between inventors and patents is that it is a **many-to-many** relationship. Each individual patent can have one or more inventors (the flying machine's invention by both Orville and Wilbur Wright, for example). Furthermore, each inventor can have one or more patents (Benjamin Franklin's invention of both bifocals and the phonograph, for example).

Another common relationship is a **one-to-many** relationship. For example, a company department may have many employees. However, each employee can belong to only one department at a time. (However, as is common with one-to-many relationships, adding the factor of time can transform them into many-to-many relationships. A particular employee may move from one department to another so that over time, she could potentially be associated with multiple departments, making another many-to-many relationship.)

Listing 14.21 provides a sample listing of Employee and Department data, and Output 14.7 shows the results.

3.0

Listing 14.21: Sample Employee and Department Data

```
public class Department
{
    public long Id { get; set; }
    public string Name { get; set; }
    public override string ToString()
    {
        return Name;
    }
}
```

```
public class Employee
{
    public int Id { get; set; }
    public string Name { get; set; }
```

```
        public string Title { get; set; }
        public int DepartmentId { get; set; }
        public override string ToString()
        {
            return $"{ Name } ({ Title })";
        }
    }
```

```
    public static class CorporateData
    {
        public static readonly Department[] Departments =
            new Department[]
          {
              new Department(){
                  Name="Corporate", Id=0},
              new Department(){
                  Name="Finance", Id=1},
              new Department(){
                  Name="Engineering", Id=2},
              new Department(){
                  Name="Information Technology",
                  Id=3},
              new Department(){
                  Name="Philanthropy",
                  Id=4},
              new Department(){
                  Name="Marketing",
                  Id=5},
          };

        public static readonly Employee[] Employees = new Employee[]
          {
              new Employee(){
                  Name="Mark Michaelis",
                  Title="Chief Computer Nerd",
                  DepartmentId = 0},
              new Employee(){
                  Name="Michael Stokesbary",
                  Title="Senior Computer Wizard",
                  DepartmentId=2},
              new Employee(){
                  Name="Brian Jones",
                  Title="Enterprise Integration Guru",
                  DepartmentId=2},
              new Employee(){
                  Name="Shane Kercheval",
                  Title="Chief Financial Officer",
                  DepartmentId=1},
              new Employee(){
                  Name="Pat Dever",
                  Title="Enterprise Architect",
                  DepartmentId = 3},
```

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```
            new Employee(){
                Name="Kevin Bost",
                Title="Programmer Extraordinaire",
                DepartmentId = 2},
            new Employee(){
                Name="Thomas Heavey",
                Title="Software Architect",
                DepartmentId = 2},
            new Employee(){
                Name="Eric Edmonds",
                Title="Philanthropy Coordinator",
                DepartmentId = 4}
        };
}
```

```
class Program
{
    static void Main()
    {
        IEnumerable<Department> departments =
            CorporateData.Departments;
        Print(departments);

        Console.WriteLine();

        IEnumerable<Employee> employees =
            CorporateData.Employees;
        Print(employees);
    }

    private static void Print<T>(IEnumerable<T> items)
    {
        foreach (T item in items)
        {
            Console.WriteLine(item);
        }
    }
}
```

3.0

Output 14.7

```
Corporate
Finance
Engineering
Information Technology
Philanthropy
Marketing

Mark Michaelis (Chief Computer Nerd)
Michael Stokesbary (Senior Computer Wizard)
Brian Jones (Enterprise Integration Guru)
Shane Kercheval (Chief Financial Officer)
Pat Dever (Enterprise Architect)
Kevin Bost (Programmer Extraordinaire)
Thomas Heavey (Software Architect)
Eric Edmonds (Philanthropy Coordinator)
```

We will use this data in the example in the following section on joining data.

Performing an Inner Join with `Join()`

In the world of objects on the client side, relationships between objects are generally already set up. For example, the relationship between files and the directories in which they reside are preestablished with the `DirectoryInfo.GetFiles()` method and the `FileInfo.Directory` method, respectively. Frequently, however, this is not the case with data being loaded from nonobject stores. Instead, the data needs to be joined together so that you can navigate from one type of object to the next in a way that makes sense for the data.

Consider the example of employees and company departments. In Listing 14.22, we join each employee to his or her department and then list each employee with his or her corresponding department. Since each employee belongs to only one (and exactly one) department, the total number of items in the list is equal to the total number of employees—each employee appears only once (each employee is said to be **normalized**). Output 14.8 shows the results.

Listing 14.22: An Inner Join Using `System.Linq.Enumerable.Join()`

3.0

```
using System;
using System.Linq;

// ...

      Department[] departments = CorporateData.Departments;
      Employee[] employees = CorporateData.Employees;

      var items = employees.Join(
          departments,
          employee => employee.DepartmentId,
          department => department.Id,
          (employee, department) => new
          {
              employee.Id,
              employee.Name,
              employee.Title,
              Department = department
          });

      foreach (var item in items)
      {
```

```
            Console.WriteLine(
                $"{ item.Name } ({ item.Title })");
            Console.WriteLine("\t" + item.Department);
        }

   // ...
```

Output 14.8

```
Mark Michaelis (Chief Computer Nerd)
        Corporate
Michael Stokesbary (Senior Computer Wizard)
        Engineering
Brian Jones (Enterprise Integration Guru)
        Engineering
Shane Kercheval (Chief Financial Officer)
        Finance
Pat Dever (Enterprise Architect)
        Information Technology
Kevin Bost (Programmer Extraordinaire)
        Engineering
Thomas Heavey (Software Architect)
        Engineering
Eric Edmonds (Philanthropy Coordinator)
        Philanthropy
```

The first parameter for `Join()` has the name `inner`. It specifies the collection, `departments`, that `employees` joins to. The next two parameters are lambda expressions that specify how the two collections will connect. `employee => employee.DepartmentId` (with a parameter name of `outerKeySelector`) identifies that on each employee, the key will be `DepartmentId`. The next lambda expression (`department => department.Id`) specifies the `Department`'s `Id` property as the key—in other words, for each employee, join a department where `employee.DepartmentId` equals `department.Id`. The last parameter, the anonymous type, is the resultant item that is selected. In this case, it is a class with `Employee`'s `Id`, `Name`, and `Title` as well as a `Department` property with the joined `department` object.

3.0

Notice in the output that *Engineering* appears multiple times—once for each employee in `CorporateData`. In this case, the `Join()` call produces a **Cartesian product** between all the departments and all the employees such that a new record is created for every case where a record exists in both collections and the specified department IDs are the same. This type of join is an **inner join.**

The data could also be joined in reverse, such that `department` joins to each employee so as to list each department-to-employee match. Notice that the output includes more records than there are departments: There are multiple employees for each department, and the output is a record for each match. As we saw before, the Engineering department appears multiple times, once for each employee.

The code in Listing 14.23 (which produces Output 14.9) is similar to that in Listing 14.22, except that the objects, `Departments` and `Employees`, are reversed. The first parameter to `Join()` is `employees`, indicating what `departments` joins to. The next two parameters are lambda expressions that specify how the two collections will connect: `department => department.Id` for `departments` and `employee => employee.DepartmentId` for `employees`. As before, a join occurs whenever `department.Id` equals `employee.EmployeeId`. The final anonymous type parameter specifies a class with `int Id`, `string Name`, and `Employee Employee` properties.

LISTING 14.23: Another Inner Join with `System.Linq.Enumerable.Join()`

```
using System;
using System.Linq;

// ...

      Department[] departments = CorporateData.Departments;
      Employee[] employees = CorporateData.Employees;

      var items = departments.Join(
          employees,
          department => department.Id,
          employee => employee.DepartmentId,
          (department, employee) => new
          {
              department.Id,
              department.Name,
              Employee = employee
          });

      foreach (var item in items)
      {
          Console.WriteLine(item.Name);
          Console.WriteLine("\t" + item.Employee);
      }

// ...
```

3.0

OUTPUT 14.9

```
Corporate
        Mark Michaelis (Chief Computer Nerd)
Finance
        Shane Kercheval (Chief Financial Officer)
Engineering
        Michael Stokesbary (Senior Computer Wizard)
Engineering
        Brian Jones (Enterprise Integration Guru)
Engineering
        Kevin Bost (Programmer Extraordinaire)
Engineering
        Thomas Heavey (Software Architect)
Information Technology
        Pat Dever (Enterprise Architect)
Philanthropy
        Eric Edmonds (Philanthropy Coordinator)
```

Grouping Results with GroupBy()

In addition to ordering and joining a collection of objects, frequently you might want to group objects with like characteristics together. For the employee data, you might want to group employees by department, region, job title, and so forth. Listing 14.24 shows an example of how to do this with the GroupBy() standard query operator (see Output 14.10 to view the output).

LISTING 14.24: Grouping Items Together Using **System.Linq.Enumerable.GroupBy()**

3.0

```
using System;
using System.Linq;

// ...

      IEnumerable<Employee> employees = CorporateData.Employees;

      IEnumerable<IGrouping<int, Employee>> groupedEmployees =
        employees.GroupBy((employee) => employee.DepartmentId);

      foreach(IGrouping<int, Employee> employeeGroup in
          groupedEmployees)
      {
          Console.WriteLine();
          foreach(Employee employee in employeeGroup)
          {
              Console.WriteLine("\t" + employee);
          }
          Console.WriteLine(
```

```
                "\tCount: " + employeeGroup.Count());
        }
    // ...
```

Output 14.10

```
Mark Michaelis (Chief Computer Nerd)
    Count: 1

Michael Stokesbary (Senior Computer Wizard)
Brian Jones (Enterprise Integration Guru)
Kevin Bost (Programmer Extraordinaire)
Thomas Heavey (Software Architect)
    Count: 4

Shane Kercheval (Chief Financial Officer)
    Count: 1

Pat Dever (Enterprise Architect)
    Count: 1

Eric Edmonds (Philanthropy Coordinator)
    Count: 1
```

Note that the items output from a `GroupBy()` call are of type `IGrouping<TKey, TElement>`, which has a property for the key that the query is grouping on (`employee.DepartmentId`). However, it does not have a property for the items within the group. Rather, `IGrouping<TKey, TElement>` derives from `IEnumerable<T>`, allowing for enumeration of the items within the group using a `foreach` statement or for aggregating the data into something such as a count of items (`employeeGroup.Count()`).

3.0

Implementing a One-to-Many Relationship with GroupJoin()

Listing 14.22 and Listing 14.23 are virtually identical. Either `Join()` call could have produced the same output just by changing the anonymous type definition. When trying to create a list of employees, Listing 14.22 provides the correct result. `department` ends up as a property of each anonymous type representing the joined employee. However, Listing 14.23 is not optimal. Given support for collections, a preferable representation of a department would have a collection of employees rather than a single anonymous type record for each department–employee relationship. Listing 14.25 demonstrates; Output 14.11 shows the preferred output.

LISTING 14.25: Creating a Child Collection with `System.Linq.Enumerable.GroupJoin()`

```
using System;
using System.Linq;

// ...

      Department[] departments = CorporateData.Departments;
      Employee[] employees = CorporateData.Employees;

      var items = departments.GroupJoin(
          employees,
          department => department.Id,
          employee => employee.DepartmentId,
          (department, departmentEmployees) => new
          {
              department.Id,
              department.Name,
              Employees = departmentEmployees
          });

      foreach (var item in items)
      {
          Console.WriteLine(item.Name);
          foreach (Employee employee in item.Employees)
          {
              Console.WriteLine("\t" + employee);
          }
      }

// ...
```

OUTPUT 14.11

3.0

```
Corporate
        Mark Michaelis (Chief Computer Nerd)
Finance
        Shane Kercheval (Chief Financial Officer)
Engineering
        Michael Stokesbary (Senior Computer Wizard)
        Brian Jones (Enterprise Integration Guru)
        Kevin Bost (Programmer Extraordinaire)
        Thomas Heavey (Software Architect)
Information Technology
        Pat Dever (Enterprise Architect)
Philanthropy
        Eric Edmonds (Philanthropy Coordinator)
```

To achieve the preferred result, we use `System.Linq.Enumerable`'s `GroupJoin()` method. The parameters are the same as those in Listing 14.22, except for the final anonymous type selected. In Listing 14.22, the lambda expression is of type `Func<Department, IEnumerable<Employee>, TResult>`, where `TResult` is the selected anonymous type. Notice that we use the second type argument (`IEnumerable<Employee>`) to project the collection of employees for each department onto the resultant department anonymous type.

(Readers familiar with SQL will notice that, unlike `Join()`, `GroupJoin()` doesn't have a SQL equivalent because data returned by SQL is record based, and not hierarchical.)

ADVANCED TOPIC

Implementing an Outer Join with GroupJoin()

The earlier inner joins are *equi-joins* because they are based on an equivalent evaluation of the keys. Records appear in the resultant collection only if there are objects in both collections. On occasion, however, it is desirable to create a record even if the corresponding object doesn't exist. For example, rather than leaving the Marketing department out from the final department list simply because it doesn't have any employees, it would be preferable if we included it with an empty employee list. To accomplish this, we perform a left outer join using a combination of both `GroupJoin()` and `SelectMany()` along with `DefaultIfEmpty()`. This is demonstrated in Listing 14.26 and Output 14.12.

Listing 14.26: Implementing an Outer Join Using GroupJoin() with SelectMany()

```
using System;
using System.Linq;

// ...

      Department[] departments = CorporateData.Departments;
      Employee[] employees = CorporateData.Employees;

      var items = departments.GroupJoin(
          employees,
          department => department.Id,
          employee => employee.DepartmentId,
          (department, departmentEmployees) => new
          {
              department.Id,
              department.Name,
              Employees = departmentEmployees
          }).SelectMany(
              departmentRecord =>
```

3.0

```
                    departmentRecord.Employees.DefaultIfEmpty(),
                (departmentRecord, employee) => new
                    {
                        departmentRecord.Id,
                        departmentRecord.Name,
                        Employees =
                            departmentRecord.Employees
                    }).Distinct();

        foreach (var item in items)
        {
            Console.WriteLine(item.Name);
            foreach (Employee employee in item.Employees)
            {
                Console.WriteLine("\t" + employee);
            }
        }

  // ...
```

OUTPUT 14.12

```
Corporate
        Mark Michaelis (Chief Computer Nerd)
Finance
        Shane Kercheval (Chief Financial Officer)
Engineering
        Michael Stokesbary (Senior Computer Wizard)
        Brian Jones (Enterprise Integration Guru)
        Kevin Bost (Programmer Extraordinaire)
        Thomas Heavey (Software Architect)
Information Technology
        Pat Dever (Enterprise Architect)
Philanthropy
        Eric Edmonds (Philanthropy Coordinator)
Marketing
```

3.0

Calling SelectMany()

On occasion, you may have collections of collections. Listing 14.27 provides an example of such a scenario. The `teams` array contains two teams, each with a string array of players.

LISTING 14.27: Calling SelectMany()

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

      var worldCup2006Finalists = new[]
```

```
        {
            new
            {
                TeamName = "France",
                Players = new string[]
                {
                    "Fabien Barthez", "Gregory Coupet",
                    "Mickael Landreau", "Eric Abidal",
                    "Jean-Alain Boumsong", "Pascal Chimbonda",
                    "William Gallas", "Gael Givet",
                    "Willy Sagnol", "Mikael Silvestre",
                    "Lilian Thuram", "Vikash Dhorasoo",
                    "Alou Diarra", "Claude Makelele",
                    "Florent Malouda", "Patrick Vieira",
                    "Zinedine Zidane", "Djibril Cisse",
                    "Thierry Henry", "Franck Ribery",
                    "Louis Saha", "David Trezeguet",
                    "Sylvain Wiltord",
                }
            },
            new
            {
                TeamName = "Italy",
                Players = new string[]
                {
                    "Gianluigi Buffon", "Angelo Peruzzi",
                    "Marco Amelia", "Cristian Zaccardo",
                    "Alessandro Nesta", "Gianluca Zambrotta",
                    "Fabio Cannavaro", "Marco Materazzi",
                    "Fabio Grosso", "Massimo Oddo",
                    "Andrea Barzagli", "Andrea Pirlo",
                    "Gennaro Gattuso", "Daniele De Rossi",
                    "Mauro Camoranesi", "Simone Perrotta",
                    "Simone Barone", "Luca Toni",
                    "Alessandro Del Piero", "Francesco Totti",
                    "Alberto Gilardino", "Filippo Inzaghi",
                    "Vincenzo Iaquinta",
                }
            }
        };

        IEnumerable<string> players =
            worldCup2006Finalists.SelectMany(
                team => team.Players);

        Print(players);

  // ...
```

3.0

The output from this Listing has each player's name displayed on its own line in the order in which it appears in the code. The difference between `Select()` and `SelectMany()` is the fact that `Select()` would return two items, one corresponding to each item in the original collection. `Select()` may project out a transform from the original type, but the number of items would not change. For example, `teams.Select(team => team.Players)` will return an `IEnumerable<string[]>`.

In contrast, `SelectMany()` iterates across each item identified by the lambda expression (the array selected by `Select()` earlier) and hoists out each item into a new collection that includes a union of all items within the child collection. Instead of two arrays of players, `SelectMany()` combines each array selected and produces a single collection of all items.

More Standard Query Operators

Listing 14.28 shows code that uses some of the simpler APIs enabled by `Enumerable`; Output 14.13 shows the results.

LISTING 14.28: More System.Linq.Enumerable Method Calls

3.0

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

class Program
{
  static void Main()
  {
      IEnumerable<object> stuff =
        new object[] { new object(), 1, 3, 5, 7, 9,
            "\"thing\"", Guid.NewGuid() };
      Print("Stuff: { stuff }");
      IEnumerable<int> even = new int[] { 0, 2, 4, 6, 8 };
      Print("Even integers: {0}", even);

      IEnumerable<int> odd = stuff.OfType<int>();
      Print("Odd integers: {0}", odd);

      IEnumerable<int> numbers = even.Union(odd);
      Print("Union of odd and even: {0}", numbers);

      Print("Union with even: {0}", numbers.Union(even));
      Print("Concat with odd: {0}", numbers.Concat(odd));
      Print("Intersection with even: {0}",
          numbers.Intersect(even));
      Print("Distinct: {0}", numbers.Concat(odd).Distinct());
      if (!numbers.SequenceEqual(
          numbers.Concat(odd).Distinct()))
      {
          throw new Exception("Unexpectedly unequal");
```

```
        }
        else
        {
            Console.WriteLine(
                @"Collection ""SequenceEquals""" +
                      $" {nameof(numbers)}.Concat(odd).Distinct())")
        }
        Print("Reverse: {0}", numbers.Reverse());
        Print("Average: {0}", numbers.Average());
        Print("Sum: {0}", numbers.Sum());
        Print("Max: {0}", numbers.Max());
        Print("Min: {0}", numbers.Min());
    }

    private static void Print<T>(
            string format, IEnumerable<T> items) =>
        Console.WriteLine(format, string.Join(
            ", ", items.Select(x => x.ToString())));

    private static void Print<T>(string format, T item)
    {
        Console.WriteLine(format, item);
    }
}
```

Output 14.13

```
Stuff: System.Object, 1, 3, 5, 7, 9, "thing"
24c24a41-ee05-41b9-958e-50dd12e3981e
Even integers: 0, 2, 4, 6, 8
Odd integers: 1, 3, 5, 7, 9
Union of odd and even: 0, 2, 4, 6, 8, 1, 3, 5, 7, 9
Union with even: 0, 2, 4, 6, 8, 1, 3, 5, 7, 9
Concat with odd: 0, 2, 4, 6, 8, 1, 3, 5, 7, 9, 1, 3, 5, 7, 9
Intersection with even: 0, 2, 4, 6, 8
Distinct: 0, 2, 4, 6, 8, 1, 3, 5, 7, 9
Collection "SequenceEquals" numbers.Concat(odd).Distinct())
Reverse: 9, 7, 5, 3, 1, 8, 6, 4, 2, 0
Average: 4.5
Sum: 45
Max: 9
Min: 0
```

3.0

None of the API calls in Listing 14.21 requires a lambda expression. Table 14.1 and Table 14.2 describe each method and provide an example. Included on `System.Linq.Enumerable` is a collection of aggregate functions that enumerate the collection and calculate a result (shown In Table 14.2). `Count` is one example of an aggregate function already shown within the chapter.

TABLE 14.1: Simpler Standard Query Operators

Comment Type	Description
`OfType<T>()`	Forms a query over a collection that returns only the items of a particular type, where the type is identified in the type parameter of the `OfType<T>()` method call.
`Union()`	Combines two collections to form a superset of all the items in both collections. The final collection does not include duplicate items even if the same item existed in both collections to start.
`Concat()`	Combines two collections together to form a superset of both collections. Duplicate items are not removed from the resultant collection. `Concat()`will preserve the ordering. That is, concatting `{A, B}` with `{C, D}` will produce `{A, B, C, D}`.
`Intersect()`	Extracts the collection of items that exist in both original collections.
`Distinct()`	Filters out duplicate items from a collection so that each item within the resultant collection is unique.
`SequenceEquals()`	Compares two collections and returns a Boolean indicating whether the collections are identical, including the order of items within the collection. (This is a very helpful message when testing expected results.)
`Reverse()`	Reverses the items within a collection so that they occur in reverse order when iterating over the collection.

3.0

TABLE 14.2: Aggregate Functions on `System.Linq.Enumerable`

Comment Type	Description
`Count()`	Provides a total count of the number of items within the collection
`Average()`	Calculates the average value for a numeric key selector
`Sum()`	Computes the sum values within a numeric collection
`Max()`	Determines the maximum value among a collection of numeric values
`Min()`	Determines the minimum value among a collection of numeric values

Note that each method listed in Tables 14.1 and 14.2 will trigger deferred execution.

ADVANCED TOPIC

Queryable Extensions for IQueryable<T>

One virtually identical interface to `IEnumerable<T>` is `IQueryable<T>`. Because `IQueryable<T>` derives from `IEnumerable<T>`, it has all the members of `IEnumerable<T>` but only those declared directly (`GetEnumerator()`, for example). Extension methods are not inherited, so `IQueryable<T>` doesn't have any of the `Enumerable` extension methods. However, it has a similar extending class called `System.Linq.Queryable` that adds to `IQueryable<T>` almost all of the same methods that `Enumerable` added to `IEnumerable<T>`. Therefore, it provides a very similar programming interface.

What makes `IQueryable<T>` unique is the fact that it enables custom LINQ providers. A LINQ provider subdivides expressions into their constituent parts. Once divided, the expression can be translated into another language, serialized for remote execution, injected with an asynchronous execution pattern, and much more. Essentially, LINQ providers allow for an interception mechanism into a standard collection API, and via this seemingly limitless functionality, behavior relating to the queries and collection can be injected.

For example, LINQ providers allow for the translation of a query expression from C# into SQL that is then executed on a remote database. In so doing, the C# programmer can remain in her primary object-oriented language and leave the translation to SQL to the underlying LINQ provider. Through this type of expression, programming languages are able to span the impedance mismatch between the object-oriented world and the relational database.

In the case of `IQueryable<T>`, vigilance regarding deferred execution is even more critical. Imagine, for example, a LINQ provider that returns data from a database. Rather than retrieving the data from a database regardless of the selection criteria, the lambda expression would provide an implementation of `IQueryable<T>` that possibly includes context information such as the connection string, but not the data itself. The data retrieval wouldn't occur until the call to `GetEnumerator()` or even `MoveNext()`. However, the `GetEnumerator()` call is generally implicit, such as when iterating over the collection with `foreach` or calling an `Enumerable` method such as `Count<T>()` or `Cast<T>()`. Obviously, cases such as this require developers to be wary of the subtle and repeated calls to any expensive operation that deferred execution might involve. For example, if calling `GetEnumerator()` involves a distributed call over the network to a database, it would be wise to avoid unintentional duplicate calls to iterations with `Count()` or `foreach`.

3.0

SUMMARY

After introducing anonymous types, implicit variables, and collection initializers, this chapter described the internals of how the `foreach` loop works and explained which interfaces are required for its execution. In addition, developers frequently filter a collection so that there are fewer items and project the collection so that the items take a different form. Toward that end, this chapter discussed the details of how to use the standard query operators—that is, common collection APIs on the `System.Linq.Enumerable` class—to perform collection manipulation.

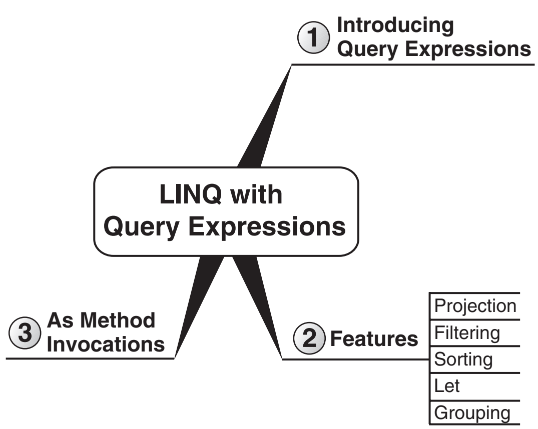
In the introduction to standard query operators, we detailed the process of deferred execution and emphasized how developers should take care to avoid unintentionally reexecuting an expression via a subtle call that enumerates over the collection contents. The deferred execution and resultant implicit execution of standard query operators is a significant factor in code efficiency, especially when the query execution is expensive. Programmers should treat the query object as the query object, not the results, and expect the query to execute fully even if it executed already. The query object doesn't know that the results will be the same as they were during a previous execution.

Listing 14.26 appeared within an Advanced Topic section because of the complexity of calling multiple standard query operators one after the other. Although requirements for similar execution may be commonplace, it is not necessary to rely on standard query operators directly. C# 3.0 includes query expressions, a SQL-like syntax for manipulating collections in a way
3.0 that is frequently easier to code and read, as we show in the next chapter.

15

LINQ with Query Expressions

THE END OF CHAPTER 14 showed a query using standard query operators for `GroupJoin()`, `SelectMany()`, and `Distinct()`, in addition to the creation of two anonymous types. The result was a statement that spanned multiple lines and was rather more complex and difficult to comprehend than statements typically written using only features of earlier versions of C#. Modern programs that manipulate rich data sets often require such complex queries; it would therefore be nice if the language made them easier to read. Domain-specific query languages such as SQL make it much easier to read and understand a query, but lack the full power of the C# language. That is why the C# language designers added **query expressions** syntax to C# 3.0. With query expressions, many standard query operator expressions are transformed into more readable code, much like SQL. 3.0



In this chapter, we introduce query expressions and use them to express many of the queries from the preceding chapter.

Introducing Query Expressions

Two of the operations that developers most frequently perform are **filtering** the collection to eliminate unwanted items and **projecting** the collection so that the items take a different form. For example, given a collection of files, we could filter it to create a new collection of only the files with a ".cs" extension, or only the files larger than 1 million bytes. We could also project the file collection to create a new collection of paths to the directories where the files are located and the corresponding directory size. Query expressions provide straightforward syntaxes for both of these common operations. Listing 15.1 shows a query expression that filters a collection of strings; Output 15.1 shows the results.

Listing 15.1: Simple Query Expression

3.0

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  static string[] Keywords = {
      "abstract", "add*", "alias*", "as", "ascending*",
      "async*", "await*", "base","bool", "break",
      "by*", "byte", "case", "catch", "char", "checked",
      "class", "const", "continue", "decimal", "default",
      "delegate", "descending*", "do", "double",
      "dynamic*", "else", "enum", "event", "equals*",
      "explicit", "extern", "false", "finally", "fixed",
      "from*", "float", "for", "foreach", "get*", "global*",
      "group*", "goto", "if", "implicit", "in", "int",
      "into*", "interface", "internal", "is", "lock", "long",
      "join*", "let*", "nameof*", "namespace", "new", "null",
      "object", "on*", "operator", "orderby*", "out",
      "override", "params", "partial*", "private", "protected",
      "public", "readonly", "ref", "remove*", "return", "sbyte",
      "sealed", "select*", "set*", "short", "sizeof",
      "stackalloc", "static", "string", "struct", "switch",
      "this", "throw", "true", "try", "typeof", "uint", "ulong",
      "unsafe", "ushort", "using", "value*", "var*", "virtual",
      "unchecked", "void", "volatile", "where*", "while", "yield*"};

  private static void ShowContextualKeywords1()
```

```
    {
        IEnumerable<string> selection =
            from word in Keywords
                where !word.Contains('*')
                select word;

        foreach (string keyword in selection)
        {
            Console.Write(keyword + " ");
        }
    }

  // ...
```

Output 15.1

```
abstract as base bool break byte case catch char checked class const
continue decimal default delegate do double else enum event explicit
extern false finally fixed float for foreach goto if implicit in int
interface internal is lock long namespace new null object operator out
override params private protected public readonly ref return sbyte
sealed short sizeof stackalloc static string struct switch this throw
true try typeof uint ulong unchecked unsafe ushort using virtual void
volatile while
```

In this query expression, `selection` is assigned the collection of C# reserved keywords. The query expression in this example includes a `where` clause that filters out the noncontextual keywords.

Query expressions always begin with a "from clause" and end with a "select clause" or a "group clause," identified by the `from`, `select`, or `group` contextual keyword, respectively. The identifier `word` in the `from` clause is called a **range variable;** it represents each item in the collection, much as the loop variable in a `foreach` loop represents each item in a collection. 3.0

Developers familiar with SQL will notice that query expressions have a syntax that is similar to that of SQL. This design was deliberate—it was intended that LINQ should be easy to learn for programmers who already know SQL. However, there are some obvious differences. The first difference that most SQL-experienced developers will notice is that the C# query expression shown here has the clauses in the following order: `from`, then `where`, then `select`. The equivalent SQL query puts the `SELECT` clause first, then the `FROM` clause, and finally the `WHERE` clause.

One reason for this change in sequence is to enable use of IntelliSense, the feature of the IDE whereby the editor produces helpful user interface elements such as drop-down lists that describe the members of a given object. Because from appears first and identifies the string array Keywords as the data source, the code editor can deduce that the range variable word is of type string. When you are entering the code into the editor and reach the dot following word, the editor will display only the members of string.

If the from clause appeared after the select, as it does in SQL, as you were typing in the query the editor would not know what the data type of word was, so it would not be able to display a list of word's members. In Listing 15.1, for example, it wouldn't be possible to predict that Contains() was a possible member of word.

The C# query expression order also more closely matches the order in which operations are logically performed. When evaluating the query, you begin by identifying the collection (described by the from clause), then filter out the unwanted items (with the where clause), and finally describe the desired result (with the select clause).

Finally, the C# query expression order ensures that the rules for "where" (range) variables are in scope are mostly consistent with the scoping rules for local variables. For example, a (range) variable must be declared by a clause (typically a from clause) before the variable can be used, much as a local variable must always be declared before it can be used.

Projection

The result of a query expression is a collection of type IEnumerable<T> or IQueryable<T>.[1] The actual type T is inferred from the select or group by clause. In Listing 15.1, for example, the compiler knows that Keywords is of
3.0 type string[], which is convertible to IEnumerable<string>, and deduces that word is therefore of type string. The query ends with select word, which means the result of the query expression must be a collection of strings, so the type of the query expression is IEnumerable<string>.

In this case, the "input" and the "output" of the query are both a collection of strings. However, the "output" type can be quite different from the "input" type if the expression in the select clause is of an entirely different type. Consider the query expression in Listing 15.2, and its corresponding output in Output 15.2.

1. The result of a query expression is, as a practical matter, almost always IEnumerable<T> or a type derived from it. It is legal, though somewhat perverse, to create an implementation of the query methods that return other types; there is no *requirement* in the language that the result of a query expression be convertible to IEnumerable<T>.

Listing 15.2: Projection Using Query Expressions

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.IO;

// ...

  static void List1(string rootDirectory, string searchPattern)
  {
      IEnumerable<string> fileNames = Directory.GetFiles(
          rootDirectory, searchPattern);
      IEnumerable<FileInfo> fileInfos =
          from fileName in fileNames
          select new FileInfo(fileName);

      foreach (FileInfo fileInfo in fileInfos)
      {
            Console.WriteLine(
                $@".{ fileInfo.Name } ({
                    fileInfo.LastWriteTime })");
      }
  }

// ...
```

Output 15.2

```
Account.cs (11/22/2011 11:56:11 AM)
Bill.cs (8/10/2011 9:33:55 PM)
Contact.cs (8/19/2011 11:40:30 PM)
Customer.cs (11/17/2011 2:02:52 AM)
Employee.cs (8/17/2011 1:33:22 AM)
Person.cs (10/22/2011 10:00:03 PM)
```

3.0

This query expression results in an `IEnumerable<FileInfo>` rather than the `IEnumerable<string>` data type returned by `Directory.GetFiles()`. The `select` clause of the query expression can potentially project out a data type that is different from what was collected by the `from` clause expression.

In this example, the type `FileInfo` was chosen because it has the two relevant fields needed for the desired output: the filename and the last write time. There might not be such a convenient type if you needed other information not captured in the `FileInfo` object. Anonymous types provide a convenient and concise way to project the exact data you need without having to find or create an explicit type. (In fact, this scenario was the key motivator for adding anonymous types to the language.) Listing 15.3 provides output similar to that in Listing 15.2, but via anonymous types rather than `FileInfo`.

LISTING 15.3: Anonymous Types within Query Expressions

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.IO;

// ...

  static void List2(string rootDirectory, string searchPattern)
  {
        var fileNames =Directory.EnumerateFiles(
            rootDirectory, searchPattern)
        var fileResults =
            from fileName in fileNames
            select new
            {
                Name = fileName,
                LastWriteTime = File.GetLastWriteTime(fileName)
            };

        foreach (var fileResult in fileResults)
        {
            Console.WriteLine(
                $@"{ fileResult.Name } ({
                    fileResult.LastWriteTime })");
        }
  }

// ...
```

In this example, the query projects out only the filename and its last file write time. A projection such as the one in Listing 15.3 makes little difference when working with something small, such as `FileInfo`. However,
3.0
"horizontal" projection that filters down the amount of data associated with each item in the collection is extremely powerful when the amount of data is significant and retrieving it (perhaps from a different computer over the Internet) is expensive. Rather than retrieving all the data when a query executes, the use of anonymous types enables the capability of storing and retrieving only the required data into the collection.

Imagine, for example, a large database that has tables with 30 or more columns. If there were no anonymous types, developers would be required either to use objects containing unnecessary information or to define small, specialized classes useful only for storing the specific data required. Instead, anonymous types enable support for types to be defined by the compiler—types that contain only the data needed for their immediate scenario. Other scenarios can have a different projection of only the properties needed for that scenario.

BEGINNER TOPIC

Deferred Execution with Query Expressions

Queries written using query expression notation exhibit deferred execution, just as the queries written in Chapter 14 did. Consider again the assignment of a query object to variable `selection` in Listing 15.1. The creation of the query and the assignment to the variable do not execute the query; rather, they simply build an object that represents the query. The method `word.Contains("*")` is not called when the query object is created. Rather, the query expression saves the selection criteria to be used when iterating over the collection identified by the `selection` variable.

To demonstrate this point, consider Listing 15.4 and the corresponding output (Output 15.3).

LISTING 15.4: Deferred Execution and Query Expressions (Example 1)

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  private static void ShowContextualKeywords2()
  {
      IEnumerable<string> selection = from word in Keywords
                                      where IsKeyword(word)
                                      select word;
      Console.WriteLine("Query created.");
      foreach (string keyword in selection)
      {
          // No space output here.
          Console.Write(keyword);
      }
  }

  // The side effect of console output is included
  // in the predicate to demonstrate deferred execution;
  // predicates with side effects are a poor practice in
  // production code.
  private static bool IsKeyword(string word)
```

3.0

```
    {
        if (word.Contains('*'))
        {
            Console.Write(" ");
            return true;
        }
        else
        {
            return false;
        }
    }
  // ...
```

Output 15.3

```
Query created.
 add* alias* ascending* async* await* by* descending* dynamic*
equals* from* get* global* group* into* join* let* nameof* on*
orderby* partial* remove* select* set* value* var* where* yield*
```

In Listing 15.4, no space is output within the `foreach` loop. The side effect of printing a space when the predicate `IsKeyword()` is executed happens when the query is iterated over—not when the query is created. Thus, although `selection` is a collection (it is of type `IEnumerable<T>` after all), at the time of assignment everything following the `from` clause comprises the selection criteria. Not until we begin to iterate over `selection` are the criteria applied.

Now consider a second example (see Listing 15.5 and Output 15.4).

3.0

Listing 15.5: Deferred Execution and Query Expressions (Example 2)

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  private static void CountContextualKeywords()
  {
      int delegateInvocations = 0;
      Func<string, string> func =
          text=>
          {
              delegateInvocations++;
              return text;
          };

      IEnumerable<string> selection =
```

```
            from keyword in Keywords
            where keyword.Contains('*')
            select func(keyword);


        Console.WriteLine(
            $"1. delegateInvocations={ delegateInvocations }");

        // Executing count should invoke func once for
        // each item selected.
        Console.WriteLine(
            $"2. Contextual keyword count={ selection.Count() }");

        Console.WriteLine(
            $"3. delegateInvocations={ delegateInvocations }");

        // Executing count should invoke func once for
        // each item selected.
        Console.WriteLine(
            $"4. Contextual keyword count={ selection.Count() }");

        Console.WriteLine(
            $"5. delegateInvocations={ delegateInvocations }");

        // Cache the value so future counts will not trigger
        // another invocation of the query.
        List<string> selectionCache = selection.ToList();

        Console.WriteLine(
            $"6. delegateInvocations={ delegateInvocations }");

        // Retrieve the count from the cached collection.
        Console.WriteLine(
            $"7. selectionCache count={ selectionCache.Count() }");

        Console.WriteLine(
            $"8. delegateInvocations={ delegateInvocations }");

    }
  // ...
```

3.0

Output 15.4

```
1. delegateInvocations=0
2. Contextual keyword count=27
3. delegateInvocations=27
4. Contextual keyword count=27
5. delegateInvocations=54
6. delegateInvocations=81
7. selectionCache count=27
8. delegateInvocations=81
```

Rather than defining a separate method, Listing 15.5 uses a statement lambda that counts the number of times the method is called.

Three things in the output are remarkable. First, notice that after `selection` is assigned, `DelegateInvocations` remains at zero. At the time of assignment to `selection`, no iteration over `Keywords` is performed. If `Keywords` were a property, the property call would run—in other words, the `from` clause executes at the time of assignment. However, neither the projection, nor the filtering, nor anything after the `from` clause will execute until the code iterates over the values within `selection`. It is as though at the time of assignment, `selection` would more appropriately be called "query."

Once we call `Count()`, however, a term such as selection or items that indicates a container or collection is appropriate because we begin to count the items within the collection. In other words, the variable selection serves a dual purpose of saving the query information and acting like a container from which the data is retrieved.

A second important characteristic to notice is that calling `Count()` twice causes `func` to again be invoked once on each item selected. Given that `selection` behaves both as a query and as a collection, requesting the count requires that the query be executed again by iterating over the `IEnumerable<string>` collection that `selection` refers to and counting the items. The C# compiler does not know whether anyone has modified the strings in the array such that the count would now be different, so the counting has to happen anew every time to ensure that the answer is correct and up-to-date. Similarly, a `foreach` loop over `selection` would trigger `func` to be called again for each item. The same is true of all the other extension
3.0 methods provided via `System.Linq.Enumerable`.

ADVANCED TOPIC

Implementing Deferred Execution

Deferred execution is implemented by using delegates and expression trees. A delegate provides the ability to create and manipulate a reference to a method that contains an expression that can be invoked later. An expression tree similarly provides the ability to create and manipulate information about an expression that can be examined and manipulated later.

In Listing 15.5, the predicate expressions of the `where` clauses and the projection expressions of the `select` clauses are transformed by the compiler into expression lambdas, and then the lambdas are transformed into delegate creations. The result of the query expression is an object that holds onto references to these delegates. Only when the query results are iterated over does the query object actually execute the delegates.

Filtering

In Listing 15.1, we include a `where` clause that filters out reserved keywords but not contextual keywords. This `where` clause filters the collection "vertically"; if you think of the collection as a vertical list of items, the `where` clause makes that vertical list shorter so that the collection holds fewer items. The filter criteria are expressed with a **predicate**—a lambda expression that returns a `bool` such as `word.Contains()` (as in Listing 15.1) or `File.GetLastWriteTime(file) < DateTime.Now.AddMonths(-1)`. The latter is shown in Listing 15.6, whose output appears in Output 15.5.

LISTING 15.6: Query Expression Filtering Using where

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.IO;

// ...

  static void FindMonthOldFiles(
      string rootDirectory, string searchPattern)
  {
      IEnumerable<FileInfo> files =
          from fileName in Directory.EnumerateFiles(
              rootDirectory, searchPattern)
          where File.GetLastWriteTime(fileName) <
              DateTime.Now.AddMonths(-1)
          select new FileInfo(fileName);

      foreach (FileInfo file in files)
      {
          //  As simplification, current directory is
          //  assumed to be a subdirectory of
          //  rootDirectory
          string relativePath = file.FullName.Substring(
                  Environment.CurrentDirectory.Length);
          Console.WriteLine(
              $".{ relativePath } ({ file.LastWriteTime })");
```

3.0

```
        }
    }

  // ...
```

OUTPUT 15.5

```
.\TestData\Bill.cs (8/10/2011 9:33:55 PM)
.\TestData\Contact.cs (8/19/2011 11:40:30 PM)
.\TestData\Employee.cs (8/17/2011 1:33:22 AM)
.\TestData\Person.cs (10/22/2011 10:00:03 PM)
```

Sorting

To order the items using a query expression, you can use the `orderby` clause, as shown in Listing 15.7.

LISTING 15.7: Sorting Using a Query Expression with an **orderby** Clause

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.IO;

// ...
  static void ListByFileSize1(
      string rootDirectory, string searchPattern)
  {
      IEnumerable<string> fileNames =
          from fileName in Directory.EnumerateFiles(
              rootDirectory, searchPattern)
          orderby (new FileInfo(fileName)).Length descending,
              fileName
          select fileName;

      foreach (string fileName in fileNames)
      {
          Console.WriteLine(fileName);
      }
  }
// ...
```

3.0

Listing 15.7 uses the `orderby` clause to sort the files returned by `Directory.GetFiles()` first by file size in descending order, and then by filename in ascending order. Multiple sort criteria are separated by commas, such that first the items are ordered by size, and then, if the size is the same, they are ordered by filename. `ascending` and `descending` are contextual keywords indicating the sort order direction. Specifying the order as ascending or descending is optional; if the direction is omitted (as it is here on `filename`), the default is `ascending`.

The `let` Clause

Listing 15.8 includes a query that is very similar to the query in Listing 15.7, except that the type argument of `IEnumerable<T>` is `FileInfo`. Notice that there is a problem with this query: We have to redundantly create a `FileInfo` twice, in both the `orderby` clause and the `select` clause.

Listing 15.8: Projecting a `FileInfo` Collection and Sorting by File Size

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.IO;

// ...
  static void ListByFileSize2(
      string rootDirectory, string searchPattern)
  {
      IEnumerable<FileInfo> files =
          from fileName in Directory.EnumerateFiles(
              rootDirectory, searchPattern)
          orderby new FileInfo(fileName).Length, fileName
          select new FileInfo(fileName);

      foreach (FileInfo file in files)
      {
          //  As a simplification, the current directory
          //  is assumed to be a subdirectory of
          //  rootDirectory
          string relativePath = file.FullName.Substring(
              Environment.CurrentDirectory.Length);
          Console.WriteLine(
              $".{ relativePath }({ file.Length })");
      }
  }
// ...
```

3.0

Unfortunately, although the end result is correct, Listing 15.8 ends up instantiating a `FileInfo` object twice for each item in the source collection, which seems wasteful and unnecessary. To avoid this kind of unnecessary and potentially expensive overhead, you can use a `let` clause, as demonstrated in Listing 15.9.

Listing 15.9: Ordering the Results in a Query Expression

```
        // ...
        IEnumerable<FileInfo> files =
            from fileName in Directory.EnumerateFiles(
                rootDirectory, searchPattern)
            let file = new FileInfo(fileName)
            orderby file.Length, fileName
            select file;
        // ...
```

The `let` clause introduces a new range variable that can hold the value of an expression that is used throughout the remainder of the query expression. You can add as many `let` clauses as you like; simply add each as an additional clause to the query after the first `from` clause but before the final `select`/`group by` clause.

Grouping

A common data manipulation scenario is the grouping of related items. In SQL, this generally involves aggregating the items to produce a summary or total or other aggregate value. LINQ, however, is notably more expressive. LINQ expressions allow for individual items to be grouped into a series of subcollections, and those groups can then be associated with items in the collection being queried. For example, Listing 15.10 and Output 15.6 demonstrate how to group together the contextual keywords and the regular keywords.

3.0

Listing 15.10: Grouping Together Query Results

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  private static void GroupKeywords1()
  {
      IEnumerable<IGrouping<bool, string>> selection =
          from word in Keywords
          group word by word.Contains('*');

      foreach (IGrouping<bool, string> wordGroup
          in selection)
      {
          Console.WriteLine(Environment.NewLine + "{0}:",
              wordGroup.Key ?
```

```
                "Contextual Keywords" : "Keywords");
            foreach (string keyword in wordGroup)
            {
                Console.Write(" " +
                    (wordGroup.Key ?
                        keyword.Replace("*", null) : keyword));
            }
        }
    }

  // ...
```

Output 15.6

```
Keywords:
abstract as base bool break byte case catch char checked class
const continue decimal default delegate do double else enum event
explicit extern false finally fixed float for foreach goto if
implicit in int interface internal is lock long namespace new null
operator out override object params private protected public
readonly ref return sbyte sealed short sizeof stackalloc static
string struct switch this throw true try typeof uint ulong unsafe
ushort using virtual unchecked void volatile while
Contextual Keywords:
 add alias ascending async await by descending dynamic equals from
get global group into join let nameof on orderby partial remove
select set value var where yield
```

There are several things to note in this listing. First, the query result is a sequence of elements of type `IGrouping<bool, string>`. The first type argument indicates that the "group key" expression following `by` was of type `bool`, and the second type argument indicates that the "group element" expression following `group` was of type `string`. That is, the query produces a sequence of groups where the Boolean key is the same for each `string` in the group. 3.0

Because a query with a `group by` clause produces a sequence of collections, the common pattern for iterating over the results is to create nested `foreach` loops. In Listing 15.10, the outer loop iterates over the groupings and prints out the type of keyword as a header. The nested `foreach` loop prints each keyword in the group as an item below the header.

The result of this query expression is itself a sequence, which you can then query like any other sequence. Listing 15.11 and Output 15.7 show how to create an additional query that adds a projection onto a query that produces a sequence of groups. (The next section, on query continuations, shows a preferable syntax for adding more query clauses to a complete query.)

Listing 15.11: Selecting an Anonymous Type Following the group Clause

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  private static void GroupKeywords1()
  {
      IEnumerable<IGrouping<bool, string>> keywordGroups =
          from word in Keywords
          group word by word.Contains('*');

      var selection =
          from groups in keywordGroups
          select new
          {
              IsContextualKeyword = groups.Key,
              Items = groups
          };

      foreach (var wordGroup in selection)
      {
          Console.WriteLine(Environment.NewLine + "{0}:",
              wordGroup.IsContextualKeyword ?
                  "Contextual Keywords" : "Keywords");
          foreach (var keyword in wordGroup.Items)
          {
              Console.Write(" " +
                  keyword.Replace("*", null));
          }
      }
  }

// ...
```

3.0

Output 15.7

```
Keywords:
 abstract as base bool break byte case catch char checked class
const continue decimal default delegate do double else enum
event explicit extern false finally fixed float for foreach goto if
implicit in int interface internal is lock long namespace new null
operator out override object params private protected public
readonly ref return sbyte sealed short sizeof stackalloc static
string struct switch this throw true try typeof uint ulong unsafe
ushort using virtual unchecked void volatile while
Contextual Keywords:
 add alias ascending async await by descending dynamic equals from
get global group into join let nameof on orderby partial remove
select set value var where yield
```

The group clause results in a query that produces a collection of IGrouping <TKey, TElement> objects—just as the GroupBy() standard query operator did (see Chapter 14). The select clause in the subsequent query uses an anonymous type to effectively rename IGrouping<TKey, TElement>.Key to IsContextualKeyword and to name the subcollection property Items. With this change, the nested foreach loop uses wordGroup.Items rather than wordGroup directly, as shown in Listing 15.10. Another potential property to add to the anonymous type would be a count of the items within the subcollection. This functionality is already available through wordGroup.Items.Count(), so the benefit of adding it to the anonymous type directly is questionable.

Query Continuation with into

As we saw in Listing 15.11, you can use an existing query as the input to a second query. However, it is not necessary to write an entirely new query expression when you want to use the results of one query as the input to another. You can extend any query with a **query continuation clause** using the contextual keyword into. A query continuation is nothing more than syntactic sugar for creating two queries and using the first as the input to the second. The range variable introduced by the into clause (groups in Listing 15.11) becomes the range variable for the remainder of the query; any previous range variables are logically a part of the earlier query and cannot be used in the query continuation. Listing 15.12 shows how to rewrite the code of Listing 15.11 to use a query continuation instead of two queries.

3.0

Listing 15.12: Selecting without the Query Continuation

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

  private static void GroupKeywords1()
  {
      var selection =
          from word in Keywords
          group word by word.Contains('*')
          into groups
              select new
              {
```

```
                    IsContextualKeyword = groups.Key,
                    Items = groups
                };

        // ...

    }

  // ...
```

The ability to run additional queries on the results of an existing query using `into` is not specific to queries ending with `group` clauses, but rather can be applied to all query expressions. Query continuation is simply a shorthand for writing query expressions that consume the results of other query expressions. You can think of `into` as a "pipeline operator," because it "pipes" the results of the first query into the second query. You can arbitrarily chain together many queries in this way.

"Flattening" Sequences of Sequences with Multiple `from` Clauses

It is often desirable to "flatten" a sequence of sequences into a single sequence. For example, each member of a sequence of customers might have an associated sequence of orders, or each member of a sequence of directories might have an associated sequence of files. The `SelectMany` sequence operator (discussed in Chapter 14) concatenates together all the subsequences; to do the same thing with query expression syntax, you can use multiple `from` clauses, as shown in Listing 15.13.

3.0

Listing 15.13: Multiple Selection

```
        var selection =
            from word in Keywords
            from character in word
            select character;
```

The preceding query will produce the sequence of characters `a`, `b`, `s`, `t`, `r`, `a`, `c`, `t`, `a`, `d`, d, *, `a`, `l`, i, a, ….

Multiple `from` clauses can also be used to produce the **Cartesian product**—the set of all possible combinations of several sequences—as shown in Listing 15.14.

Listing 15.14: Cartesian Product

```
        var numbers = new[] { 1, 2, 3 };
        var product =
            from word in Keywords
            from number in numbers
            select new {word, number};
```

This would produce a sequence of pairs (`abstract`, `1`), (`abstract`, `2`), (abstract, 3), (as, 1), (as, 2), ….

Beginner Topic

Distinct Members

Often, it is desirable to return only distinct (that is, unique) items from within a collection, discarding any duplicates. Query expressions do not have explicit syntax for distinct members, but the functionality is available via the query operator `Distinct()`, which was introduced in Chapter 14. To apply a query operator to a query expression, the expression must be enclosed in parentheses so that the compiler does not think that the call to `Distinct()` is a part of the `select` clause. Listing 15.15 gives an example; Output 15.8 shows the results.

Listing 15.15: Obtaining Distinct Members from a Query Expression

```
using System;
using System.Collections.Generic;
using System.Linq;

// ...

        public static void ListMemberNames()
        {
            IEnumerable<string> enumerableMethodNames = (
                from method in typeof(Enumerable).GetMembers(
                    System.Reflection.BindingFlags.Static |
                    System.Reflection.BindingFlags.Public)
                    orderby method.Name
                    select method.Name).Distinct();
            foreach(string method in enumerableMethodNames)
            {
                Console.Write($"{ method }, ");
            }
        }

// ...
```

3.0

OUTPUT 15.8

```
Aggregate, All, Any, AsEnumerable, Average, Cast, Concat, Contains,
Count, DefaultIfEmpty, Distinct, ElementAt, ElementAtOrDefault,
Empty, Except, First, FirstOrDefault, GroupBy, GroupJoin,
Intersect, Join, Last, LastOrDefault, LongCount, Max, Min, OfType,
OrderBy, OrderByDescending, Range, Repeat, Reverse, Select,
SelectMany, SequenceEqual, Single, SingleOrDefault, Skip,
SkipWhile, Sum, Take, TakeWhile, ThenBy, ThenByDescending, ToArray,
ToDictionary, ToList, ToLookup, Union, Where, Zip,
```

In this example, `typeof(Enumerable).GetMembers()` returns a list of all the members (methods, properties, and so on) on `System.Linq.Enumerable`. However, many of these members are overloaded, sometimes more than once. Rather than displaying the same member multiple times, `Distinct()` is called from the query expression. This eliminates the duplicate names from the list. (We cover the details of `typeof()` and reflection [where methods like `GetMembers()` are available] in Chapter 17.)

Query Expressions Are Just Method Invocations

Somewhat surprisingly, adding query expressions to C# 3.0 required no changes to the CLR or to the CIL language. Rather, the C# compiler simply translates query expressions into a series of method calls. Consider, for example, the query expression from Listing 15.1, a portion of which appears in Listing 15.16.

3.0

LISTING 15.16: Simple Query Expression

```
    private static void ShowContextualKeywords1()
    {
        IEnumerable<string> selection =
            from word in Keywords
                where word.Contains('*')
                select word;
        // ...
    }

  // ...
```

After compilation, the expression from Listing 15.16 is converted to an `IEnumerable<T>` extension method call from `System.Linq.Enumerable`, as shown in Listing 15.17.

LISTING 15.17: Query Expression Translated to Standard Query Operator Syntax

```
    private static void ShowContextualKeywords3()
    {
        IEnumerable<string> selection =
            Keywords.Where(word => word.Contains('*'));

        // ...
    }

  // ...
```

As discussed in Chapter 14, the lambda expression is then itself translated by the compiler to emit a method with the body of the lambda, and the usage of it becomes allocation of a delegate to that method.

Every query expression can (and must) be translated into method calls, but not every sequence of method calls has a corresponding query expression. For example, there is no query expression equivalent for the extension method `TakeWhile<T>(Func<T, bool> predicate)`, which repeatedly returns items from the collection as long as the predicate returns `true`.

For those queries that do have both a method call form and a query expression form, which is better? This is a judgment call; some queries are better suited for query expressions, whereas others are more readable as method invocations.

Guidelines

DO use query expression syntax to make queries easier to read, particularly if they involve complex `from`, `let`, `join`, or `group` clauses.

CONSIDER using the standard query operators (method call form) if the query involves operations that do not have a query expression syntax, such as `Count()`, `TakeWhile()`, or `Distinct()`.

3.0

SUMMARY

This chapter introduced a new syntax—namely, query expressions. Readers familiar with SQL will immediately see the similarities between query expressions and SQL. However, query expressions also introduce additional functionality, such as grouping into a hierarchical set of new objects, which is unavailable with SQL. All of the functionality of query expressions was already available via standard query operators, but query expressions frequently provide a simpler syntax for expressing such a query. Whether through standard query operators or query expression syntax, however, the end result is a significant improvement in the way developers can code against collection APIs—an improvement that ultimately provides a paradigm shift in the way object-oriented languages are able to interface with relational databases.

In the next chapter, we continue our discussion of collections, by investigating some of the .NET Framework collection types and exploring how to define custom collections.

End 3.0

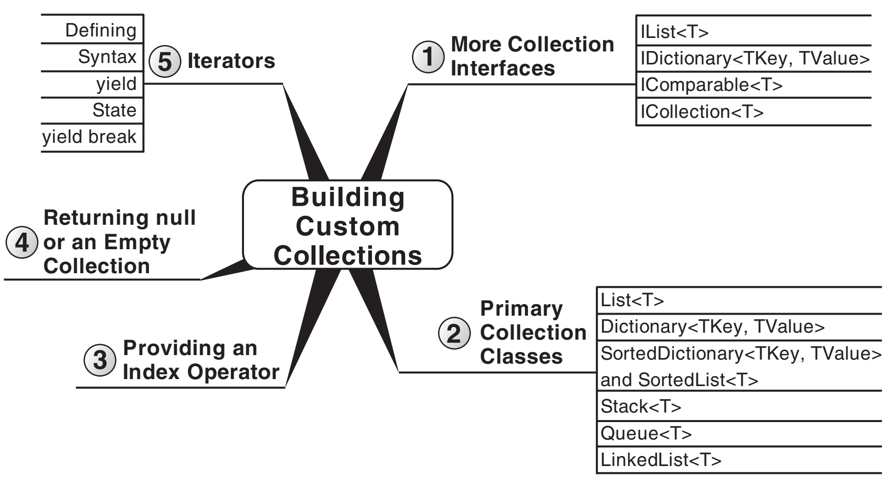
16

Building Custom Collections

Begin 2.0

CHAPTER 14 COVERED THE STANDARD query operators—that is, the extension methods on `IEnumerable<T>` that provide methods common to all collections. However, these operators do not make all collections equally suited for all tasks; there is still a need for different collection types. Some collections are better suited to searching by key, whereas others are better suited to accessing items by position. Some collections act like queues: The first element in is the first out. Others are more like stacks: The first element in is the last out. Others are not ordered at all.

The .NET Framework provides a plethora of collection types suited for many of the scenarios in which collections are needed. This chapter provides



an introduction to some of these collection types and the interfaces they implement. It also describes how to create custom-built collections that support standard functionality, such as indexing. In addition, it explores the use of the yield return statement to create classes and methods that implement IEnumerable<T>. This C# 2.0 feature greatly simplifies implementation of collections that can be enumerated with the foreach statement.

Many nongeneric collection classes and interfaces are available in the .NET Framework, but in general these exist today only for backward compatibility with code written before generics came into use. The generic collection types are both faster, because they avoid boxing costs, and more type-safe than the nongeneric collections. Thus, new code should almost always use the generic collection types exclusively. Throughout this book, we assume that you are primarily using generic collection types.

More Collection Interfaces

We've already seen how collections implement IEnumerable<T>, the primary interface that enables iteration over the elements of a collection. Many additional interfaces exist that are implemented by more complex collections. Figure 16.1 shows the hierarchy of interfaces implemented by collection classes.

These interfaces provide a standard way to perform common tasks such as iterating, indexing, and counting elements in a collection. This section examines these interfaces (at least all of the generic ones), starting at the bottom of Figure 16.1 and moving upward.

IList<T> versus IDictionary<TKey, TValue>

An English-language dictionary can be thought of as a collection of definitions. A specific definition can be rapidly accessed by looking up its associated "key"—that is, the word being defined. A dictionary collection class is similarly a collection of values, in which each value can be rap-
2.0 idly accessed by using its associated unique key. Note, however, that a language dictionary typically stores the definitions sorted alphabetically by key; a dictionary class might choose to do so but typically does not. Dictionary collections are best thought of as an unordered list of keys and associated values unless specifically documented as being ordered. Similarly, one does not normally think of looking up "the sixth definition in the

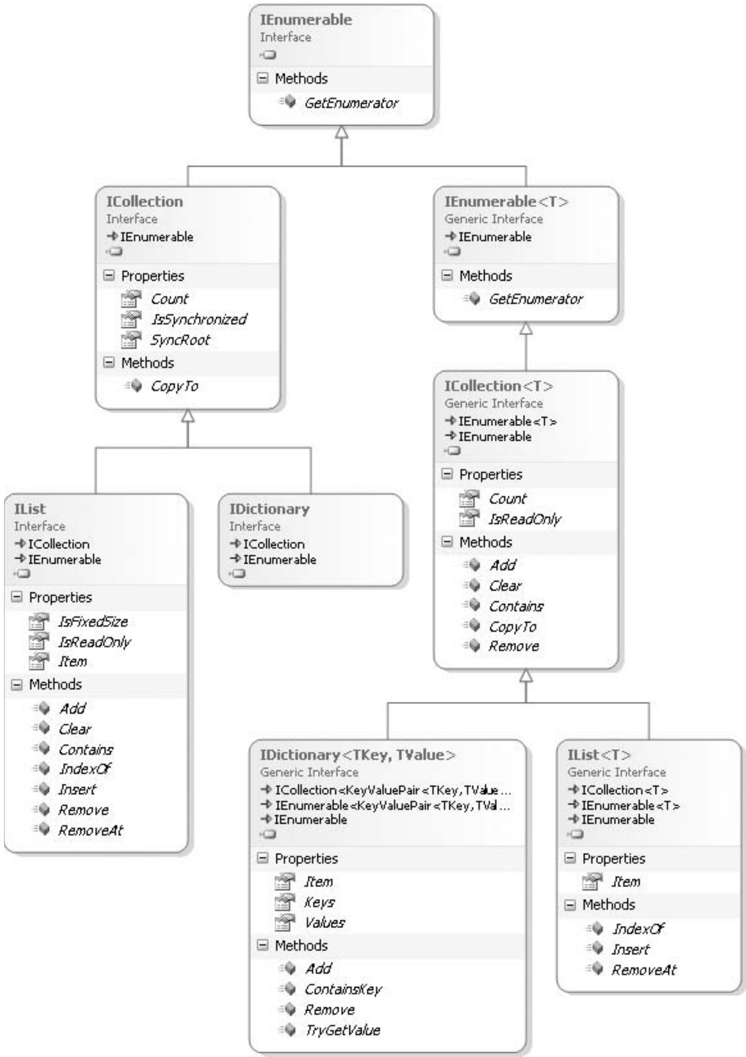


FIGURE 16.1: Generic Collection Interface Hierarchy

dictionary"; dictionary classes usually provide indexing only by key, not by position.

A list, by contrast, stores values in a specific order, and accesses them by their position. In a sense, lists are just the special case of dictionaries where the "key" is always an integer and the "key set" is always a contiguous set of non-negative integers starting with zero. Nevertheless, that is a strong enough difference that it is worth having an entirely different type to represent it.

2.0

Thus, when selecting a collection class to solve some data storage or retrieval problem, the first two interfaces to look for are `IList<T>` and `IDictionary<TKey, TValue>`. These interfaces indicate whether the collection type is focused on retrieval of a value when given its positional index or retrieval of a value when given its associated key.

Both of these interfaces require that a class that implements them provide an indexer. In the case of `IList<T>`, the operand of the indexer corresponds to the position of the element being retrieved: The indexer takes an integer and gives you access to the nth element in the list. In the case of the `IDictionary<TKey, TValue>` interface, the operand of the indexer corresponds to the key associated with a value, and gives you access to that value.

ICollection<T>

Both `IList<T>` and `IDictionary<TKey, TValue>` implement `ICollection<T>`. A collection that does not implement either `IList<T>` or `IDictionary<TKey, TValue>` will more than likely implement `ICollection<T>` (although not necessarily, because collections could implement the lesser requirement of `IEnumerable` or `IEnumerable<T>`). `ICollection<T>` is derived from `IEnumerable<T>` and includes two members: `Count` and `CopyTo()`.

- The `Count` property returns the total number of elements in the collection. Initially, it might appear that this would be sufficient to iterate through each element in the collection using a `for` loop, but, in fact, the collection would also need to support retrieval by index, which the `ICollection<T>` interface does not include (although `IList<T>` does include it).
- The `CopyTo()` method provides the ability to convert the collection into an array. This method includes an `index` parameter so that you can specify where to insert elements in the target array. To use the method, you must initialize the array target with sufficient capacity, starting at the `index`, to contain all the elements in `ICollection<T>`.

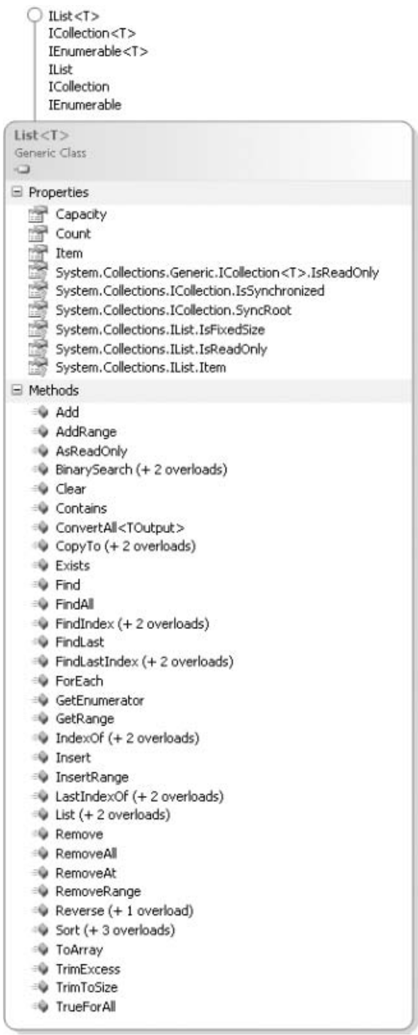
2.0

Primary Collection Classes

Five key categories of collection classes exist, and they differ from one another in terms of how data is inserted, stored, and retrieved. Each generic class is located in the `System.Collections.Generic` namespace, and their nongeneric equivalents are found in the `System.Collections` namespace.

List Collections: List<T>

The `List<T>` class has properties similar to an array. The key difference is that these classes automatically expand as the number of elements increases. (In contrast, an array size is constant.) Furthermore, lists can shrink via explicit calls to `TrimToSize()` or `Capacity` (see Figure 16.2).



2.0

FIGURE 16.2: `List<>` Class Diagrams

These classes are categorized as **list collections** whose distinguishing functionality is that each element can be individually accessed by index, just like an array. Therefore, you can set and access elements in the list collection classes using the index operator, where the index parameter value corresponds to the position of an element in the collection. Listing 16.1 shows an example, and Output 16.1 shows the results.

Listing 16.1: Using List<T>

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      List<string> list = new List<string>();

      // Lists automatically expand as elements
      // are added.
      list.Add("Sneezy");
      list.Add("Happy");
      list.Add("Dopey");
      list.Add("Doc");
      list.Add("Sleepy");
      list.Add("Bashful");
      list.Add("Grumpy");

      list.Sort();

      Console.WriteLine(
          $"In alphabetical order { list[0] } is the "
          + $"first dwarf while { list[6] } is the last.");

      list.Remove("Grumpy");
  }
}
```

Output 16.1

```
In alphabetical order Bashful is the first dwarf while Sneezy is the last.
```

C# is zero-index based; therefore, index 0 in Listing 16.1 corresponds to the first element and index 6 indicates the seventh element. Retrieving
2.0 elements by index does not involve a search. Rather, it entails a quick and simple "jump" operation to a location in memory.

A `List<T>` is an ordered collection; the `Add()` method appends the given item to the end of the list. Before the call to `Sort()` in Listing 16.1, `"Sneezy"` was first and `"Grumpy"` was last; after the call, the list is sorted into alphabetical order, rather than the order in which items were added. Some collections automatically sort elements as they are added, but `List<T>` is not one of them; an explicit call to `Sort()` is required for the elements to be sorted.

To remove an element, you use the `Remove()` or `RemoveAt()` method, to either remove a given element or remove whatever element is at a particular index, respectively.

ADVANCED TOPIC

Customizing Collection Sorting

You might have wondered how the `List<T>.Sort()` method in Listing 16.1 knew how to sort the elements of the list into alphabetical order. The `string` type implements the `IComparable<string>` interface, which has one method, `CompareTo()`. It returns an integer indicating whether the element passed is greater than, less than, or equal to the current element. If the element type implements the generic `IComparable<T>` interface (or the nongeneric `IComparable` interface), the sorting algorithm will, by default, use it to determine the sorted order.

But what if either the element type does not implement `IComparable<T>` or the default logic for comparing two things does not meet your needs? To specify a nondefault sort order, you can call the overload of `List<T>.Sort()`, which takes an `IComparer<T>` as an argument.

The difference between `IComparable<T>` and `IComparer<T>` is subtle but important. The first interface means, "I know how to compare myself to another instance of my type." The latter means, "I know how to compare two things of a given type."

The `IComparer<T>` interface is typically used when there are many different possible ways of sorting a data type and none is obviously the best. For example, you might have a collection of `Contact` objects that you sometimes want to sort by name, by location, by birthday, by geographic region, or by any number of other possibilities. Rather than choosing sorting strategy and making the `Contact` class implement `IComparable<Contact>`, it might be wiser to create several different classes that implement `IComparer<Contact>`. Listing 16.2 shows a sample implementation of a `LastName`, `FirstName` comparison. 2.0

Listing 16.2: Implementing `IComparer<T>`

```
class Contact
{
  public string FirstName { get; private set; }
```

```
    public string LastName { get; private set; }
    public Contact(string firstName, string lastName)
    {
      this.FirstName = firstName;
      this.LastName = lastName;
    }
  }
```

```
using System;
using System.Collections.Generic;

class NameComparison : IComparer<Contact>
{
  public int Compare(Contact x, Contact y)
  {
      if (Object.ReferenceEquals(x, y))
          return 0;
      if (x == null)
          return 1;
      if (y == null)
          return -1;
      int result = StringCompare(x.LastName, y.LastName);
      if (result == 0)
          result = StringCompare(x.FirstName, y.FirstName);
      return result;
  }

  private static int StringCompare(string x, string y)
  {
      if (Object.ReferenceEquals(x, y))
          return 0;
      if (x == null)
          return 1;
      if (y == null)
          return -1;
      return x.CompareTo(y);
  }
}
```

To sort a `List<Contact>` by last name and then first name, you can call `contactList.Sort(new NameComparer())`.

Total Ordering

2.0 You are required to produce a **total order** when implementing `IComparable<T>` or `IComparer<T>`. Your implementation of `CompareTo` must provide a fully consistent ordering for any possible pair of items. This ordering is required to have a number of basic characteristics. For example, every element is required to be considered equal to itself. If an element

X is considered to be equal to element Y, and element Y is considered to be equal to element Z, all three elements X, Y, and Z must be considered equal to one another. If an element X is considered to be greater than Y, Y must be considered to be less than X. And there must be no "transitivity paradoxes"—that is, you cannot have X greater than Y, Y greater than Z, and Z greater than X. If you fail to provide a total ordering, the action of the sort algorithm is undefined; it may produce a crazy ordering, it may crash, it may go into an infinite loop, and so on.

Notice, for example, how the comparer in Listing 16.2 ensures a total order, even if the arguments are null references. It would not be legal to say, "If either element is null, then return zero," for example, because then two non-null things could be equal to null but not equal to each other.

> **Guidelines**
>
> **DO** ensure that custom comparison logic produces a consistent "total order."

Searching a `List<T>`

To search `List<T>` for a particular element, you use the `Contains()`, `IndexOf()`, `LastIndexOf()`, and `BinarySearch()` methods. The first three methods search through the array, starting at the first element (or the last element for `LastIndexOf()`), and examine each element until the desired one is found. The execution time for these algorithms is proportional to the number of elements searched before a hit occurs. (Be aware that the collection classes do not require that all the elements within the collection are unique. If two or more elements in the collection are the same, `IndexOf()` returns the first index and `LastIndexOf()` returns the last index.)

`BinarySearch()` uses a much faster binary search algorithm but requires that the elements be sorted. A useful feature of the `BinarySearch()` method is that if the element is not found, a negative integer is returned. The bitwise complement (~) of this value is the index of the next element larger than the element being sought, or the total element count if there is no greater value. This provides a convenient means to insert new values into the list at the specific location so as to maintain sorting. Listing 16.3 provides an example. 2.0

Listing 16.3: Using the Bitwise Complement of the `BinarySearch()` Result

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      List<string> list = new List<string>();
      int search;

      list.Add("public");
      list.Add("protected");
      list.Add("private");

      list.Sort();

      search = list.BinarySearch("protected internal");
      if (search < 0)
      {
        list.Insert(~search, "protected internal");
      }

      foreach (string accessModifier in list)
      {
          Console.WriteLine(accessModifier);
      }
  }
}
```

Beware that if the list is not first sorted, an element will not necessarily be found with this code, even if it is in the list. The results of Listing 16.3 appear in Output 16.2.

Output 16.2

```
private
protected
protected internal
public
```

2.0

ADVANCED TOPIC

Finding Multiple Items with `FindAll()`

Sometimes you must find multiple items within a list and your search criteria are more complex than merely looking for specific values. To support this, `System.Collections.Generic.List<T>` includes a `FindAll()` method.

`FindAll()` takes a parameter of type `Predicate<T>`, which is a reference to a method called a delegate. Listing 16.4 demonstrates how to use the `FindAll()` method.

LISTING 16.4: Demonstrating `FindAll()` and Its Predicate Parameter

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      List<int> list = new List<int>();
      list.Add(1);
      list.Add(2);
      list.Add(3);
      list.Add(2);

      List<int> results = list.FindAll(Even);

      foreach(int number in results)
      {
          Console.WriteLine(number);
      }
  }

  public static bool Even(int value) =>
      (value % 2) == 0;
}
```

In Listing 16.4's call to `FindAll()`, you pass a delegate instance, `Even()`. This method returns `true` when the integer argument value is even. `FindAll()` takes the delegate instance and calls into `Even()` for each item within the list (this listing uses C# 2.0's delegate type inferencing). Each time the return value is `true`, it adds it to a new `List<T>` instance and then returns this instance once it has checked each item within `list`. A complete discussion of delegates occurs in Chapter 12.

Dictionary Collections: `Dictionary<TKey, TValue>`

2.0

Another category of collection classes is the dictionary classes—specifically, `Dictionary<TKey, TValue>` (see Figure 16.3). Unlike the list collections, dictionary classes store name/value pairs. The name functions as a unique key that can be used to look up the corresponding element in a manner similar to that of using a primary key to access a record in a database. This adds some complexity to the access of dictionary elements, but because lookups by key are efficient operations, this is a useful collection. Note that the key may be any data type, not just a string or a numeric value.

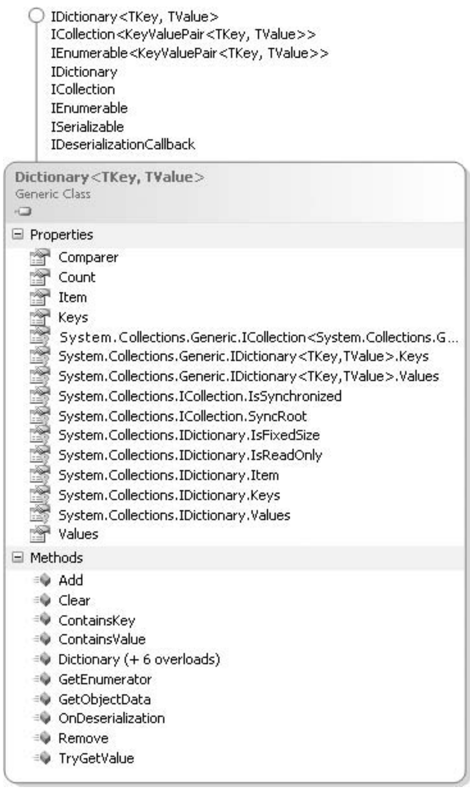


FIGURE 16.3: `Dictionary` Class Diagrams

One option for inserting elements into a dictionary is to use the `Add()` method, passing both the key and the value, as shown in Listing 16.5.

LISTING 16.5: Adding Items to a `Dictionary<TKey, TValue>`

2.0

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      // C# 6.0 (use {"Error", ConsoleColor.Red} pre-C# 6.0)
      var colorMap = new Dictionary<string, ConsoleColor>
          {
```

```
                ["Error"] = ConsoleColor.Red,
                ["Warning"] = ConsoleColor.Yellow,
                ["Information"] = ConsoleColor.Green
            };

        colorMap.Add("Verbose", ConsoleColor.White);
        // ...
    }
}
```

After initializing the dictionary with a C# 6.0 dictionary initializer (see the section "Collection Initializers" in Chapter 14), Listing 16.5 inserts the string a `ConsoleColor of white for the key of "Verbose."` If an element with the same key has already been added, an exception is thrown.

An alternative for adding elements is to use the indexer, as shown in Listing 16.6.

LISTING 16.6: Inserting Items in a `Dictionary<TKey, TValue>` Using the Index Operator

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      // C# 6.0 (use {"Error", ConsoleColor.Red} pre-C# 6.0)
      var colorMap = new Dictionary<string, ConsoleColor>
          {
              ["Error"] = ConsoleColor.Red,
              ["Warning"] = ConsoleColor.Yellow,
              ["Information"] = ConsoleColor.Green
          };

      colorMap["Verbose"] = ConsoleColor.White;
      colorMap["Error"] = ConsoleColor.Cyan;

      // ...
  }
}
```

The first thing to observe in Listing 16.6 is that the index operator does not require an integer. Instead, the index operand type is specified by the first type argument (`string`), and the type of the value that is set or retrieved by the indexer is specified by the second type argument (`ConsoleColor`). 2.0

The second thing to notice in Listing 16.6 is that the same key ("Error") is used twice. In the first assignment, no dictionary value corresponds to the given key. When this happens, the dictionary collection classes insert a new value with the supplied key. In the second assignment, an element with the specified key already exists. Instead of inserting an additional element, the prior `ConsoleColor` value for the "Error" key is replaced `ConsoleColor.Cyan`.

Attempting to read a value from a dictionary with a nonexistent key throws a `KeyNotFoundException`. The `ContainsKey()` method allows you to check whether a particular key is used before accessing its value, thereby avoiding the exception.

The `Dictionary<TKey, TValue>` is implemented as a "hash table"; this data structure provides extremely fast access when searching by key, regardless of the number of values stored in the dictionary. By contrast, checking whether there is a particular value in the dictionary collections is a time-consuming operation with linear performance characteristics, much like searching an unsorted list. To do this you use the `ContainsValue()` method, which searches sequentially through each element in the collection.

You remove a dictionary element using the `Remove()` method, passing the key, not the element value.

Because both the key and the value are required to add a value to the dictionary, the loop variable of a `foreach` loop that enumerates elements of a dictionary must be `KeyValuePair<TKey, TValue>`. Listing 16.7 shows a snippet of code demonstrating the use of a `foreach` loop to enumerate the keys and values in a dictionary. The output appears in Output 16.3.

LISTING 16.7: Iterating over `Dictionary<TKey, TValue>` with `foreach`

2.0

```
using System;
using System.Collections.Generic;

class Program
{
  static void Main()
  {
      // C# 6.0 (use {"Error", ConsoleColor.Red} pre-C# 6.0)
      Dictionary<string, ConsoleColor> colorMap =
          new Dictionary<string, ConsoleColor>
          {
              ["Error"] = ConsoleColor.Red,
              ["Warning"] = ConsoleColor.Yellow,
              ["Information"] = ConsoleColor.Green,
              ["Verbose"] = ConsoleColor.White
          };

          Print(colorMap);
```

```
        }

        private static void Print(
            IEnumerable<KeyValuePair<string, ConsoleColor>> items)
        {
            foreach (KeyValuePair<string, ConsoleColor> item in items)
            {
                Console.ForegroundColor = item.Value;
                Console.WriteLine(item.Key);
            }
        }
    }
```

Output 16.3

```
Error
Warning
Information
Verbose
```

Note that the order of the items shown here is the order in which the items were added to the dictionary, just as if they had been added to a list. Implementations of dictionaries will often enumerate the keys and values in the order in which they were added to the dictionary, but this feature is neither required nor documented, so you should not rely on it.

Guidelines

DO NOT make any unwarranted assumptions about the order in which elements of a collection will be enumerated. If the collection is not documented as enumerating its elements in a particular order, it is not guaranteed to produce elements in any particular order.

If you want to deal only with keys or only with elements within a dictionary class, they are available via the `Keys` and `Values` properties, respectively. The data type returned from these properties is of type `ICollection<T>`. The data returned by these properties is a reference to the data within the original dictionary collection, rather than a copy; changes within the dictionary are automatically reflected in the collection returned by the `Keys` and `Values` properties.

2.0

ADVANCED TOPIC

Customizing Dictionary Equality

To determine whether a given key matches any existing key in the dictionary, the dictionary must be able to compare two keys for equality. This is analogous to the way that lists must be able to compare two items to determine their order. (For an example, see the Advanced Topic, "Customizing Collection Sorting," earlier in this chapter.) By default, two instances of a value type are compared by checking whether they contain exactly the same data, and two instances of a reference type are compared to see whether both reference the same object. However, it is occasionally necessary to be able to compare two instances as equal even if they are not exactly the same value or exactly the same reference.

For example, suppose you wish to create a `Dictionary<Contact, string>` using the `Contact` type from Listing 16.2. However, you want any two `Contact` objects to compare as equal if they have the same first and last names, regardless of whether the two objects are reference equal. Much as you can provide an implementation of `IComparer<T>` to sort a list, so you can similarly provide an implementation of `IEqualityComparer<T>` to determine if two keys are to be considered equal. This interface requires two methods: one that returns whether two items are equal, and one that returns a "hash code" that the dictionary can use to facilitate fast indexing. Listing 16.8 shows an example.

LISTING 16.8: Implementing `IEqualityComparer<T>`

2.0

```
using System;
using System.Collections.Generic;

class ContactEquality : IEqualityComparer<Contact>
{
  public bool Equals(Contact x, Contact y)
  {
      if (Object.ReferenceEquals(x, y))
          return true;
      if (x == null || y == null)
          return false;
      return x.LastName == y.LastName &&
          x.FirstName == y.FirstName;
  }

  public int GetHashCode(Contact x)
  {
```

```
        if (Object.ReferenceEquals(x, null))
            return 0;
        int h1 = x.FirstName == null ? 0 : x.FirstName.GetHashCode();
        int h2 = x.LastName == null ? 0 : x.LastName.GetHashCode();
        return h1 * 23 + h2;
    }
}
```

To create a dictionary that uses this equality comparer, you can use the constructor `new Dictionary<Contact, string>(new ContactEquality)`.

BEGINNER TOPIC

Requirements of Equality Comparisons

As discussed in Chapter 9, Well-Formed Types, there are several important rules for the equality and hash code algorithms. Conformance to these rules is critical in the context of collections. Just as correctly sorting a list requires a custom ordering comparison to provide a total order, so too does a hash table require certain guarantees to be met by a custom equality comparison. The most important requirement is that if `Equals()` returns `true` for two objects, `GetHashCode()` must return the same value for those two objects. Note that the converse is not true: Two unequal items may have the same hash code. (Indeed, there must be two unequal items that have the same hash code because there are only 232 possible hash codes, but more than that many unequal objects!)

The second most important requirement is that two calls to `GetHashCode()` on the same item must produce the same result for at least as long as the item is in the hash table. Note, however, that two objects that "look equal" are not required to give the same hash code in two separate runs of a program. For example, it is perfectly legal for a given contact to be assigned one hash code today, and two weeks later when you run the program a second time for "the same" contact to be given a different hash code. Do not persist hash codes into a database and expect them to remain stable across different runs of a program. 2.0

Ideally, the result of `GetHashCode()` should appear to be "random." That is, small changes to the input should cause large changes to the output, and the result should be distributed roughly evenly across all possible integer values. It is difficult, however, to devise a hash algorithm that is extremely fast and produces extremely well-distributed output; try to find a good middle ground.

Finally, `GetHashCode()` and `Equals()` must not throw exceptions. Notice how the code in Listing 16.8 is careful to never dereference a null reference, for example.

To summarize, here are the key principles:

- Equal objects must have equal hash codes.
- The hash code of an object should not change for the life of the instance (at least while it is in the hash table).
- The hashing algorithm should quickly produce a well-distributed hash.
- The hashing algorithm should avoid throwing exceptions in all possible object states.

Sorted Collections: SortedDictionary<TKey, TValue> and SortedList<T>

The sorted collection classes (see Figure 16.4) store their elements sorted by key for `SortedDictionary<TKey, TValue>` and by value for `SortedList<T>`. If we change the code in Listing 16.7 to use a `SortedDictionary<string, string>` instead of a `Dictionary<string, string>`, the output of the program is as appears in Output 16.4.

Output 16.4

```
Error
Information
Verbose
Warning
```

Note that the elements are sorted into order by key, not by value.

Because sorted collections must do extra work to maintain the sorted order of their elements, insertion and removal are typically slightly slower
2.0 than insertion and removal of values in an unordered dictionary.

Because sorted collections must store their items in a particular order, it is possible to access values both by key and by index. To access a key or value by its index in the sorted list, use the `Keys` and `Values` properties. They return `IList<TKey>` and `IList<TValue>` instances, respectively; the resultant collection can be indexed like any other list.

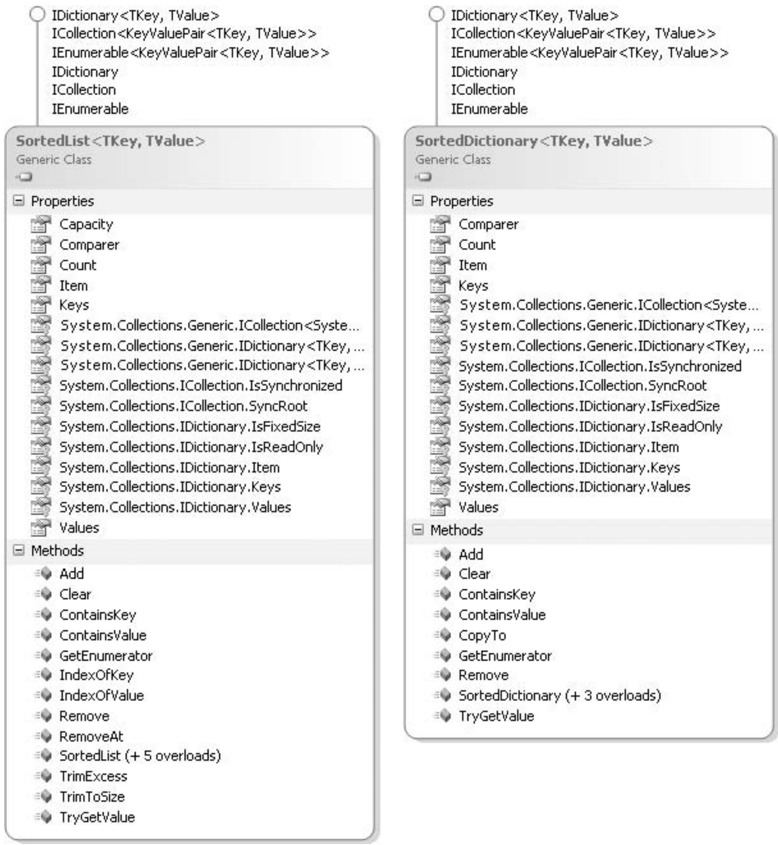


FIGURE 16.4: **`SortedList<>`** and **`SortedDictionary<>`** Class Diagrams

Stack Collections: `Stack<T>`

Chapter 11 discussed the stack collection classes (see Figure 16.5). The stack collection classes are designed as "last in, first out" (LIFO) collections. The two key methods are `Push()` and `Pop()`.

- `Push()` inserts elements into the collection. The elements do not have to be unique.
- `Pop()` removes elements in the reverse order in which they were added.

2.0

To access the elements on the stack without modifying the stack, you use the `Peek()` and `Contains()` methods. The `Peek()` method returns the next element that `Pop()` will retrieve.

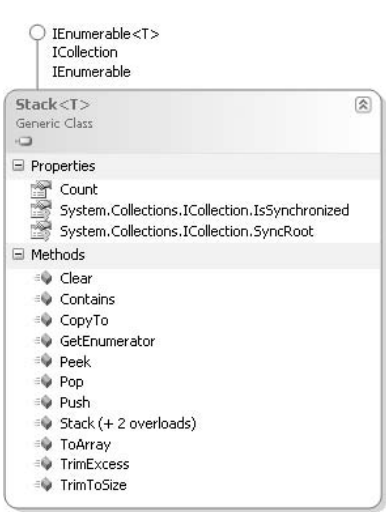


FIGURE 16.5: `Stack<T>` Class Diagram

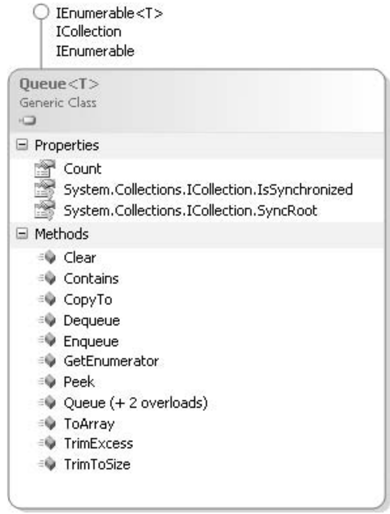


FIGURE 16.6: `Queue<T>` Class Diagram

As with most collection classes, you use the `Contains()` method to determine whether an element exists anywhere in the stack. As with all collections, it is also possible to use a `foreach` loop to iterate over the elements in a stack. This allows you to access values from anywhere in the stack. Note, however, that accessing a value via the `foreach` loop does not remove it from the stack—only `Pop()` provides this functionality.

Queue Collections: `Queue<T>`

Queue collection classes, shown in Figure 16.6, are identical to stack collection classes, except that they follow the ordering pattern of "first in, first out" (FIFO). In place of the `Pop()` and `Push()` methods are the `Enqueue()` and `Dequeue()` methods. The queue collection behaves like a pipe: You place objects into the queue at one end using the `Enqueue()` method and remove them from the other end using the `Dequeue()` method. As with stack collection classes, the objects do not have to be unique, and queue collection classes automatically increase in size as required. As a queue
2.0 shrinks, it does not necessarily reclaim the storage space previously used, because that would make inserting a new element potentially more expensive. If you happen to know that a queue will remain the same size for a long time, however, you can hint to it that you would like to reclaim storage space by using the `TrimToSize()` method.

Linked Lists: LinkedList<T>

`System.Collections.Generic` also supports a linked list collection that enables both forward and reverse traversal. Figure 16.7 shows the class diagram. (There is no corresponding nongeneric type.)

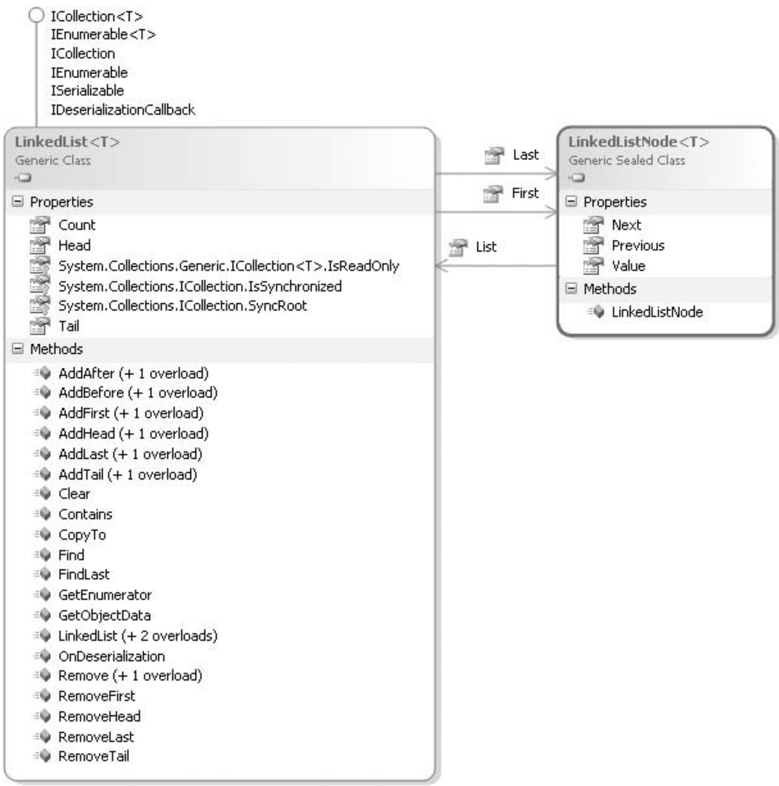


FIGURE 16.7: `LinkedList<T>` and `LinkedListNode<T>` Class Diagrams

Providing an Indexer

2.0

Arrays, dictionaries, and lists all provide an **indexer** as a convenient way to get or set a member of a collection based on a key or index. As we've seen, to use the indexer you simply put the index (or indices) in square brackets after the collection name. It is possible to define your own indexer; Listing 16.9 shows an example using `Pair<T>`.

LISTING 16.9: Defining an Indexer

```
interface IPair<T>
{
  T First { get;  }
  T Second { get;  }

  T this[PairItem index] { get; }
}
```

```
public enum PairItem
{
    First,
    Second
}
```

```
public struct Pair<T> : IPair<T>
{
  public Pair(T first, T second)
  {
      First = first;
      Second = second;
  }
  public T First { get; }  // C# 6.0 Getter-only Autoproperty
  public T Second { get; } // C# 6.0 Getter-only Autoproperty

  public T this[PairItem index]
  {
      get
      {
          switch (index)
          {
              case PairItem.First:
                  return First;
              case PairItem.Second:
                  return Second;
              default :
                  throw new NotImplementedException(
                      string.Format(
                      "The enum {0} has not been implemented",
                      index.ToString()));
          }
      }
  }
}
```

2.0

An indexer is declared much as a property is declared, except that instead of the name of the property, you use the keyword `this` followed by a parameter list in square brackets. The body is also like a property, with `get` and `set` blocks. As Listing 16.9 shows, the parameter does not have to be an `int`. In fact, the index can take multiple parameters and can even be overloaded. This example uses an `enum` to reduce the likelihood that callers will supply an index for a nonexistent item.

The CIL code that the C# compiler creates from an index operator is a special property called `Item` that takes an argument. Properties that accept arguments cannot be created explicitly in C#, so the `Item` property is unique in this aspect. Any additional member with the identifier `Item`, even if it has an entirely different signature, will conflict with the compiler-created member, so it will not be allowed.

ADVANCED TOPIC

Assigning the Indexer Property Name Using IndexerName

As indicated earlier, the CIL property name for an indexer defaults to `Item`. Using the `IndexerNameAttibute`, you can specify a different name, however. Listing 16.10, for example, changes the name to `"Entry"`.

Listing 16.10: Changing the Indexer's Default Name

```
[System.Runtime.CompilerServices.IndexerName("Entry")]
public T this[params PairItem[] branches]
{
    // ...
}
```

This makes no difference to C# callers of the index, but it specifies the name for languages that do not support indexers directly.

This attribute is merely an instruction to the compiler to use a different name for the indexer; the attribute is not actually emitted into metadata by the compiler, so it is not available via reflection.

ADVANCED TOPIC

Defining an Index Operator with Variable Parameters

An index operator can also take a variable parameter list. For example, Listing 16.11 defines an index operator for `BinaryTree<T>`, discussed in Chapter 11 (and again in the next section). 2.0

LISTING 16.11: Defining an Index Operator with Variable Parameters

```
using System;

public class BinaryTree<T>
{

  // ...

  public BinaryTree<T> this[params PairItem[] branches]
  {
      get
      {
          BinaryTree<T> currentNode = this;

          // Allow either an empty array or null
          // to refer to the root node.
          int totalLevels = branches?.Length ?? 0;
          int currentLevel = 0;

          while (currentLevel < totalLevels)
          {
              System.Diagnostics.Debug.Assert(branches != null,
                  $"{ nameof(branches) } != null");
              currentNode = currentNode.SubItems[
                  branches[currentLevel]];
              if (currentNode == null)
              {
                  // The binary tree at this location is null.
                  throw new IndexOutOfRangeException();
              }
              currentLevel++;
          }
          return currentNode;
      }
  }
}
```

Each item within `branches` is a `PairItem` and indicates which branch to navigate down in the binary tree. For example,

```
tree[PairItem.Second, PairItem.First].Value
```

will retrieve the value located at the second item in the first branch followed by the first branch within that branch.

2.0

Returning Null or an Empty Collection

When returning an array or collection, you must indicate that there are zero items by returning either `null` or a collection instance with no items. The better choice in general is to return a collection instance with no items. In so doing, you avoid forcing the caller to check for `null` before iterating over the items in the collection. For example, given a zero-size `IEnumerable<T>` collection, the caller can immediately and safely use a `foreach` loop over the collection without concern that the generated call to `GetEnumerator()` will throw a `NullReferenceException`. Consider using the `Enumerable.Empty<T>()` method to easily generate an empty collection of a given type.

One of the few times to deviate from this guideline is when `null` is intentionally indicating something different from zero items. For example, a collection of user names for a website might be `null` to indicate that an up-to-date collection could not be obtained for some reason; that is semantically different from an empty collection.

Guidelines

DO NOT represent an empty collection with a null reference.

CONSIDER using the `Enumerable.Empty<T>()` method instead.

Iterators

Chapter 14 went into detail on the internals of the `foreach` loop. This section discusses how to use **iterators** to create your own implementation of the `IEnumerator<T>`, `IEnumerable<T>`, and corresponding nongeneric interfaces for custom collections. Iterators provide clean syntax for specifying how to iterate over data in collection classes, especially using the `foreach` loop. The iterator allows end users of a collection to navigate its internal structure without knowledge of that structure.

ADVANCED TOPIC

2.0

Origin of Iterators

In 1972, Barbara Liskov and a team of scientists at MIT began researching programming methodologies, focusing on user-defined data abstractions. To prove much of their work, they created a language called CLU that had a concept called "clusters" (CLU being the first three letters of this term). Clusters were predecessors to the primary data abstraction that programmers use today: objects. During their research, the team realized that although they were able to use the CLU language to abstract some data representation away from end users of their types, they consistently found themselves having to reveal the inner structure of their data to allow others to intelligently consume it. The result of their consternation was the creation of a language construct called an iterator. (The CLU language offered many insights into what would eventually be popularized as "object-oriented programming.")

If classes want to support iteration using the foreach loop construct, they must implement the enumerator pattern. As Chapter 14 describes, in C# the foreach loop construct is expanded by the compiler into the while loop construct based on the IEnumerator<T> interface that is retrieved from the IEnumerable<T> interface.

The problem with the enumeration pattern is that it can be cumbersome to implement manually, because it must maintain all the state necessary to describe the current position in the collection. This internal state may be simple for a list collection type class; the index of the current position suffices. In contrast, for data structures that require recursive traversal, such as binary trees, the state can be quite complicated. To mitigate the challenges associated with implementing this pattern, C# 2.0 included a construct that makes it easier for a class to dictate how the foreach loop iterates over its contents.

Defining an Iterator

Iterators are a means to implement methods of a class, and they are syntactic shortcuts for the more complex enumerator pattern. When the C# compiler encounters an iterator, it expands its contents into CIL code that implements the enumerator pattern. As such, there are no runtime dependencies for implementing iterators. Because the C# compiler handles implementation through CIL code generation, there is no real runtime performance benefit to using iterators. However, there is a substantial programmer productivity gain in choosing iterators over manual implementation of the enumerator pattern. To understand improvement, we first consider how an iterator is defined in code.

2.0

Iterator Syntax

An iterator provides shorthand implementation of iterator interfaces, the combination of the IEnumerable<T> and IEnumerator<T> interfaces. Listing

16.12 declares an iterator for the generic `BinaryTree<T>` type by creating a `GetEnumerator()` method. Next, you will add support for the iterator interfaces.

LISTING 16.12: Iterator Interfaces Pattern

```
using System;
using System.Collections.Generic;

public class BinaryTree<T>:
    IEnumerable<T>
{
  public BinaryTree ( T value)
  {
      Value = value;
  }

  #region IEnumerable<T>
  public IEnumerator<T> GetEnumerator()
  {
      //...
  }
  #endregion IEnumerable<T>

  public T Value { get; }  // C# 6.0 Getter-only Autoproperty
  public Pair<BinaryTree<T>> SubItems { get; set; }
}

public struct Pair<T>
{
  public Pair(T first, T second) : this()
  {
      First = first;
      Second = second;
  }
  public T First { get; }  // C# 6.0 Getter-only Autoproperty
  public T Second { get; } // C# 6.0 Getter-only Autoproperty
}
```

As Listing 16.12 shows, we need to provide an implementation for the `GetEnumerator()` method.

Yielding Values from an Iterator

2.0

Iterators are like functions, but instead of returning a single value, they yield a sequence of values, one at a time. In the case of `BinaryTree<T>`, the iterator yields a sequence of values of the type argument provided for `T`. If the nongeneric version of `IEnumerator` is used, the yielded values will instead be of type `object`.

To correctly implement the iterator pattern, you need to maintain some internal state to keep track of where you are while enumerating the collection. In the `BinaryTree<T>` case, you track which elements within the tree have already been enumerated and which are still to come. Iterators are transformed by the compiler into a "state machine" that keeps track of the current position and knows how to "move itself" to the next position.

The `yield return` statement yields a value each time an iterator encounters it; control immediately returns to the caller that requested the item. When the caller requests the next item, the code begins to execute immediately following the previously executed `yield return` statement. In Listing 16.13, you return the C# built-in data type keywords sequentially.

LISTING 16.13: Yielding Some C# Keywords Sequentially

2.0

```
using System;
using System.Collections.Generic;

public class CSharpBuiltInTypes: IEnumerable<string>
{
  public IEnumerator<string> GetEnumerator()
  {
      yield return "object";
      yield return "byte";
      yield return "uint";
      yield return "ulong";
      yield return "float";
      yield return "char";
      yield return "bool";
      yield return "ushort";
      yield return "decimal";
      yield return "int";
      yield return "sbyte";
      yield return "short";
      yield return "long";
      yield return "void";
      yield return "double";
      yield return "string";
  }

      // The IEnumerable.GetEnumerator method is also required
      // because IEnumerable<T> derives from IEnumerable.
  System.Collections.IEnumerator
      System.Collections.IEnumerable.GetEnumerator()
  {
      // Invoke IEnumerator<string> GetEnumerator() above.
      return GetEnumerator();
  }
}
```

```
public class Program
{
  static void Main()
  {
      var keywords = new CSharpBuiltInTypes();
      foreach (string keyword in keywords)
      {
          Console.WriteLine(keyword);
      }
  }
}
```

The results of Listing 16.13 appear in Output 16.5.

OUTPUT 16.5

```
object
byte
uint
ulong
float
char
bool
ushort
decimal
int
sbyte
short
long
void
double
string
```

The output from this listing is a listing of the C# built-in types.

Iterators and State

When `GetEnumerator()` is first called in a `foreach` statement (such as `foreach (string keyword in keywords)` in Listing 16.13), an iterator object is created and its state is initialized to a special "start" state that represents the fact that no code has executed in the iterator and, therefore, no values have been yielded yet. The iterator maintains its state as long as the `foreach` statement at the call site continues to execute. Every time the loop requests the next value, control enters the iterator and continues where it left off the previous time around the loop; the state information stored in the iterator object is used to determine where control must resume. When the `foreach` statement at the call site terminates, the iterator's state is no longer saved. 2.0

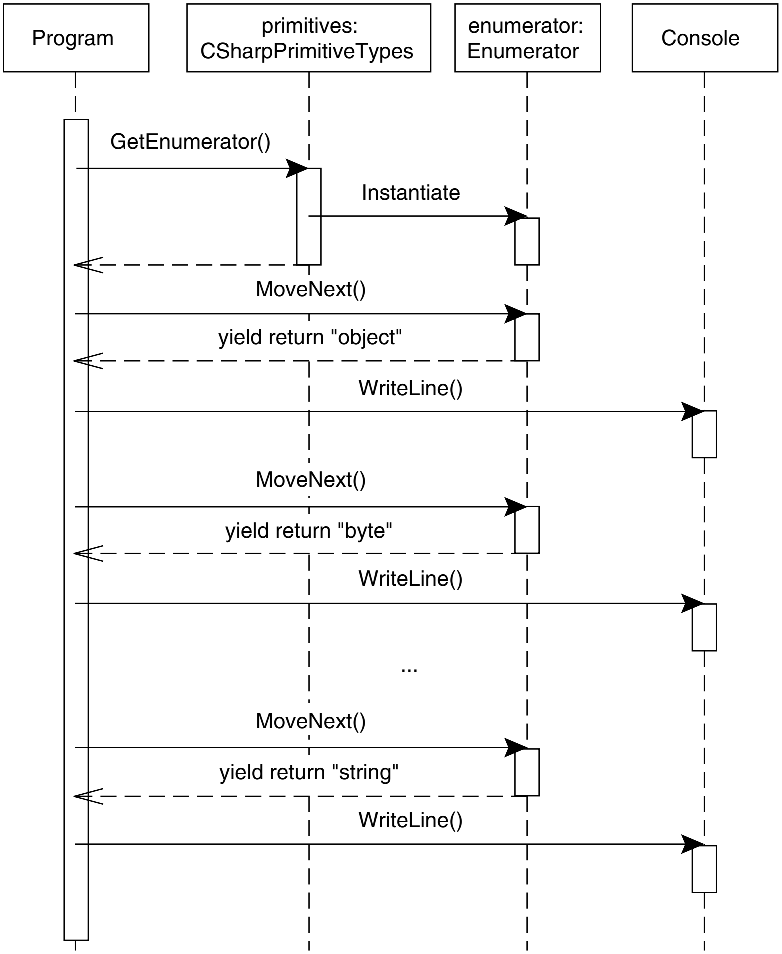


FIGURE 16.8: Sequence Diagram with `yield return`

It is always safe to call `GetEnumerator()` again; "fresh" enumerator objects will be created when necessary.

Figure 16.8 shows a high-level sequence diagram of what takes place. Remember that the `MoveNext()` method appears on the `IEnumerator<T>` interface.

2.0

In Listing 16.13, the `foreach` statement at the call site initiates a call to `GetEnumerator()` on the `CSharpBuiltInTypes` instance called `keywords`. Given the iterator instance (referenced by `iterator`), `foreach` begins each iteration with a call to `MoveNext()`. Within the iterator, you yield a value back to the `foreach` statement at the call site. After the `yield return` statement, the `GetEnumerator()` method seemingly pauses until the next `MoveNext()` request. Back at the loop body, the `foreach` statement displays the yielded value on the screen. It then loops back around and calls `MoveNext()` on the iterator again. Notice that the second time, control picks up at the second `yield return` statement. Once again, the `foreach` displays on the screen what `CSharpBuiltInTypes` yielded and starts the loop again. This process continues until there are no more `yield return` statements within the iterator. At that point, the `foreach` loop at the call site terminates because `MoveNext()` returns `false`.

More Iterator Examples

Before you modify `BinaryTree<T>`, you must modify `Pair<T>` to support the `IEnumerable<T>` interface using an iterator. Listing 16.14 is an example that yields each element in `Pair<T>`.

LISTING 16.14: Using `yield` to Implement `BinaryTree<T>`

```
public struct Pair<T>: IPair<T>,
    IEnumerable<T>
{
  public Pair(T first, T second) : this()
  {
      First = first;
      Second = second;
  }
  public T First { get; }  // C# 6.0 Getter-only Autoproperty
  public T Second { get; } // C# 6.0 Getter-only Autoproperty

  #region IEnumerable<T>
  public IEnumerator<T> GetEnumerator()
  {
      yield return First;
      yield return Second;
  }
#endregion IEnumerable<T>

  #region IEnumerable Members
  System.Collections.IEnumerator
      System.Collections.IEnumerable.GetEnumerator()
  {
      return GetEnumerator();
  }
  #endregion
}
```

2.0

In Listing 16.14, the iteration over the `Pair<T>` data type loops twice: first through `yield return First`, and then through `yield return Second`. Each time the `yield return` statement within `GetEnumerator()` is encountered, the state is saved and execution appears to “jump” out of the `GetEnumerator()`

method context and into the loop body. When the second iteration starts, GetEnumerator() begins to execute again with the yield return Second statement.

System.Collections.Generic.IEnumerable<T> inherits from System.Collections.IEnumerable. Therefore, when implementing IEnumerable<T>, it is also necessary to implement IEnumerable. In Listing 16.14, you do so explicitly, and the implementation simply involves a call to IEnumerable<T>'s GetEnumerator() implementation. This call from IEnumerable.GetEnumerator() to IEnumerable<T>.GetEnumerator() will always work because of the type compatibility (via inheritance) between IEnumerable<T> and IEnumerable. Since the signatures for both GetEnumerator()s are identical (the return type does not distinguish a signature), one or both implementations must be explicit. Given the additional type safety offered by IEnumerable<T>'s version, you implement IEnumerable's implementation explicitly.

Listing 16.15 uses the Pair<T>.GetEnumerator() method and displays "Inigo" and "Montoya" on two consecutive lines.

LISTING 16.15: Using Pair<T>.GetEnumerator() via foreach

```
var fullname = new Pair<string>("Inigo", "Montoya");
foreach (string name in fullname)
{
    Console.WriteLine(name);
}
```

Notice that the call to GetEnumerator() is implicit within the foreach loop.

Placing a yield return within a Loop

It is not necessary to hardcode each yield return statement, as you did in both CSharpPrimitiveTypes and Pair<T>. Using the yield return statement, you can return values from inside a loop construct. Listing 16.16 uses a foreach loop. Each time the foreach within GetEnumerator() executes, it returns the next value.

2.0 **LISTING 16.16: Placing yield return Statements within a Loop**

```
public class BinaryTree<T>: IEnumerable<T>
{
  // ...

  #region IEnumerable<T>
  public IEnumerator<T> GetEnumerator()
  {
```

```
        // Return the item at this node.
        yield return Value;

        // Iterate through each of the elements in the pair.
        foreach (BinaryTree<T> tree in SubItems)
        {
            if (tree != null)
            {
                // Since each element in the pair is a tree,
                // traverse the tree and yield each
                // element.
                foreach (T item in tree)
                {
                    yield return item;
                }
            }
        }
    }
    #endregion IEnumerable<T>

    #region IEnumerable Members
    System.Collections.IEnumerator
        System.Collections.IEnumerable.GetEnumerator()
    {
        return GetEnumerator();
    }
    #endregion
}
```

In Listing 16.16, the first iteration returns the root element within the binary tree. During the second iteration, you traverse the pair of subelements. If the subelement pair contains a non-null value, you traverse into that child node and yield its elements. Note that `foreach (T item in tree)` is a recursive call to a child node.

As observed with `CSharpBuiltInTypes` and `Pair<T>`, you can now iterate over `BinaryTree<T>` using a `foreach` loop. Listing 16.17 demonstrates this process, and Output 16.6 shows the results.

LISTING 16.17: Using `foreach` with `BinaryTree<string>`

2.0

```
// JFK
var jfkFamilyTree = new BinaryTree<string>(
    "John Fitzgerald Kennedy");

jfkFamilyTree.SubItems = new Pair<BinaryTree<string>>(
    new BinaryTree<string>("Joseph Patrick Kennedy"),
    new BinaryTree<string>("Rose Elizabeth Fitzgerald"));

// Grandparents (Father's side)
```

```
jfkFamilyTree.SubItems.First.SubItems =
    new Pair<BinaryTree<string>>(
    new BinaryTree<string>("Patrick Joseph Kennedy"),
    new    BinaryTree<string>("Mary Augusta Hickey"));

// Grandparents (Mother's side)
jfkFamilyTree.SubItems.Second.SubItems =
    new Pair<BinaryTree<string>>(
    new BinaryTree<string>("John Francis Fitzgerald"),
    new BinaryTree<string>("Mary Josephine Hannon"));

foreach (string name in jfkFamilyTree)
{
    Console.WriteLine(name);
}
```

Output 16.6

```
John Fitzgerald Kennedy
Joseph Patrick Kennedy
Patrick Joseph Kennedy
Mary Augusta Hickey
Rose Elizabeth Fitzgerald
John Francis Fitzgerald
Mary Josephine Hannon
```

ADVANCED TOPIC

The Dangers of Recursive Iterators

The code in Listing 16.16 creates new "nested" iterators as it traverses the binary tree. As a consequence, when the value is yielded by a node, the value is yielded by the node's iterator, and then yielded by its parent's iterator, and then yielded by its parent's iterator, and so on, until it is finally yielded to the original loop by the root's iterator. A value that is n levels deep must actually pass its value up a chain of n iterators. If the binary tree is relatively shallow, this is not typically a problem; however, an imbalanced binary tree can be extremely deep, and therefore expensive to iterate recursively.

2.0

Guidelines

CONSIDER using nonrecursive algorithms when iterating over potentially deep data structures.

BEGINNER TOPIC

struct versus class

An interesting side effect of defining `Pair<T>` as a `struct` rather than a `class` is that `SubItems.First` and `SubItems.Second` cannot be assigned directly, even if the setter were public. If you modify the setter to be public, the following will produce a compile error indicating that `SubItems` cannot be modified, "because it is not a variable":

```
jfkFamilyTree.SubItems.First =
    new BinaryTree<string>("Joseph Patrick Kennedy");
```

The issue is that `SubItems` is a property of type `Pair<T>`, a `struct`. Therefore, when the property returns the value, a copy of `SubItems` is made, and assigning `First` on a copy that is promptly lost at the end of the statement would be misleading. Fortunately, the C# compiler prevents this error.

To overcome the issue, don't assign `First` (see the approach in Listing 16.17), use `class` rather than `struct` for `Pair<T>`, don't create a `SubItems` property and instead use a field, or provide properties in `BinaryTree<T>` that give direct access to `SubItems` members.

Canceling Further Iteration: yield break

Sometimes you might want to cancel further iteration. You can do so by including an `if` statement so that no further statements within the code are executed. However, you can also use `yield break` to cause `MoveNext()` to return `false` and control to return immediately to the caller and end the loop. Listing 16.18 shows an example of such a method.

LISTING 16.18: Escaping Iteration via yield break

```
public System.Collections.Generic.IEnumerable<T>
    GetNotNullEnumerator()
{
  if((First == null) || (Second == null))
  {
      yield break;
  }
  yield return Second;
  yield return First;
}
```

2.0

This method cancels the iteration if either of the elements in the `Pair<T>` class is `null`.

A `yield break` statement is similar to placing a `return` statement at the top of a function when it is determined that there is no work to do. It is a way to exit from further iterations without surrounding all remaining code with an `if` block. As such, it allows multiple exits. Use it with caution, because a casual reading of the code may overlook the early exit.

ADVANCED TOPIC

How Iterators Work

When the C# compiler encounters an iterator, it expands the code into the appropriate CIL for the corresponding enumerator design pattern. In the generated code, the C# compiler first creates a nested private class to implement the `IEnumerator<T>` interface, along with its `Current` property and a `MoveNext()` method. The `Current` property returns a type corresponding to the return type of the iterator. Listing 16.14 of `Pair<T>` contains an iterator that returns a `T` type. The C# compiler examines the code contained within the iterator and creates the necessary code within the `MoveNext` method and the `Current` property to mimic its behavior. For the `Pair<T>` iterator, the C# compiler generates roughly equivalent code (see Listing 16.19).

LISTING 16.19: C# Equivalent of Compiler-Generated C# Code for Iterators

2.0

```
using System;
using System.Collections.Generic;

public class Pair<T> : IPair<T>, IEnumerable<T>
{
  // ...

  // The iterator is expanded into the following
  // code by the compiler
  public virtual IEnumerator<T> GetEnumerator()
  {
      __ListEnumerator result = new __ListEnumerator(0);
      result._Pair = this;
      return result;
  }
  public virtual System.Collections.IEnumerator
      System.Collections.IEnumerable.GetEnumerator()
  {
      return new GetEnumerator();
  }

  private sealed class __ListEnumerator<T> : IEnumerator<T>
```

```
    {
        public __ListEnumerator(int itemCount)
        {
            _ItemCount = itemCount;
        }

        Pair<T> _Pair;
        T _Current;
        int _ItemCount;

        public object Current
        {
            get
            {
                return _Current;
            }
        }

        public bool MoveNext()
        {
            switch (_ItemCount)
            {
                case 0:
                    _Current = _Pair.First;
                    _ItemCount++;
                    return true;
                case 1:
                    _Current = _Pair.Second;
                    _ItemCount++;
                    return true;
                default:
                    return false;
            }
        }
    }
  }
```

Because the compiler takes the `yield return` statement and generates classes that correspond to what you probably would have written manually, iterators in C# exhibit the same performance characteristics as classes that implement the enumerator design pattern manually. Although there is no performance improvement, the gains in programmer productivity are significant.

2.0

ADVANCED TOPIC

Contextual Keywords

Many C# keywords are "reserved" and cannot be used as identifiers unless preceded with an `@` sign. The `yield` keyword is a contextual keyword, not a reserved keyword; it is legal (though confusing) to declare a local variable called `yield`. In fact, all the keywords added to C# after version 1.0 have been contextual keywords; this helps prevent accidental breakages when upgrading existing programs to use new versions of the language.

Had the C# designers chosen to use `yield value;` as the syntax for an iterator to yield instead of `yield return value;`, a possible ambiguity would have been introduced: `yield(1+2);` now might be yielding a value, or it might be passing the value as an argument to a method called `yield`.

Since it was previously never legal to have the identifier `yield` appear immediately before `return` or `break`, the C# compiler knows that such a usage of `yield` must be as a keyword, not an identifier.

Creating Multiple Iterators in a Single Class

Previous iterator examples implemented `IEnumerable<T>.GetEnumerator()`—the method that `foreach` seeks implicitly. Sometimes you might want different iteration sequences, such as iterating in reverse, filtering the results, or iterating over an object projection other than the default. You can declare additional iterators in the class by encapsulating them within properties or methods that return `IEnumerable<T>` or `IEnumerable`. If you want to iterate over the elements of `Pair<T>` in reverse, for example, you could provide a `GetReverseEnumerator()` method, as shown in Listing 16.20.

LISTING 16.20: Using `yield return` in a Method That Returns `IEnumerable<T>`

2.0

```
public struct Pair<T>: IEnumerable<T>
{
    ...

    public IEnumerable<T> GetReverseEnumerator()
    {
        yield return Second;
        yield return First;
    }
    ...
}

public void Main()
{
```

```
        var game = new Pair<string>("Redskins", "Eagles");
        foreach (string name in game.GetReverseEnumerator())
        {
            Console.WriteLine(name);
        }
    }
```

Note that you return `IEnumerable<T>`, not `IEnumerator<T>`. This is different from `IEnumerable<T>.GetEnumerator()`, which returns `IEnumerator<T>`. The code in `Main()` demonstrates how to call `GetReverseEnumerator()` using a `foreach` loop.

yield Statement Requirements

You can use the `yield return` statement only in members that return an `IEnumerator<T>` or `IEnumerable<T>` type, or their nongeneric equivalents. Members whose bodies include a `yield return` statement may not have a simple `return`. If the member uses the `yield return` statement, the C# compiler generates the necessary code to maintain the state of the iterator. In contrast, if the member uses the `return` statement instead of `yield return`, the programmer is responsible for maintaining his own state machine and returning an instance of one of the iterator interfaces. Further, just as all code paths in a method with a return type must contain a `return` statement accompanied by a value (assuming they don't throw an exception), so all code paths in an iterator must contain a `yield return` statement if they are to return any data.

The following additional restrictions on the `yield` statement result in compiler errors if they are violated:

- The `yield` statement may appear only inside a method, a user-defined operator, or the `get` accessor of an indexer or property. The member must not take any `ref` or `out` parameter.
- The `yield` statement may not appear anywhere inside an anonymous method or lambda expression (see Chapter 12).
- The `yield` statement may not appear inside the `catch` and `finally` clauses of the `try` statement. Furthermore, a `yield` statement may appear in a try block only if there is no catch block. 2.0

SUMMARY

The generic collection classes and interfaces made available in C# 2.0 are universally superior to their nongeneric counterparts; by avoiding boxing penalties and enforcing type safety at compile time, they execute more rapidly and are safer. Unless you must maintain compatibility with legacy C# 1.0 code, you should consider the entire namespace of `System.Collections` to be obsolete. In other words, don't go back and necessarily remove all code that already uses this namespace. Instead, use `System.Collections.Generics` for any new code and, over time, consider migrating existing code to use the corresponding generic collections that contain both the interfaces and the classes for working with collections of objects.

The introduction of the `System.Collections.Generic` namespace is not the only change that C# 2.0 brought to collections. Another significant addition is the iterator. Iterators involve a new contextual keyword, `yield`, that C# uses to generate underlying CIL code that implements the iterator pattern used by the `foreach` loop.

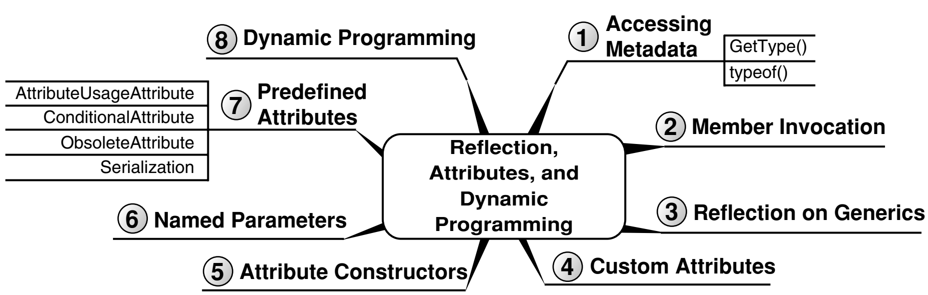
In the next chapter we explore reflection, a topic briefly touched on earlier, albeit with little to no explanation. Reflection allows one to examine the structure of a type within CIL code at runtime.

End 2.0

17

Reflection, Attributes, and Dynamic Programming

ATTRIBUTES ARE A MEANS OF inserting additional metadata into an assembly and associating the metadata with a programming construct such as a class, method, or property. This chapter investigates the details surrounding attributes that are built into the framework and describes how to define custom attributes. To take advantage of custom attributes, it is necessary to identify them. This is handled through reflection. This chapter begins with a look at reflection, including how you can use it to dynamically bind at execution time based on member invocation by name (or metadata) at compile time. This is frequently performed within tools such as a code generator. In addition, reflection is used at execution time when the call target is unknown.



The chapter ends with a discussion of dynamic programming, a feature added in C# 4.0 that greatly simplifies working with data that is dynamic and requires execution-time rather than compile-time binding.

Reflection

Using reflection, it is possible to do the following.

- Access the metadata for types within an assembly. This includes constructs such as the full type name, member names, and any attributes decorating the construct.
- Dynamically invoke a type's members at runtime using the metadata, rather than a compile-time–defined binding.

Reflection is the process of examining the metadata within an assembly. Traditionally, when code compiles down to a machine language, all the metadata (such as type and method names) about the code is discarded. In contrast, when C# compiles into the CIL, it maintains most of the metadata about the code. Furthermore, using reflection, it is possible to enumerate through all the types within an assembly and search for those that match certain criteria. You access a type's metadata through instances of `System.Type`, and this object includes methods for enumerating the type instance's members. Additionally, it is possible to invoke those members on particular objects that are of the examined type.

The facility for reflection enables a host of new paradigms that otherwise are unavailable. For example, reflection enables you to enumerate over all the types within an assembly, along with their members, and in the process create stubs for documentation of the assembly API. You can then combine the metadata retrieved from reflection with the XML document created from XML comments (using the `/doc` switch) to create the API documentation. Similarly, programmers use reflection metadata to generate code for persisting (serializing) business objects into a database. It could also be used in a list control that displays a collection of objects. Given the collection, a list control could use reflection to iterate over all the properties of an object in the collection, defining a column within the list for each property. Furthermore, by invoking each property on each object, the list control could populate each row and column with the data contained in the object, even though the data type of the object is unknown at compile time.

`XmlSerializer`, `ValueType`, and `DataBinder` are a few of the classes in the framework that use reflection for portions of their implementation as well.

Accessing Metadata Using `System.Type`

The key to reading a type's metadata is to obtain an instance of `System.Type` that represents the target type instance. `System.Type` provides all the methods for retrieving the information about a type. You can use it to answer questions such as the following:

- What is the type's name (`Type.Name`)?
- Is the type public (`Type.IsPublic`)?
- What is the type's base type (`Type.BaseType`)?
- Does the type support any interfaces (`Type.GetInterfaces()`)?
- Which assembly is the type defined in (`Type.Assembly`)?
- What are a type's properties, methods, fields, and so on (`Type.GetProperties()`, `Type.GetMethods()`, `Type.GetFields()`, and so on)?
  - Which attributes decorate a type (`Type.GetCustomAttributes()`)?

There are more such members, but all of them provide information about a particular type. The key is to obtain a reference to a type's `Type` object, and the two primary ways to do so are through `object.GetType()` and `typeof()`.

Note that the `GetMethods()` call does not return extension methods. These methods are available only as static members on the implementing type.

`GetType()`

`object` includes a `GetType()` member and, therefore, all types include this function. You call `GetType()` to retrieve an instance of `System.Type` corresponding to the original object. Listing 17.1 demonstrates this process, using a `Type` instance from `DateTime`. Output 17.1 shows the results.

Listing 17.1: Using `Type.GetProperties()` to Obtain an Object's Public Properties

```
DateTime dateTime = new DateTime();

Type type = dateTime.GetType();
foreach (
    System.Reflection.PropertyInfo property in
        type.GetProperties())
{
    Console.WriteLine(property.Name);
}
```

OUTPUT 17.1

```
Date
Day
DayOfWeek
DayOfYear
Hour
Kind
Millisecond
Minute
Month
Now
UtcNow
Second
Ticks
TimeOfDay
Today
Year
```

After calling `GetType()`, you iterate over each `System.Reflection.PropertyInfo` instance returned from `Type.GetProperties()` and display the property names. The key to calling `GetType()` is that you must have an object instance. However, sometimes no such instance is available. Static classes, for example, cannot be instantiated, so there is no way to call `GetType()`.

typeof()

Another way to retrieve a `Type` object is with the `typeof` expression. `typeof` binds at compile time to a particular `Type` instance, and it takes a type directly as a parameter. Listing 17.2 demonstrates the use of `typeof` with `Enum.Parse()`.

LISTING 17.2: Using **typeof()** to Create a **System.Type** Instance

```
using System.Diagnostics;
// ...
    ThreadPriorityLevel priority;
    priority = (ThreadPriorityLevel)Enum.Parse(
            typeof(ThreadPriorityLevel), "Idle");
// ...
```

In this listing, `Enum.Parse()` takes a `Type` object identifying an enum and then converts a string to the specific enum value. In this case, it converts `"Idle"` to `System.Diagnostics.ThreadPriorityLevel.Idle`.

Similarly, Listing 7.3 used the `typeof` expression inside the `CompareTo(object obj)` method to verify that the type of the `obj` parameter was indeed what was expected:

```
if(obj.GetType() != typeof(Contact)) { ... }
```

The typeof expression is resolved at compile time such that a type comparison—perhaps comparing the type returned from a call to `GetType()`—can determine if an object is of a specific type.

Member Invocation

The possibilities with reflection don't stop with retrieving the metadata. The next step is to take the metadata and dynamically invoke the members it references. Consider the possibility of defining a class to represent an application's command line. The difficulty with a `CommandLineInfo` class such as this relates to populating the class with the actual command-line data that started the application. However, using reflection, you can map the command-line options to property names and then dynamically set the properties at runtime. Listing 17.3 demonstrates this process.

LISTING 17.3: Dynamically Invoking a Member

```
using System;
using System.Diagnostics;

public partial class Program
{
  public static void Main(string[] args)
  {
      string errorMessage;
      CommandLineInfo commandLine = new CommandLineInfo();
      if (!CommandLineHandler.TryParse(
          args, commandLine, out errorMessage))
      {
          Console.WriteLine(errorMessage);
          DisplayHelp();
      }

      if (commandLine.Help)
      {
          DisplayHelp();
      }
      else
      {
          if (commandLine.Priority !=
              ProcessPriorityClass.Normal)
          {
              // Change thread priority
          }

      }
      // ...

  }
```

```
  private static void DisplayHelp()
  {
      // Display the command-line help.
      Console.WriteLine(
                "Compress.exe / Out:< file name > / Help \n"
                + "/ Priority:RealTime | High | "
                + "AboveNormal | Normal | BelowNormal | Idle");
  }
}
```

```
using System;
using System.Diagnostics;

public partial class Program
{
  private class CommandLineInfo
  {
      public bool Help { get; set; }

      public string Out { get; set; }

      public ProcessPriorityClass Priority { get; set; }
          = ProcessPriorityClass.Normal;
  }
}
```

```
using System;
using System.Diagnostics;
using System.Reflection;

public class CommandLineHandler
{
  public static void Parse(string[] args, object commandLine)
  {
      string errorMessage;
      if (!TryParse(args, commandLine, out errorMessage))
      {
          throw new ApplicationException(errorMessage);
      }
  }

  public static bool TryParse(string[] args, object commandLine,
      out string errorMessage)
  {
      bool success = false;
      errorMessage = null;
      foreach (string arg in args)
      {
          string option;
          if (arg[0] == '/' || arg[0] == '-')
          {
              string[] optionParts = arg.Split(
                  new char[] { ':' }, 2);
```

```
        // Remove the slash|dash
        option = optionParts[0].Remove(0, 1);
        PropertyInfo property =
            commandLine.GetType().GetProperty(option,
                BindingFlags.IgnoreCase |
                BindingFlags.Instance |
                BindingFlags.Public);
        if (property != null)
        {
            if (property.PropertyType == typeof(bool))
            {
                // Last parameters for handling indexers
                property.SetValue(
                    commandLine, true, null);
                success = true;
            }
            else if (
                property.PropertyType == typeof(string))
            {
                property.SetValue(
                    commandLine, optionParts[1], null);
                success = true;
            }
            else if (property.PropertyType.IsEnum)
            {
                try
                {
                    property.SetValue(commandLine,
                        Enum.Parse(
                            typeof(ProcessPriorityClass),
                            optionParts[1], true),
                        null);
                    success = true;
                }
                catch (ArgumentException )
                {
                    success = false;
                    errorMessage =
                          errorMessage =
                              $@"The option '{
                                  optionParts[1]
                                  }' is invalid for '{
                                  option }'";
                }
            }
            else
            {
                success = false;
                    errorMessage =
                        $@"Data type '{
                            property.PropertyType.ToString()
                            }' on {
                            commandLine.GetType().ToString()
```

```
                                } is not supported."
                        }
                    }
                    else
                    {
                        success = false;
                              errorMessage =
                                 $"Option '{ option }' is not supported.";
                    }
                }
            }
            return success;
        }
    }
```

Although Listing 17.3 is long, the code is relatively simple. `Main()` begins by instantiating a `CommandLineInfo` class. This type is defined specifically to contain the command-line data for this program. Each property corresponds to a command-line option for the program, where the command line is as shown in Output 17.2.

Output 17.2

```
Compress.exe /Out:<file name> /Help
    /Priority:RealTime|High|AboveNormal|Normal|BelowNormal|Idle
```

The `CommandLineInfo` object is passed to the `CommandLineHandler`'s `TryParse()` method. This method begins by enumerating through each option and separating out the option name (`Help` or `Out`, for example). Once the name is determined, the code reflects on the `CommandLineInfo` object, looking for an instance property with the same name. If the property is found, it assigns the property using a call to `SetValue()` and specifies the data corresponding to the property type. (For arguments, this call accepts the object on which to set the value, the new value, and an additional `index` parameter that is `null` unless the property is an indexer.) This listing handles three property types: Boolean, string, and enum. In the case of enums, you parse the option value and assign the property the text's enum equivalent. Assuming the `TryParse()` call was successful, the method exits and the `CommandLineInfo` object is initialized with the data from the command line.

Interestingly, in spite of the fact that `CommandLineInfo` is a private class nested within `Program`, `CommandLineHandler` has no trouble reflecting over it and even invoking its members. In other words, reflection is able to circumvent accessibility rules as long as appropriate code access security (CAS; see Chapter 21) permissions are established. If, for example, `Out` was private, it would still be possible for the `TryParse()` method to assign it a value. Because of this, it would be possible to move `CommandLineHandler` into a separate assembly and share it across multiple programs, each with its own `CommandLineInfo` class.

In this particular example, you invoke a member on `CommandLineInfo` using `PropertyInfo.SetValue()`. Not surprisingly, `PropertyInfo` also includes a `GetValue()` method for retrieving data from the property. For a method, however, there is a `MethodInfo` class with an `Invoke()` member. Both `MethodInfo` and `PropertyInfo` derive from `MemberInfo` (albeit indirectly), as shown in Figure 17.1.

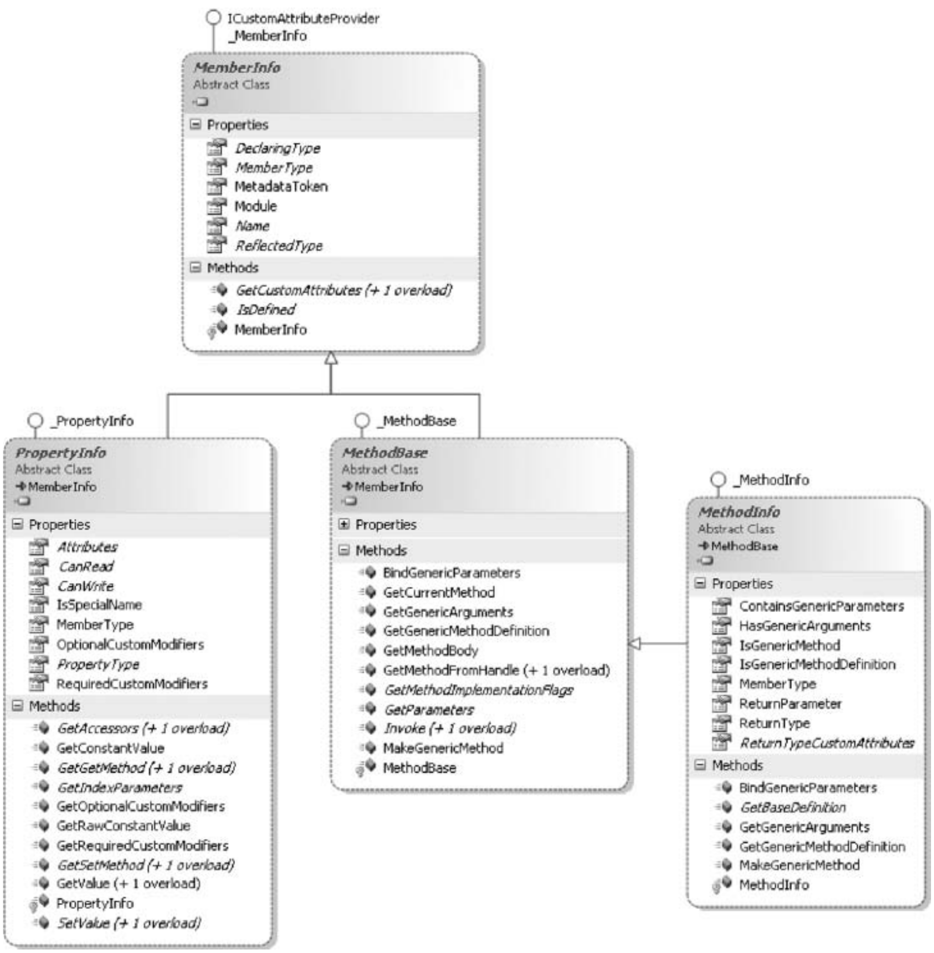


FIGURE 17.1: `MemberInfo` Derived Classes

The CAS permissions are set up to allow private member invocation in this case because the program runs from the local computer. By default, locally installed programs are part of the trusted zone and have appropriate permissions granted. Programs run from a remote location will need to be explicitly granted such a right.

Begin 2.0

Reflection on Generic Types

The introduction of generic types in version 2.0 of the CLR necessitated additional reflection features. Runtime reflection on generics determines whether a class or method contains a generic type, and any type parameters or arguments it may include.

Determining the Type of Type Parameters

In the same way that you can use a `typeof` operator with nongeneric types to retrieve an instance of `System.Type`, so you can use the `typeof` operator on type parameters in a generic type or generic method. Listing 17.4 applies the `typeof` operator to the type parameter in the `Add` method of a `Stack` class.

LISTING 17.4: Declaring the `Stack<T>` Class

```
public class Stack<T>
{
    // ...
    public void Add(T i)
    {
        // ...
        Type t = typeof(T);
        // ...
    }
    // ...
}
```

Once you have an instance of the `Type` object for the type parameter, you may then use reflection on the type parameter itself to determine its behavior and tailor the `Add` method to the specific type more effectively.

Determining Whether a Class or Method Supports Generics

In the `System.Type` class for the version 2.0 release of CLR, a handful of methods were added that determine whether a given type supports generic parameters and arguments. A generic argument is a type parameter supplied when a generic class is instantiated. You can determine whether a class or method contains generic parameters that have not yet been set by querying the `Type.ContainsGenericParameters` property, as demonstrated in Listing 17.5.

LISTING 17.5: Reflection with Generics

```
using System;

public class Program
{
  static void Main()
  {
      Type type;
      type = typeof(System.Nullable<>);
      Console.WriteLine(type.ContainsGenericParameters);
      Console.WriteLine(type.IsGenericType);

      type = typeof(System.Nullable<DateTime>);
      Console.WriteLine(!type.ContainsGenericParameters);
      Console.WriteLine(type.IsGenericType);
  }
}
```

Output 17.3 shows the results of Listing 17.5.

OUTPUT 17.3

```
True
True
True
True
```

`Type.IsGenericType` is a Boolean property that evaluates whether a type is generic.

Obtaining Type Parameters for a Generic Class or Method

You can obtain a list of generic arguments, or type parameters, from a generic class by calling the `GetGenericArguments()` method. The result is an array of `System.Type` instances that corresponds to the order in which they are declared as type parameters of the generic class. Listing 17.6 reflects into a generic type and obtains each type parameter; Output 17.4 shows the results. 2.0

Listing 17.6: Using Reflection with Generic Types

```
using System;
using System.Collections.Generic;

public partial class Program
{
  public static void Main()
  {

      Stack<int> s = new Stack<int>();

      Type t = s.GetType();

      foreach(Type type in t.GetGenericArguments())
      {
          System.Console.WriteLine(
              "Type parameter: " + type.FullName);
      }
      // ...
  }
}
```

Output 17.4

End 2.0

```
Type parameter: System.Int32
```

Begin 6.0

nameof Operator

We briefly touched on the `nameof` operator in Chapter 10, where it was used to provide the name of a parameter in an argument exception:

```
throw new ArgumentException(
    "The argument did not represent a digit", nameof(textDigit));
```

Introduced in C# 6.0, this contextual keyword produces a constant string containing the unqualified name of whatever program element is specified as an argument. In this case, `textDigit` is a parameter to the method, so `nameof(textDigit)` returns “textDigit.” (Given that this activity happens at compile time, `nameof` is not technically reflection. We include it here because ultimately it receives data about the assembly and it structure.)

One might ask what advantage is gained by using `nameof(textDigit)` over simply `"textDigit"` (especially given that the latter might even seem easier to use to some programmers). The advantages are twofold:

- The C# compiler ensures that the argument to the `nameof` operator is, in fact, a valid program element. This helps prevent errors when a program element name is changed, helps prevent misspellings, and so on.
- IDE tools work better with the `nameof` operator than with literal strings. For example, the "find all references" tool will find program elements mentioned in a `nameof` expression, but not in a literal string. The automatic renaming refactoring also works better, and so on.

In the snippet given earlier, `nameof(textDigit)` produces the name of a parameter. However, the `nameof` operator works with any program element. For example, Listing 17.7 uses `nameof` to pass the property name to `INotifyPropertyChanged.PropertyChanged`.

Listing 17.7: Dynamically Invoking a Member

```
using System.ComponentModel;

public class Person : INotifyPropertyChanged
{
    public event PropertyChangedEventHandler PropertyChanged;
    public Person(string name)
    {
        Name = name;
    }
    private string _Name;
    public string Name
    {
        get { return _Name; }
        set
        {
            if (_Name != value)
            {
                _Name = value;
                // Using C# 6.0 conditional null reference.
                PropertyChanged?.Invoke(
                    this,
                    new PropertyChangedEventArgs(
                        nameof(Name)));
            }
        }
    }
    // ...
}
```

Notice that whether only the unqualified "Name" is provided (because it's in scope) or the fully (or partially) qualified name like `Person.Name` is used, the result is only the final identifier (the last element in a dotted name).

End 6.0

You can still use C# 5.0's `CallerMemberName` parameter attribute to obtain a property's name; see http://itl.tc/CallerMemberName for an example.

Attributes

Before delving into details on how to program attributes, we should consider a use case that demonstrates their utility. In the `CommandLineHandler` example in Listing 17.3, you dynamically set a class's properties based on the command-line option matching the property name. This approach is insufficient, however, when the command-line option is an invalid property name. `/?`, for example, cannot be supported. Furthermore, this mechanism doesn't provide any way of identifying which options are required versus which are optional.

Instead of relying on an exact match between the option name and the property name, attributes provide a way of identifying additional metadata about the decorated construct—in this case, the option that the attribute decorates. With attributes, you can decorate a property as `Required` and provide a `/?` option alias. In other words, attributes are a means of associating additional data with a property (and other constructs).

Attributes appear within square brackets preceding the construct they decorate. For example, you can modify the `CommandLineInfo` class to include attributes, as shown in Listing 17.8.

LISTING 17.8: Decorating a Property with an Attribute

```
class CommandLineInfo
{
  [CommandLineSwitchAlias("?")]
  public bool Help { get; set; }

  [CommandLineSwitchRequired]
  public string Out { get; set; }

  public System.Diagnostics.ProcessPriorityClass Priority
      { get; set; } =
          System.Diagnostics.ProcessPriorityClass.Normal;
}
```

In Listing 17.8, the `Help` and `Out` properties are decorated with attributes. The purpose of these attributes is to allow an alias of `/?` for `/Help`, and to indicate that `/Out` is a required parameter. The idea is that from within the

`CommandLineHandler.TryParse()` method, you enable support for option aliases and, assuming the parsing was successful, you check that all required switches were specified.

There are two ways to combine attributes on the same construct. First, you can separate the attributes with commas within the same square brackets. Alternatively, you can place each attribute within its own square brackets. Listing 17.9 provides examples.

LISTING 17.9: Decorating a Property with Multiple Attributes

```
[CommandLineSwitchRequired]
[CommandLineSwitchAlias("FileName")]
  public string Out { get; set; }
```

```
[CommandLineSwitchRequired,
CommandLineSwitchAlias("FileName")]
  public string Out { get; set; }
```

In addition to decorating properties, developers can use attributes to decorate classes, interfaces, structs, enums, delegates, events, methods, constructors, fields, parameters, return values, assemblies, type parameters, and modules. For the majority of these cases, applying an attribute involves the same square bracket syntax shown in Listing 17.9. However, this syntax doesn't work for return values, assemblies, and modules.

Assembly attributes are used to add metadata about the assembly. Visual Studio's Project Wizard, for example, generates an `AssemblyInfo.cs` file that includes numerous attributes about the assembly. Listing 17.10 is an example of such a file.

LISTING 17.10: Assembly Attributes within `AssemblyInfo.cs`

```
using System.Reflection;
using System.Runtime.CompilerServices;
using System.Runtime.InteropServices;

// General information about an assembly is controlled
// through the following set of attributes. Change these
// attribute values to modify the information
// associated with an assembly.
[assembly: AssemblyTitle("CompressionLibrary")]
[assembly: AssemblyDescription("")]
[assembly: AssemblyConfiguration("")]
[assembly: AssemblyCompany("IntelliTect")]
[assembly: AssemblyProduct("Compression Library")]
```

```
[assembly: AssemblyCopyright("Copyright© IntelliTect 2006-2015")]
[assembly: AssemblyTrademark("")]
[assembly: AssemblyCulture("")]

// Setting ComVisible to false makes the types in this
// assembly not visible to COM components. If you need to
// access a type in this assembly from COM, set the ComVisible
// attribute to true on that type.
[assembly: ComVisible(false)]

// The following GUID is for the ID of the typelib
// if this project is exposed to COM.
[assembly: Guid("417a9609-24ae-4323-b1d6-cef0f87a42c3")]

// Version information for an assembly consists
// of the following four values:
//
//      Major Version
//      Minor Version
//      Build Number
//      Revision
//
// You can specify all the values or you can
// default the Revision and Build Numbers
// by using the '*' as shown below:
// [assembly: AssemblyVersion("1.0.*")]
[assembly: AssemblyVersion("1.0.0.0")]
[assembly: AssemblyFileVersion("1.0.0.0")]
```

The `assembly` attributes define things such as the company, product, and assembly version number. Similar to `assembly`, identifying an attribute usage as `module` requires prefixing it with `module:`. The restriction on `assembly` and `module` attributes is that they must appear after the `using` directive but before any namespace or class declarations. The attributes in Listing 17.10 are generated by the Visual Studio Project Wizard and should be included in all projects to mark the resultant binaries with information about the contents of the executable or DLL.

Return attributes, such as the one shown in Listing 17.11, appear before a method declaration but use the same type of syntax structure.

Listing 17.11: Specifying a Return Attribute

```
  [return: Description(
      "Returns true if the object is in a valid state.")]
  public bool IsValid()
  {
    // ...
    return true;
  }
```

In addition to `assembly:` and `return:`, C# allows for explicit target identifications of `module:`, `class:`, and `method:`, corresponding to attributes that decorate the module, class, and method, respectively. `class:` and `method:`, however, are optional, as demonstrated earlier.

One of the conveniences of using attributes is that the language takes into consideration the attribute naming convention, which calls for `Attribute` to appear at the end of the name. However, in all the attribute *uses* in the preceding listings, no such suffix appears, despite the fact that each attribute used follows the naming convention. This is because although the full name (`DescriptionAttribute`, `AssemblyVersionAttribute`, and so on) is allowed when applying an attribute, C# makes the suffix optional. Generally, no such suffix appears when *applying* an attribute; rather, it appears only when defining one or using the attribute inline (such as `typeof(DescriptionAttribute)`).

Guidelines

DO apply `AssemblyVersionAttribute` to assemblies with public types.

CONSIDER applying the `AssemblyFileVersionAttribute` and `AssemblyCopyrightAttribute` to provide additional information about the assembly.

DO apply the following information assembly attributes: `System.Reflection.AssemblyTitleAttribute`, `System.Reflection.AssemblyCompanyAttribute`, `System.Reflection.AssemblyProductAttribute`, `System.Reflection.AssemblyDescriptionAttribute`, `System.Reflection.AssemblyFileVersionAttribute`, and `System.Reflection.AssemblyCopyrightAttribute`.

Custom Attributes

Defining a custom attribute is relatively trivial. Attributes are objects; therefore, to define an attribute, you need to define a class. The characteristic that turns a general class into an attribute is that it derives from `System.Attribute`. Consequently, you can create a `CommandLineSwitchRequiredAttribute` class, as shown in Listing 17.12.

LISTING 17.12: Defining a Custom Attribute

```
public class CommandLineSwitchRequiredAttribute : Attribute
{
}
```

With that simple definition, you now can use the attribute as demonstrated in Listing 17.8. So far, no code responds to the attribute; therefore, the `Out` property that includes the attribute will have no effect on command-line parsing.

Guidelines

DO name custom attribute classes with the suffix “Attribute”.

Looking for Attributes

In addition to providing properties for reflecting on a type’s members, `Type` includes methods to retrieve the `Attributes` decorating that type. Similarly, all the reflection types (`PropertyInfo` and `MethodInfo`, for example) include members for retrieving a list of attributes that decorate a type. Listing 17.13 defines a method to return a list of required switches that are missing from the command line.

LISTING 17.13: Retrieving a Custom Attribute

```
using System;
using System.Collections.Specialized;
using System.Reflection;

public class CommandLineSwitchRequiredAttribute : Attribute
{
  public static string[] GetMissingRequiredOptions(
      object commandLine)
  {
      List<string> missingOptions = new List<string>();
      PropertyInfo[] properties =
          commandLine.GetType().GetProperties();

      foreach (PropertyInfo property in properties)
      {
          Attribute[] attributes =
               (Attribute[])property.GetCustomAttributes(
                  typeof(CommandLineSwitchRequiredAttribute),
                  false);
          if ((attributes.Length > 0) &&
              (property.GetValue(commandLine, null) == null))
```

```
            {
                missingOptions.Add(property.Name);
            }
        }
        return missingOptions.ToArray();
    }
}
```

The code that checks for an attribute is relatively simple. Given a `PropertyInfo` object (obtained via reflection), you call `GetCustomAttributes()` and specify the attribute sought, then indicate whether to check any overloaded methods. (Alternatively, you can call the `GetCustomAttributes()` method without the attribute type to return all of the attributes.)

Although it is possible to place code for finding the `CommandLineSwitchRequiredAttribute` attribute within the `CommandLineHandler`'s code directly, it makes for better object encapsulation to place the code within the `CommandLineSwitchRequiredAttribute` class itself. This is frequently the pattern for custom attributes. What better location to place code for finding an attribute than in a static method on the attribute class?

Initializing an Attribute through a Constructor

The call to `GetCustomAttributes()` returns an array of objects that can be cast to an `Attribute` array. In our example, because the attribute in this example didn't have any instance members, the only metadata information that it provided in the returned attribute was whether it appeared. Attributes can also encapsulate data, however. Listing 17.14 defines a `CommandLineAliasAttribute` attribute—a custom attribute that provides alias command-line options. For example, you can provide command-line support for `/Help` or `/?` as an abbreviation. Similarly, `/S` could provide an alias to `/Subfolders` that indicates the command should traverse all the subdirectories.

To support this functionality, you need to provide a constructor for the attribute. Specifically, for the alias you need a constructor that takes a string argument. (Similarly, if you want to allow multiple aliases, you need to define an attribute that has a `params string` array for a parameter.)

LISTING 17.14: Providing an Attribute Constructor

```
public class CommandLineSwitchAliasAttribute : Attribute
{
```

```
    public CommandLineSwitchAliasAttribute(string alias)
    {
        Alias = alias;
    }

    public string Alias { get; private set; }

}
```

```
class CommandLineInfo
{
  [CommandLineSwitchAlias("?")]
  public bool Help { get; set; }

  // ...
}
```

When applying an attribute to a construct, only constant values and `typeof()` expressions are allowed as arguments. This constraint is intended to enable their serialization into the resultant CIL. It implies that an attribute constructor should require parameters of the appropriate types; creating a constructor that takes arguments of type `System.DateTime` would be of little value, as there are no `System.DateTime` constants in C#.

The objects returned from `PropertyInfo.GetCustomAttributes()` will be initialized with the specified constructor arguments, as demonstrated in Listing 17.15.

Listing 17.15: Retrieving a Specific Attribute and Checking Its Initialization

```
PropertyInfo property =
    typeof(CommandLineInfo).GetProperty("Help");
CommandLineSwitchAliasAttribute attribute =
    (CommandLineSwitchAliasAttribute)
        property.GetCustomAttributes(
        typeof(CommandLineSwitchAliasAttribute), false)[0];
if(attribute.Alias == "?")
{
  Console.WriteLine("Help(?)");
};
```

Furthermore, as Listing 17.16 and Listing 17.17 demonstrate, you can use similar code in a `GetSwitches()` method on `CommandLineAliasAttribute` that returns a dictionary collection of all the switches, including those from the property names, and associate each name with the corresponding attribute on the command-line object.

LISTING 17.16: Retrieving Custom Attribute Instances

```
using System;
using System.Reflection;
using System.Collections.Generic;

public class CommandLineSwitchAliasAttribute : Attribute
{
  public CommandLineSwitchAliasAttribute(string alias)
  {
      Alias = alias;
  }

  public string Alias { get; set; }

  public static Dictionary<string, PropertyInfo> GetSwitches(
      object commandLine)
  {
      PropertyInfo[] properties = null;
      Dictionary<string, PropertyInfo> options =
          new Dictionary<string, PropertyInfo>();

      properties = commandLine.GetType().GetProperties(
          BindingFlags.Public | BindingFlags.NonPublic |
          BindingFlags.Instance);
      foreach (PropertyInfo property in properties)
      {
          options.Add(property.Name.ToLower(), property);
          foreach (CommandLineSwitchAliasAttribute attribute in
              property.GetCustomAttributes(
              typeof(CommandLineSwitchAliasAttribute), false))
          {
              options.Add(attribute.Alias.ToLower(), property);
          }
      }
      return options;
  }
}
```

LISTING 17.17: Updating `CommandLineHandler.TryParse()` to Handle Aliases

```
using System;
using System.Reflection;
using System.Collections.Generic;

public class CommandLineHandler
{
  // ...

  public static bool TryParse(
      string[] args, object commandLine,
      out string errorMessage)
  {
```

```
        bool success = false;
        errorMessage = null;

        Dictionary<string, PropertyInfo> options =
            CommandLineSwitchAliasAttribute.GetSwitches(
                commandLine);

        foreach (string arg in args)
        {
            PropertyInfo property;
            string option;
            if (arg[0] == '/' || arg[0] == '-')
            {
                string[] optionParts = arg.Split(
                    new char[] { ':' }, 2);
                option = optionParts[0].Remove(0, 1).ToLower();

                if (options.TryGetValue(option, out property))
                {
                    success = SetOption(
                        commandLine, property,
                        optionParts, ref errorMessage);
                }
                else
                {
                    success = false;
                    errorMessage =
                        $"Option '{ option }' is not supported.";
                }
            }
        }

        return success;
    }

      private static bool SetOption(
          object commandLine, PropertyInfo property,
          string[] optionParts, ref string errorMessage)
        {
          bool success;

          if (property.PropertyType == typeof(bool))
          {
              // Last parameters for handling indexers.
              property.SetValue(
                  commandLine, true, null);
              success = true;
          }
          else
          {
```

```
                if ((optionParts.Length < 2)
                    || optionParts[1] == ""
                    || optionParts[1] == ":")
                {
                    // No setting was provided for the switch.
                    success = false;
                    errorMessage = string.Format(
                        "You must specify the value for the {0} option.",
                        property.Name);
                }
                else if (
                    property.PropertyType == typeof(string))
                {
                    property.SetValue(
                        commandLine, optionParts[1], null);
                    success = true;
                }
                else if (property.PropertyType.IsEnum)
                {
                    success = TryParseEnumSwitch(
                        commandLine, optionParts,
                        property, ref errorMessage);
                }
                else
                {
                    success = false;
                    errorMessage = string.Format(
                        "Data type '{0}' on {1} is not supported.",
                        property.PropertyType.ToString(),
                        commandLine.GetType().ToString());
                }
            }
            return success;
        }
    }
```

Guidelines

DO provide get-only properties (with private setters) on attributes with required property values.

DO provide constructor parameters to initialize properties on attributes with required properties. Each parameter should have the same name (albeit with different casing) as the corresponding property.

AVOID providing constructor parameters to initialize attribute properties corresponding to the optional arguments (and therefore, avoid overloading custom attribute constructors).

System.AttributeUsageAttribute

Most attributes are intended to decorate only particular constructs. For example, it makes no sense to allow CommandLineOptionAttribute to decorate a class or an assembly. The attribute in those contexts would be meaningless. To avoid inappropriate use of an attribute, custom attributes can be decorated with System.AttributeUsageAttribute. Listing 17.18 (for CommandLineOptionAttribute) demonstrates how to do this.

Listing 17.18: Restricting the Constructs an Attribute Can Decorate

```
[AttributeUsage(AttributeTargets.Property)]
public class CommandLineSwitchAliasAttribute : Attribute
{
  // ...
}
```

If the attribute is used inappropriately, as it is in Listing 17.19, it will cause a compile-time error, as Output 17.5 demonstrates.

Listing 17.19: AttributeUsageAttribute Restricting Where to Apply an Attribute

```
// ERROR: The attribute usage is restricted to properties
[CommandLineSwitchAlias("?")]
class CommandLineInfo
{
}
```

Output 17.5

```
...Program+CommandLineInfo.cs(24,17): error CS0592: Attribute
'CommandLineSwitchAlias' is not valid on this declaration type. It is
valid on 'property, indexer' declarations only.
```

AttributeUsageAttribute's constructor takes an AttributeTargets flag. This enum provides a list of all possible targets that the runtime allows an attribute to decorate. For example, if you also allowed CommandLineSwitchAliasAttribute on a field, you would update the AttributeUsageAttribute class as shown in Listing 17.20.

Listing 17.20: Limiting an Attribute's Usage with AttributeUsageAttribute

```
// Restrict the attribute to properties and methods
[AttributeUsage(
  AttributeTargets.Field | AttributeTargets.Property)]
```

```
public class CommandLineSwitchAliasAttribute : Attribute
{
  // ...
}
```

Guidelines

DO apply the `AttributeUsageAttribute` class to custom attributes.

Named Parameters

In addition to restricting what an attribute can decorate, `AttributeUsageAttribute` provides a mechanism for allowing duplicates of the same attribute on a single construct. The syntax appears in Listing 17.21.

LISTING 17.21: Using a Named Parameter

```
[AttributeUsage(AttributeTargets.Property, AllowMultiple=true)]
public class CommandLineSwitchAliasAttribute : Attribute
{
  // ...
}
```

This syntax is different from the constructor initialization syntax discussed earlier. The `AllowMultiple` parameter is a **named parameter**, similar to the named parameter syntax used for optional method parameters (added in C# 4.0). Named parameters provide a mechanism for setting specific public properties and fields within the attribute constructor call, even though the constructor includes no corresponding parameters. The named attributes are optional designations, but they provide a means of setting additional instance data on the attribute without providing a constructor parameter for the purpose. In this case, `AttributeUsageAttribute` includes a public member called `AllowMultiple`. Therefore, you can set this member using a named parameter assignment when you use the attribute. Assigning named parameters must occur as the last portion of a constructor, following any explicitly declared constructor parameters.

Named parameters allow for assigning attribute data without providing constructors for every conceivable combination of which attribute properties are specified and which are not. Given that many of an attribute's properties may be optional, this is a useful construct in many cases.

BEGINNER TOPIC

FlagsAttribute

Chapter 8 introduced enums and included an Advanced Topic covering `FlagsAttribute`. This framework-defined attribute targets enums that represent flag type values. The Beginner Topic here also addresses `FlagsAttribute`, starting with the sample code shown in Listing 17.22.

Listing 17.22: Using FlagsAttribute

```
// FileAttributes defined in System.IO.

[Flags]  // Decorating an enum with FlagsAttribute.
public enum FileAttributes
{
  ReadOnly =          1<<0,      // 000000000000001
  Hidden =            1<<1,      // 000000000000010
  // ...
}
```

```
using System;
using System.Diagnostics;
using System.IO;

class Program
{
  public static void Main()
  {
      // ...

      string fileName = @"enumtest.txt";
      FileInfo file = new FileInfo(fileName);

      file.Attributes = FileAttributes.Hidden |
          FileAttributes.ReadOnly;

      Console.WriteLine("\"{0}\" outputs as \"{1}\"",
          file.Attributes.ToString().Replace(",", " |"),
          file.Attributes);

      FileAttributes attributes =
          (FileAttributes)Enum.Parse(typeof(FileAttributes),
          file.Attributes.ToString());

      Console.WriteLine(attributes);

       // ...
  }
}
```

Output 17.6 shows the results of Listing 17.22.

Output 17.6

```
"ReadOnly | Hidden" outputs as "ReadOnly, Hidden"
```

The flag documents that the enumeration values can be combined. Furthermore, it changes the behavior of the `ToString()` and `Parse()` methods. For example, calling `ToString()` on an enumeration that is decorated with `FlagsAttribute` writes out the strings for each enumeration flag that is set. In Listing 17.22, `file.Attributes.ToString()` returns `"ReadOnly, Hidden"` rather than the `3` it would have returned without the `FlagsAttribute` flag. If two enumeration values are the same, the `ToString()` call would return the first one. As mentioned earlier, however, you should use caution when relying on this outcome because it is not localizable.

Parsing a value from a string to the enumeration also works, provided each enumeration value identifier is separated by a comma.

Note that `FlagsAttribute` does not automatically assign the unique flag values or check that flags have unique values. The values of each enumeration item still must be assigned explicitly.

Predefined Attributes

The `AttributeUsageAttribute` attribute has a special characteristic that you haven't seen yet in the custom attributes you have created in this book. This attribute affects the behavior of the compiler, causing the compiler to sometimes report an error. Unlike the reflection code you wrote earlier for retrieving `CommandLineRequiredAttribute` and `CommandLineSwitchAliasAttribute`, `AttributeUsageAttribute` has no runtime code; instead, it has built-in compiler support.

`AttributeUsageAttribute` is a predefined attribute. Not only do such attributes provide additional metadata about the constructs they decorate, but the runtime and compiler also behave differently to facilitate these attributes' functionality. Attributes such as `AttributeUsageAttribute`, `FlagsAttribute`, `ObsoleteAttribute`, and `ConditionalAttribute` are examples of predefined attributes. They implement special behavior that only the CLI provider or compiler can offer because there are no extension points for additional noncustom attributes. In contrast, custom attributes are entirely passive. Listing 17.22 includes a couple of predefined attributes; Chapter 18 includes a few more.

System.ConditionalAttribute

Within a single assembly, the `System.Diagnostics.ConditionalAttribute` attribute behaves a little like the `#if/#endif` preprocessor identifier. However, instead of eliminating the CIL code from the assembly, `System.Diagnostics.ConditionalAttribute` will optionally cause the call to behave like a **no-op,** an instruction that does nothing. Listing 17.23 demonstrates the concept, and Output 17.7 shows the results.

Listing 17.23: Using `ConditionalAttribute` to Eliminate a Call

```
#define CONDITION_A

using System;
using System.Diagnostics;

public class Program
{
  public static void Main()
  {
      Console.WriteLine("Begin...");
      MethodA();
      MethodB();
      Console.WriteLine("End...");
  }

  [Conditional("CONDITION_A")]
  static void MethodA()
  {
      Console.WriteLine("MethodA() executing...");
  }

  [Conditional("CONDITION_B")]
  static void MethodB()
  {
      Console.WriteLine("MethodB() executing...");
  }
}
```

Output 17.7

```
Begin...
MethodA() executing...
End...
```

This example defined `CONDITION_A`, so `MethodA()` executed normally. `CONDITION_B`, however, was not defined either through `#define` or by using the `csc.exe /Define` option. As a result, all calls to `Program.MethodB()` from within this assembly will do nothing.

Functionally, `ConditionalAttribute` is similar to placing an `#if/#endif` around the method invocation. The syntax is cleaner, however, because developers create the effect by adding the `ConditionalAttribute` attribute to the target method without making any changes to the caller itself.

The C# compiler notices the attribute on a called method during compilation, and assuming the preprocessor identifier exists, it eliminates any calls to the method. `ConditionalAttibute`, however, does not affect the compiled CIL code on the target method itself (besides the addition of the attribute metadata). Instead, it affects the call site during compilation by removing the calls. This further distinguishes `ConditionalAttribute` from `#if/#endif` when calling across assemblies. Because the decorated method is still compiled and included in the target assembly, the determination of whether to call a method is based not on the preprocessor identifier in the callee's assembly, but rather on the caller's assembly. In other words, if you create a second assembly that defines `CONDITION_B`, any calls to `Program.MethodB()` from the second assembly will execute. This is a useful characteristic in many tracing and testing scenarios. In fact, calls to `System.Diagnostics.Trace` and `System.Diagnostics.Debug` use this trait with `ConditionalAttributes` on `TRACE` and `DEBUG` preprocessor identifiers.

Because methods don't execute whenever the preprocessor identifier is not defined, `ConditionalAttribute` may not be used on methods that include an `out` parameter or specify a return other than `void`. Doing so causes a compile-time error. This makes sense because potentially none of the code within the decorated method will execute, so it is unknown what to return to the caller. Similarly, properties cannot be decorated with `ConditionalAttribute`. The `AttributeUsage` (see the section titled "`System.AttributeUsageAttribute`" earlier in this chapter) for `ConditionalAttribute` is `AttributeTargets.Class` (starting in .NET Framework 2.0) and `AttributeTargets.Method`, which allows the attribute to be used on either a method or a class. However, the class usage is special because `ConditionalAttribute` is allowed only on `System.Attribute`-derived classes.

When `ConditionalAttribute` decorates a custom attribute, a feature started in .NET Framework 2.0, the latter can be retrieved via reflection only if the conditional string is defined in the calling assembly. Without such a conditional string, reflection that looks for the custom attribute will fail to find it.

System.ObsoleteAttribute

As mentioned earlier, predefined attributes affect the compiler's and/or the runtime's behavior. `ObsoleteAttribute` provides another example of attributes affecting the compiler's behavior. Its purpose is to help with the versioning of code, providing a means of indicating to callers that a particular member or type is no longer current. Listing 17.24 is an example of `ObsoleteAttribute` usage. As Output 17.8 shows, any callers that compile code that invokes a member marked with `ObsoleteAttribute` will cause a compile-time warning, optionally an error.

Listing 17.24: Using `ObsoleteAttribute`

```
class Program
{
  public static void Main()
  {
      ObsoleteMethod();
  }

  [Obsolete]
  public static void ObsoleteMethod()
  {
  }
}
```

Output 17.8

```
c:\SampleCode\ObsoleteAttributeTest.cs(24,17): warning CS0612:
Program.ObsoleteMethod()' is obsolete
```

In this case, `ObsoleteAttribute` simply displays a warning. However, there are two additional constructors on the attribute. One of them, `ObsoleteAttribute(string message)`, appends the additional message argument to the compiler's obsolete message. The best practice for this message is to provide direction on what replaces the obsolete code. The second constructor is a `bool error` parameter that forces the warning to be recorded as an error instead.

`ObsoleteAttribute` allows third parties to notify developers of deprecated APIs. The warning (not an error) allows the original API to continue to work until the developer is able to update the calling code.

Serialization-Related Attributes

Using predefined attributes, the framework supports the capacity to serialize objects onto a stream so that they can be deserialized back into objects at a later time. This provides a means of easily saving a document type object to disk before shutting down an application. Later on, the document may be deserialized so that the user can continue to work on it.

In spite of the fact that an object can be relatively complex and can include links to many other types of objects that also need to be serialized, the serialization framework is easy to use. For an object to be serializable, the only requirement is that it include a `System.SerializableAttribute`. Given the attribute, a formatter class reflects over the serializable object and copies it into a stream (see Listing 17.25).

Listing 17.25: Saving a Document Using `System.SerializableAttribute`

```
using System;
using System.IO;
using System.Runtime.Serialization.Formatters.Binary;

class Program
{
  public static void Main()
  {
      Stream stream;
      Document documentBefore = new Document();
      documentBefore.Title =
          "A cacophony of ramblings from my potpourri of notes";
      Document documentAfter;

      using (stream = File.Open(
          documentBefore.Title + ".bin", FileMode.Create))
      {
          BinaryFormatter formatter =
              new BinaryFormatter();
          formatter.Serialize(stream, documentBefore);
      }

      using (stream = File.Open(
          documentBefore.Title + ".bin", FileMode.Open))
      {
          BinaryFormatter formatter =
              new BinaryFormatter();
          documentAfter = (Document)formatter.Deserialize(
              stream);
      }
```

```
            Console.WriteLine(documentAfter.Title);
        }
    }
```

```
    // Serializable classes use SerializableAttribute.
    [Serializable]
    class Document
    {

      public string Title = null;
      public string Data = null;

      [NonSerialized]
      public long _WindowHandle = 0;

      class Image
      {
      }
      [NonSerialized]
      private Image Picture = new Image();
    }
```

Output 17.9 shows the results of Listing 17.25.

Output 17.9

```
A cacophony of ramblings from my potpourri of notes
```

Listing 17.25 serializes and deserializes a `Document` object. Serialization involves instantiating a formatter (`System.Runtime.Serialization.Formatters.Binary.BinaryFormatter`, in this example) and calling `Serialization()` with the appropriate stream object. Deserializing the object simply involves calling the formatter's `Deserialize()` method, specifying the stream that contains the serialized object as an argument. However, given that the return from `Deserialize()` is of type `object`, you also need to cast it specifically to the type that was serialized.

Notice that serialization occurs for the entire object graph (all items associated with the serialized object [`Document`] via a field). Therefore, all fields in the object graph also must be serializable.

System.NonSerializable

Fields that are not serializable should be decorated with the `System.NonSerializable` attribute, which tells the serialization framework to ignore them. The same attribute should appear on fields that should not be persisted for use-case reasons. Passwords and Windows handles are good examples of fields that should not be serialized: Windows handles because they change each time a window is re-created, and passwords because data serialized into a stream is not encrypted and can be readily accessed. Consider the Notepad view of the serialized document in Figure 17.2.

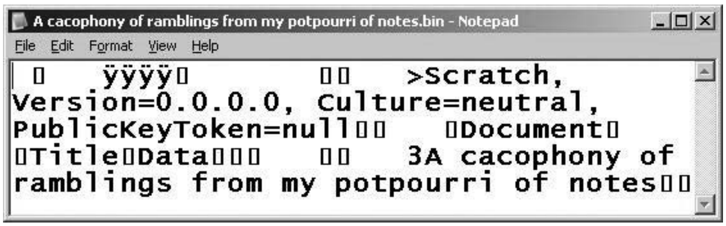


FIGURE 17.2: **BinaryFormatter** Does Not Encrypt Data

Listing 17.25 set the `Title` field, and the resultant `*.BIN` file includes the text in plain view.

Providing Custom Serialization

One way to add encryption is to provide custom serialization. Ignoring the complexities of encrypting and decrypting, this requires implementing the `ISerializable` interface in addition to using `SerializableAttribute`. The interface requires only the `GetObjectData()` method to be implemented. However, this is sufficient only for serialization. To support deserialization as well, it is necessary to provide a constructor that takes parameters of type `System.Runtime.Serialization.SerializationInfo` and `System.Runtime.Serialization.StreamingContext` (see Listing 17.26).

LISTING 17.26: Implementing **System.Runtime.Serialization.ISerializable**

```
using System;
using System.Runtime.Serialization;

[Serializable]
class EncryptableDocument :
    ISerializable
{
  public EncryptableDocument(){ }

  enum Field
  {
      Title,
      Data
```

```
    }
    public string Title;
    public string Data;

    public static string Encrypt(string data)
    {
        string encryptedData = data;
        // Key-based encryption ...
        return encryptedData;
    }

    public static string Decrypt(string encryptedData)
    {
        string data = encryptedData;
      // Key-based decryption...
        return data;
    }

  #region ISerializable Members
        public void GetObjectData(
        SerializationInfo info, StreamingContext context)
    {
        info.AddValue(
            Field.Title.ToString(), Title);
        info.AddValue(
            Field.Data.ToString(), Encrypt(Data));
    }

    public EncryptableDocument(
        SerializationInfo info, StreamingContext context)
    {
        Title = info.GetString(
            Field.Title.ToString());
        Data = Decrypt(info.GetString(
            Field.Data.ToString()));
    }
  #endregion
  }
```

Essentially, the `System.Runtime.Serialization.SerializationInfo` object is a collection of name/value pairs. When serializing, the `GetObject()` implementation calls `AddValue()`. To reverse the process, you call one of the `Get*()` members. In this case, you encrypt and decrypt prior to serialization and deserialization, respectively.

Versioning the Serialization

One more serialization point deserves mention: versioning. Objects such as documents may be serialized using one version of an assembly and deserialized using a newer version; the reverse may also occur. If the programmer is not paying sufficient attention, however, version incompatibilities can easily be introduced in this process, sometimes unexpectedly. Consider the scenario shown in Table 17.1.

TABLE 17.1: Deserialization of a New Version Throws an Exception

<table>
<tr><th>Step</th><th>Description</th><th>Code</th></tr>
<tr><td>1.</td><td>Define a class decorated with <code>System.SerializableAttribute</code>.</td><td rowspan="2">[Serializable]
class Document
{
  public string Title;
  public string Data;
}</td></tr>
<tr><td>2.</td><td>Add a field or two (public or private) of any serializable type.</td></tr>
<tr><td>3.</td><td>Serialize the object to a file called <code>*.v1.bin</code>.</td><td>Stream stream;
Document documentBefore = new
Document();
documentBefore.Title =
  "A cacophony of ramblings from my
potpourri of notes";
Document documentAfter;

using (stream = File.Open(
    documentBefore.Title + ".bin",
    FileMode.Create))
{
  BinaryFormatter formatter =
      new BinaryFormatter();
  formatter.Serialize(
      stream, documentBefore);
}</td></tr>
<tr><td>4.</td><td>Add an additional field to the serializable class.</td><td>[Serializable]
class Document
{
  public string Title;
  public string Author;
  public string Data;
}</td></tr>
<tr><td>5.</td><td>Deserialize the <code>*v1.bin</code> file into the new object (<code>Document</code>) version.</td><td>using (stream = File.Open(
    documentBefore.Title + ".bin",
    FileMode.Open))
{
    BinaryFormatter formatter =
        new BinaryFormatter();
    documentAfter =

(Document)formatter.Deserialize(
        stream);
}</td></tr>
</table>

Surprisingly, even though all you did was to add a new field, deserializing the original file throws a `System.Runtime.Serialization.SerializationException`. This is because the formatter looks for data corresponding to the new field within the stream. Failure to locate such data throws an exception.

Begin 2.0

To avoid this problem, .Net Framework 2.0 and later include a `System.Runtime.Serialization.OptionalFieldAttribute`. When backward compatibility is required, you must decorate serialized fields—even private ones—with `OptionalFieldAttribute` (unless, of course, a latter version begins to require it).

End 2.0

ADVANCED TOPIC

`System.SerializableAttribute` and the CIL

In many ways, the serialization attributes behave just like custom attributes. At runtime, the formatter class searches for these attributes, and if the attributes exist, the classes are formatted appropriately. One of the characteristics that makes `System.SerializableAttribute` more than just a custom attribute, however, is the fact that the CIL has a special header notation for serializable classes. Listing 17.28 shows the class header for the `Person` class in the CIL.

LISTING 17.28: The CIL for `SerializableAttribute`

```
class auto ansi serializable nested private
  beforefieldinit Person
  extends [mscorlib]System.Object
{
} // end of class Person
```

In contrast, attributes (including most predefined attributes) generally appear within a class definition (see Listing 17.29).

LISTING 17.29: The CIL for Attributes in General

```
.class private auto ansi beforefieldinit Person
       extends [mscorlib]System.Object
{
  .custom instance void CustomAttribute::.ctor() =
      ( 01 00 00 00 )
} // end of class Person
```

In Listing 17.29, `CustomAttribute` is the full name of the decorating attribute.

`SerializableAttribute` translates to a set bit within the metadata tables. This makes `SerializableAttribute` a **pseudoattribute**—that is, an attribute that sets bits or fields in the metadata tables.

Programming with Dynamic Objects

Begin 4.0

The introduction of dynamic objects in C# 4.0 simplified a host of programming scenarios and enabled several new ones previously not available. At its core, programming with dynamic objects enables developers to code operations using a dynamic dispatch mechanism that the runtime will resolve at execution time, rather than the compiler verifying and binding to it at compile time.

Why? Many times, objects are inherently not statically typed. Examples include loading data from an XML/CSV file, a database table, the Internet Explorer DOM, or COM's `IDispatch` interface, or calling code in a dynamic language such as an IronPython object. C# 4.0's `Dynamic` object support provides a common solution for talking to runtime environments that don't necessarily have a compile-time–defined structure. In the initial implementation of dynamic objects in C# 4.0, four binding methods are available:

1. Using reflection against an underlying CLR type
2. Invoking a custom `IDynamicMetaObjectProvider` that makes available a `DynamicMetaObject`
3. Calling through the `IUnknown` and `IDispatch` interfaces of COM
4. Calling a type defined by dynamic languages such as IronPython

Of these four approaches, we will delve into the first two. The principles underlying them translate seamlessly to the remaining cases—COM interoperability and dynamic language interoperability.

Invoking Reflection Using `dynamic`

One of the key features of reflection is the ability to dynamically find and invoke a member on a particular type based on an execution-time identification of the member name or some other quality, such as an attribute (see Listing 17.3). However, C# 4.0's addition of dynamic objects provides a simpler way of invoking a member by reflection, assuming compile-time knowledge of the member signature. To reiterate, this restriction states that at compile time we need to know the member name along with the signature (the number of parameters and whether the specified parameters will be type-compatible with the signature). Listing 17.30 (with Output 17.10) provides an example.

Listing 17.30: Dynamic Programming Using "Reflection"

4.0

```
using System;

// ...
dynamic data =
  "Hello!  My name is Inigo Montoya";
Console.WriteLine(data);
data = (double)data.Length;
data = data * 3.5 + 28.6;
if(data == 2.4 + 112 + 26.2)
{
  Console.WriteLine(
      $"{ data } makes for a long triathlon.");
}
else
{
  data.NonExistentMethodCallStillCompiles();
}
// ...
```

Output 17.10

```
Hello!  My name is Inigo Montoya
140.6 makes for a long triathlon.
```

In this example, there is no explicit code for determining the object type, finding a particular `MemberInfo` instance, and then invoking it. Instead, `data` is declared as type `dynamic` and methods are called against it directly. At compile time, there is no check as to whether the members specified are available, or even a check regarding which type underlies the `dynamic` object. Hence, it is possible at compile time to make any call so long as the syntax is valid. At compile time, it is irrelevant whether there is really a corresponding member.

However, type safety is not abandoned altogether. For standard CLR types (such as those used in Listing 17.30), the same type checker normally used at compile time for non-`dynamic` types is instead invoked at execution time for the `dynamic` type. Therefore, at execution time, if no such member is available, the call will result in a `Microsoft.CSharp.RuntimeBinder.RuntimeBinderException`.

Note that this capability is not nearly as flexible as the reflection described earlier in the chapter, although the API is undoubtedly simpler. The key difference when using a dynamic object is that it is necessary to identify the signature at compile time, rather than determine things such as the member name at runtime (as we did when parsing the command-line arguments).

`dynamic` Principles and Behaviors

Listing 17.30 and the accompanying text reveal several characteristics of the `dynamic` data type.

- `dynamic` *is a directive to the compiler to generate code.*

  `dynamic` involves an interception mechanism so that when a dynamic call is encountered by the runtime, it can compile the request to CIL and then invoke the newly compiled call. (See the Advanced Topic titled "`dynamic` Uncovered" later in this chapter for more details.)

  The principle at work when a type is assigned to `dynamic` is to conceptually "wrap" the original type so that no compile-time validation occurs. Additionally, when a member is invoked at runtime, the "wrapper" intercepts the call and dispatches it appropriately (or rejects it). Calling `GetType()` on the `dynamic` object reveals the type underlying the dynamic instance—it does not return `dynamic` as a type.

- *Any type that converts to object will convert to* `dynamic`.

  In Listing 17.29, we successfully cast both a value type (`double`) and a reference type (`string`) to `dynamic`. In fact, all types can successfully be converted into a `dynamic` object. There is an implicit conversion from any reference type to `dynamic`. Similarly, there is an implicit conversion (a boxing conversion) from a value type to `dynamic`. In addition, there is an implicit conversion from `dynamic` to `dynamic`. This is perhaps obvious, but with `dynamic` this process is more complicated than simply copying the "pointer" (address) from one location to the next.

4.0

- *Successful conversion from* `dynamic` *to an alternative type depends on support in the underlying type.*

  Conversion from a `dynamic` object to a standard CLR type is an explicit cast (for example, `(double)data.Length`). Not surprisingly, if the target type is a value type, an unboxing conversion is required. If the underlying type supports the conversion to the target type, the conversion from `dynamic` will also succeed.

- *The type underlying the* `dynamic` *type can change from one assignment to the next.*

  Unlike an implicitly typed variable (`var`), which cannot be reassigned to a different type, `dynamic` involves an interception mechanism for compilation before the underlying type's code is executed. Therefore, it is possible to successfully swap out the underlying type instance to an entirely different type. This will result in another interception call site that will need to be compiled before invocation.

- *Verification that the specified signature exists on the underlying type doesn't occur until runtime—but it does occur.*

  4.0

  As the method call to `person.NonExistentMethodCallStillCompiles()` demonstrates, the compiler makes almost no verification of operations on a `dynamic` type. This step is left entirely to the work of the runtime when the code executes. Moreover, if the code never executes, even though surrounding code does (as with `person.NonExistentMethodCallStillCompiles()`), no verification and binding to the member will ever occur.

- *The result of any* `dynamic` *member invocation is of compile-time type* `dynamic`.

  A call to any member on a `dynamic` object will return a `dynamic` object. Therefore, calls such as `data.ToString()` will return a `dynamic` object rather than the underlying `string` type. However, at execution time, when `GetType()` is called on the `dynamic` object, an object representing the runtime type is returned.

- *If the member specified does not exist at runtime, the runtime will throw a* `Microsoft.CSharp.RuntimeBinder.RuntimeBinderException` *exception.*

  If an attempt to invoke a member at execution time does occur, the runtime will verify that the member call is truly valid (that the signatures are type-compatible in the case of reflection, for example). If the method signatures are not compatible, the runtime will throw a `Microsoft.CSharp.RuntimeBinder.RuntimeBinderException`.

- `dynamic` *with reflection does not support extension methods.*

  Just like with reflection using `System.Type`, reflection using `dynamic` does not support extension methods. Invocation of extension methods is still available on the implementing type (`System.Linq.Enumerable`, for example), just not on the extended type directly.

- *At its core,* `dynamic` *is a* `System.Object`.

  Given that any object can be successfully converted to `dynamic`, and that `dynamic` may be explicitly converted to a different object type, `dynamic` behaves like `System.Object`. Like `System.Object`, it even returns `null` for its default value (`default(dynamic)`), indicating it is a reference type. The special dynamic behavior of `dynamic` that distinguishes it from a `System.Object` appears only at compile time.

ADVANCED TOPIC

4.0

dynamic Uncovered

The CIL disassembler reveals that within the CIL, the `dynamic` type is actually a `System.Object`. In fact, without any invocations, declaration of the `dynamic` type is indistinguishable from `System.Object`. However, the difference becomes apparent when invoking a member. To invoke the member, the compiler declares a variable of type `System.Runtime.CompilerServices.CallSite<T>`. `T` varies based on the member signature, but something simple such as the invocation of `ToString()` would require instantiation of the type `CallSite<Func<CallSite, object, string>>`, along with a method call with parameters of `CallSite site`, `object dynamicTarget`, and `string result`. `site` is the call site itself, `dynamicTarget` is the `object` on which the method call is invoked, and `result` is the underlying return value from the `ToString()` method call. Rather than instantiate `CallSite<Func<CallSite _site, object dynamicTarget, string result>>` directly, a `Create()` factory method is available for instantiating it. (`Create()` takes a parameter of type `Microsoft.CSharp.RuntimeBinder.CSharpConvertBinder`.) Given an instance of the `CallSite<T>`, the final step involves a call to `CallSite<T>.Target()` to invoke the actual member.

Under the covers at execution time, the framework uses reflection to look up members and to verify that the signatures match. Next, the runtime builds an expression tree that represents the dynamic expression as defined by the call site. Once the expression tree is compiled, we have a CIL method body that is similar to what the compiler would have generated had the call not been dynamic. This CIL code is then cached in the call site, and the invocation occurs using a delegate invoke. As the CIL is now cached at the call site, the next invocation doesn't require all the reflection and compilation overhead again.

Why Dynamic Binding?

In addition to reflection, we can define custom types that we invoke dynamically. You might consider using dynamic invocation to retrieve the values of an XML element, for example. Rather than using the strongly typed syntax of Listing 17.31, using dynamic invocation we could call `person.FirstName` and `person.LastName`.

4.0

Listing 17.31: Runtime Binding to XML Elements without dynamic

```
using System;
using System.Xml.Linq;

// ...
XElement person = XElement.Parse(
   @"<Person>
      <FirstName>Inigo</FirstName>
      <LastName>Montoya</LastName>
</Person>");

Console.WriteLine("{0} {1}",
  person.Descendants("FirstName").FirstOrDefault().Value,
  person.Descendants("LastName").FirstOrDefault().Value);
// ...
```

Although the code in Listing 17.31 is not overly complex, compare it to Listing 17.32—an alternative approach that uses a dynamically typed object.

Listing 17.32: Runtime Binding to XML Elements with dynamic

```
using System;

// ...
dynamic person = DynamicXml.Parse(
  @"<Person>
```

```
        <FirstName>Inigo</FirstName>
        <LastName>Montoya</LastName>
    </Person>");

    Console.WriteLine(
        $"{ person.FirstName } { person.LastName }");
  // ...
```

The advantages are clear, but does that mean dynamic programming is preferable to static compilation?

Static Compilation versus Dynamic Programming

In Listing 17.32, we have the same functionality as in Listing 17.31, albeit with one very important difference: Listing 17.31 is entirely statically typed. Thus, at compile time, all types and their member signatures are verified with this approach. Method names are required to match, and all parameters are checked for type compatibility. This is a key feature of C# and something we have highlighted throughout the book.

In contrast, Listing 17.32 has virtually no statically typed code; the variable `person` is instead `dynamic`. As a result, there is no compile-time verification that `person` has a `FirstName` or `LastName` property—or any other members, for that matter. Furthermore, when coding within an IDE, there is no IntelliSense identifying any members on `person`.

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The loss of typing would seem to result in a significant decrease in functionality. Why, then, is such a possibility even available in C#—a functionality that was added in C# 4.0, in fact?

To understand this apparent paradox, let's reexamine Listing 17.32. Notice the call to retrieve the `"FirstName"` element: `Element.Descendants("LastName").FirstOrDefault().Value`. The listing uses a `string` (`"LastName"`) to identify the element name, but there is no compile-time verification that the string is correct. If the casing was inconsistent with the element name or if there was a space, the compile would still succeed, even though a `NullReferenceException` would occur with the call to the `Value` property. Furthermore, the compiler does not attempt to verify that the `"FirstName"` element even exists; if it doesn't, we would also get the `NullReferenceException` message. In other words, in spite of all the type-safety advantages, type safety doesn't offer many benefits when you're accessing the dynamic data stored within the XML element.

Listing 17.32 is no better than Listing 17.31 when it comes to compile-time verification of the element retrieval. If a case mismatch occurs or if the `FirstName` element didn't exist, there would still be an exception.[1] However, compare the call to access the first name in Listing 17.32 (`person.FirstName`) with the call in Listing 17.31. The call in the latter listing is undoubtedly significantly simpler.

In summary, there are situations in which type safety doesn't—and likely can't—make certain checks. In such cases, code that makes a dynamic call that is verified only at runtime, rather than also being verified at compile time, is significantly more readable and succinct. Obviously, if compile-time verification is possible, statically typed programming is preferred because readable and succinct APIs can accompany it. However, in the cases where it isn't effective, C# 4.0 enables programmers to write simpler code rather than emphasizing the purity of type safety.

Implementing a Custom Dynamic Object

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Listing 17.32 included a method call to `DynamicXml.Parse(...)` that was essentially a factory method call for `DynamicXml`—a custom type rather than one built into the CLR framework. However, `DynamicXml` doesn't implement a `FirstName` or `LastName` property. To do so would break the dynamic support for retrieving data from the XML file at execution time, rather than fostering compile-time-based implementation of the XML elements. In other words, `DynamicXml` does not use reflection for accessing its members, but rather dynamically binds to the values based on the XML content.

The key to defining a custom dynamic type is implementation of the `System.Dynamic.IDynamicMetaObjectProvider` interface. Rather than implementing the interface from scratch, however, the preferred approach is to derive the custom dynamic type from `System.Dynamic.DynamicObject`. This provides default implementations for a host of members and allows you to override the ones that don't fit. Listing 17.33 shows the full implementation.

LISTING 17.33: Implementing a Custom Dynamic Object

```
using System;
using System.Dynamic;
using System.Xml.Linq;
```

1. You cannot use a space in the `FirstName` property call, but neither does XML support spaces in element names, so let's ignore this fact.

```
public class DynamicXml : DynamicObject
{
  private XElement Element { get; set; }

  public DynamicXml(System.Xml.Linq.XElement element)
  {
      Element = element;
  }

  public static DynamicXml Parse(string text)
  {
      return new DynamicXml(XElement.Parse(text));
  }

  public override bool TryGetMember(
      GetMemberBinder binder, out object result)
  {
      bool success = false;
      result = null;
      XElement firstDescendant =
          Element.Descendants(binder.Name).FirstOrDefault();
      if (firstDescendant != null)
      {
          if (firstDescendant.Descendants().Count() > 0)
          {
              result = new DynamicXml(firstDescendant);
          }
          else
          {
              result = firstDescendant.Value;
          }
          success = true;
      }
      return success;
  }

  public override bool TrySetMember(
      SetMemberBinder binder, object value)
  {
      bool success = false;
      XElement firstDescendant =
          Element.Descendants(binder.Name).FirstOrDefault();
      if (firstDescendant != null)
      {
          if (value.GetType() == typeof(XElement))
          {
              firstDescendant.ReplaceWith(value);
          }
          else
          {
              firstDescendant.Value = value.ToString();
          }
          success = true;
      }
```

```
        return success;
    }
  }
```

The key dynamic implementation methods for this use case are `TryGetMember()` and `TrySetMember()` (assuming you want to assign the elements as well). Only these two method implementations are necessary to support the invocation of the dynamic getter and setter properties. Furthermore, the implementations are straightforward. First, they examine the contained `XElement`, looking for an element with the same name as the `binder.Name`—the name of the member invoked. If a corresponding XML element exists, the value is retrieved (or set). The return value is set to `true` if the element exists and `false` if it doesn't. A return value of `false` will immediately cause the runtime to throw a `Microsoft.CSharp.RuntimeBinder.RuntimeBinderException` at the call site of the dynamic member invocation.

`System.Dynamic.DynamicObject` supports additional virtual methods if more dynamic invocations are required. Listing 17.34 produces a list of all overridable members.

4.0

LISTING 17.34: Overridable Members on `System.Dynamic.DynamicObject`

```
using System.Dynamic;

public class DynamicObject : IDynamicMetaObjectProvider
{
  protected DynamicObject();

  public virtual IEnumerable<string> GetDynamicMemberNames();
  public virtual DynamicMetaObject GetMetaObject(
      Expression parameter);
  public virtual bool TryBinaryOperation(
      BinaryOperationBinder binder, object arg,
          out object result);
  public virtual bool TryConvert(
      ConvertBinder binder, out object result);
  public virtual bool TryCreateInstance(
      CreateInstanceBinder binder, object[] args,
           out object result);
  public virtual bool TryDeleteIndex(
      DeleteIndexBinder binder, object[] indexes);
  public virtual bool TryDeleteMember(
      DeleteMemberBinder binder);
  public virtual bool TryGetIndex(
      GetIndexBinder binder, object[] indexes,
           out object result);
```

```
    public virtual bool TryGetMember(
        GetMemberBinder binder, out object result);
    public virtual bool TryInvoke(
        InvokeBinder binder, object[] args, out object result);
    public virtual bool TryInvokeMember(
        InvokeMemberBinder binder, object[] args,
              out object result);
    public virtual bool TrySetIndex(
        SetIndexBinder binder, object[] indexes, object value);
    public virtual bool TrySetMember(
        SetMemberBinder binder, object value);
    public virtual bool TryUnaryOperation(
        UnaryOperationBinder binder, out object result);
}
```

As Listing 17.34 shows, there are member implementations for everything—from casts and various operations, to index invocations. In addition, there is a method for retrieving all the possible member names: `GetDynamicMemberNames()`.

End 4.0

SUMMARY

This chapter discussed how to use reflection to read the metadata that is compiled into the CIL. Using reflection, it is possible to provide a late binding in which the code to call is defined at execution time rather than at compile time. Although reflection is entirely feasible for deploying a dynamic system, it executes considerably more slowly than statically linked (compile-time), defined code. This tends to make it more prevalent and useful in development tools when performance is potentially not as critical.

Reflection also enables the retrieval of additional metadata decorating various constructs in the form of attributes. Typically, custom attributes are sought using reflection. You can define your own custom attributes that insert additional metadata of your own choosing into the CIL. At runtime, you can then retrieve this metadata and use it within the programming logic.

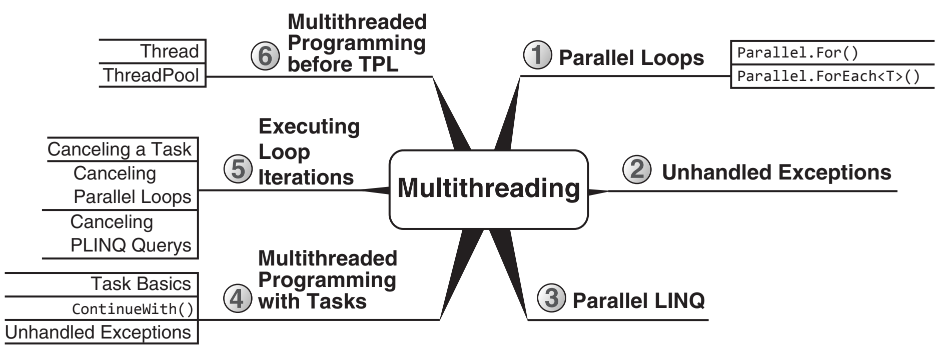
Many programmers view attributes as a precursor to a concept known as aspect-oriented programming, in which you add functionality through constructs such as attributes instead of manually implementing the functionality wherever it is needed. It will take some time before you see true aspects within C# (if ever); however, attributes provide a clear steppingstone in that direction, without creating a significant risk to the stability of the language.

Finally, this chapter included a feature introduced in C# 4.0—dynamic programming using the new type `dynamic`. This coverage included a discussion of why static binding, although preferred when the API is strongly typed, has limitations when working with dynamic data.

The next chapter looks at multithreading, where attributes are used for synchronization.

18
Multithreading

TWO SIGNIFICANT TRENDS OF THE past decade have had an enormous effect on the field of software development. First, the continued decrease in the cost of performing computations is no longer driven by increases in clock speed and transistor density, as illustrated by Figure 18.1. Rather, the cost of computation is now falling because it is economical to make hardware that has multiple CPUs.



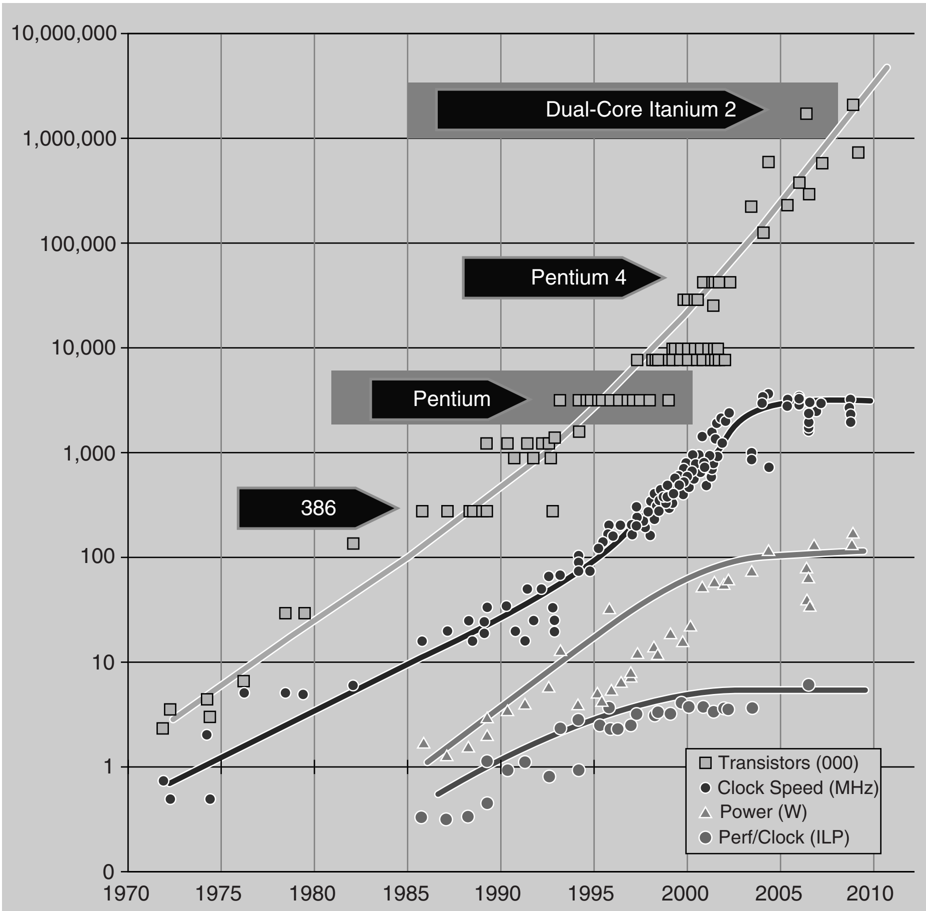


FIGURE 18.1: Clock Speeds over Time
(Graph compiled by Herb Sutter. Used with permission. Original at www.gotw.ca.)

Second, computations now routinely involve enormous **latency.** Latency is, simply put, the amount of time required to obtain a desired result. There are two principal causes of latency. **Processor-bound latency** occurs when the computational task is complex; if a computation requires performing 12 billion arithmetic operations and the total processing power available is only 6 billion operations per second, at least 2 seconds of processor-bound latency will be incurred between asking for the result and obtaining it. **I/O-bound latency,** by contrast, is latency incurred by the need to obtain data from an external source such as a disk drive, web server, and so on. Any computation that requires fetching data from a web server physically located far from the client machine will incur latency equivalent to millions of processor cycles.

These two trends together create an enormous challenge for modern software developers. Given that machines have more computing power than ever, how are we to make effective use of that power to deliver results to the user quickly, and without compromising on the user experience? How do we avoid creating frustrating user interfaces that freeze up when a high-latency operation is triggered? Moreover, how do we go about splitting CPU-bound work among multiple processors to decrease the time required for the computation?

The standard technique for engineering software that keeps the user interface responsive and CPU utilization high is to write **multithreaded** programs that do multiple computations "in parallel." Unfortunately, multithreading logic is notoriously difficult to get right; we'll spend the next two chapters exploring what makes multithreading difficult, and learning how to use higher-level abstractions and new language features to ease that burden.

The higher-level abstractions we'll discuss are, first, the two principal components of the Parallel Extensions library that was released with .NET 4.0[1]—the **Task Parallel Library (TPL)** and **Parallel LINQ (PLINQ)**—and second, the **Task-based Asynchronous Pattern (TAP)** and its accompanying language support in C# 5.0. Although we strongly encourage you to use these higher-level abstractions, we will also cover some of the lower-level threading APIs from previous versions of the .NET runtime in this chapter. Additional multithreading patterns prior to C# 5.0 are available for download at http://IntelliTect.com/EssentialCSharp along with the chapters from Essential C# 3.0. Thus, if you want to fully understand the resources from multithreaded programming without the later features, you still have access to that material.

We'll start this chapter with a few beginner topics in case you are new to multithreading. Then we'll briefly discuss "traditional" thread manipulation without using the Parallel Extensions libraries to ensure that you have a basic understanding of thread manipulation; the following chapter goes into more details on that topic. We'll then spend most of this chapter covering the TPL, TAP, and PLINQ, in that order.

---

1. These libraries are available in .NET 3.5 by downloading the Reactive Extensions library for .NET 3.5, but this is not officially supported.

Multithreading Basics

BEGINNER TOPIC

Multithreading Jargon

There is a lot of confusing jargon associated with multithreading, so let's define a few terms.

A **CPU** (central processing unit) or **core**[2] is the unit of hardware that actually executes a given program. Every machine has at least one CPU, though today multiple CPU machines are common. Many modern CPUs support **simultaneous multithreading** (which Intel trademarks as **Hyper-Threading**), a mode where a single CPU can appear as multiple "virtual" CPUs.

A **process** is a currently executing instance of a given program; the fundamental purpose of the operating system is to manage processes. Each process contains one or more threads. A process is represented by an instance of the `Process` class in the `System.Diagnostics` namespace.

C# programming at the level of statements and expressions is fundamentally about describing **flow of control,** and thus far in this book we've made the implicit assumption that a given program has only a single "point of control." You can imagine the point of control as being a cursor that enters the text of your program at the `Main` method when you start it up, and then moves around the program as the various conditions, loops, method calls, and so on, are executed. A **thread** is this point of control. A thread is represented by an instance of the `System.Threading.Thread` class and the API for manipulating a `Thread` is in the same `System.Threading` namespace.

A **single-threaded** program is one in which there is only one thread in the process. A **multithreaded** program has two or more threads in the process.

A piece of code is said to be **thread safe** if it behaves correctly when used in a multithreaded program. The **threading model** of a piece of code is the set of requirements that the code places upon its caller in exchange for guaranteeing thread safety. (For example, the threading model of many classes

---

2. Technically we ought to say that "CPU" always refers to the physical chip and "core" may refer to a physical or virtual CPU. This distinction is unimportant for the purposes of this book, so we will use these terms interchangeably.

is “static methods may be called from any thread but instance methods may be called only from the thread that allocated the instance.”)

A **task** is a unit of potentially high-latency work that produces a resultant value or desired side effect. The distinction between tasks and threads is as follows: A task represents a job that needs to be performed, whereas a thread represents the worker that does the job. A task is useful only for its side effects and is represented by an instance of the `Task` class. A task used to produce a value of a given type is represented by the `Task<T>` class, which derives from the nongeneric `Task` type. These can be found in the `System.Threading.Tasks` namespace.

A **thread pool** is a collection of threads, along with logic for determining how to assign work to those threads. When your program has a task to perform, it can delegate a worker thread from the pool, assign the thread to perform the task, and then de-allocate it when the work completes, thereby making it available the next time additional work is requested.

BEGINNER TOPIC

The Why and How of Multithreading

There are two principal scenarios for multithreading: enabling multitasking and dealing with latency.

Users think nothing of running dozens of processes at the same time. They might have presentations and spreadsheets open for editing while at the same time they are browsing documents on the Internet, listening to music, receiving instant messages and email arrival notifications, and watching the little clock in the corner. Each of these processes has to continue to do its job even though it is not the only task the machine has to attend to. This kind of multitasking is usually implemented at the process level, but there are situations in which you want to do this sort of multitasking within a single process.

For the purposes of this book, however, we will mostly be considering multithreading as a technique for dealing with latency. For example, to import a large file while simultaneously allowing a user to click Cancel, a developer creates an additional thread to perform the import. By performing the import on a different thread, the user can request cancellation instead of freezing the user interface until the import completes.

If enough cores are available that each thread can be assigned a core, each thread essentially gets its own little machine. However, more often than not there are more threads than cores. Even the relatively common multicore machines of today still have only a handful of cores, while each process could quite possibly run dozens of threads.

To overcome the discrepancy between the numerous threads and the handful of cores, an operating system simulates multiple threads running concurrently by **time slicing.** The operating system switches execution from one thread to the next so quickly that it appears the threads are executing simultaneously. The period of time that the processor executes a particular thread before switching to another is the **time slice** or **quantum.** The act of changing which thread is executing in a given core is called a **context switch.**

The effect is similar to that of a fiber-optic telephone line in which the fiber-optic line represents the processor and each conversation represents a thread. A (single-mode) fiber-optic telephone line can send only one signal at a time, but many people can hold simultaneous conversations over the line. The fiber-optic channel is fast enough to switch between conversations so quickly that each conversation appears uninterrupted. Similarly, each thread of a multithreaded process appears to run continuously with other threads.

If two operations are running "in parallel," via either true multicore parallelism or simulated parallelism using time slicing, they are said to be **concurrent.** To implement such concurrency, you invoke it **asynchronously,** such that both the execution and the completion of the invoked operation are separate from the control flow that invoked it. Concurrency, therefore, occurs when work dispatched asynchronously executes in parallel with the current control flow. **Parallel programming** is the act of taking a single problem and splitting it into pieces, whereby you **asynchronously** initiate the process of each piece such that the pieces can all be processed concurrently.

BEGINNER TOPIC

Performance Considerations

A thread that is servicing an I/O bound operation can essentially be ignored by the operating system until the result is available from the I/O subsystem; switching away from an I/O bound thread to a processor-bound thread results in more efficient processor utilization because the CPU is not idle while waiting for the I/O operation to complete.

However, context switching is not free; the current internal state of the CPU must be saved to memory, and the state associated with the new thread must be loaded. If there are too many threads, the switching overhead can begin to noticeably affect performance. Adding more threads will likely decrease performance further, to the point where the processor spends more time switching from one thread to another than it does accomplishing the work of each thread.

Even if we ignore the cost of context switching, time slicing itself can have a huge impact on performance. Suppose, for example, that you have two processor-bound high-latency tasks, each working out the average of two lists of 1 billion numbers each. Suppose the processor can perform 1 billion operations per second. If the two tasks are each associated with a thread, and the two threads each have their own core, obviously we can get both results in 1 second.

If, however, we have a single processor that the two threads share, time slicing will perform a few hundred thousand operations on one thread, then switch to the other thread, then switch back, and so on. Each task will consume a total of 1 second of processor time, and the results of both will therefore be available after 2 seconds, leading to an average completion time of 2 seconds. (Again, we are ignoring the cost of context switching.)

If we assigned those two tasks to a single thread that performed the first task and did not even start the second until after the first was completed, the result of the first task would be obtained in 1 second and the result of the subsequent task would be obtained 1 second after that, leading to an average time of 1.5 seconds (a task completes in either 1 or 2 seconds and, therefore, on average completes in 1.5 seconds).

Guidelines

DO NOT fall into the common error of believing that more threads always makes code faster.

DO carefully measure performance when attempting to speed up processor-bound problems through multithreading.

BEGINNER TOPIC

Threading Problems

We've said several times that writing multithreaded programs is complex and difficult, but we have not said why. In a nutshell, the problem is that many of our reasonable assumptions that are true of single-threaded programs are violated in multithreaded programs. The issues include a lack of atomicity, race conditions, complex memory models, and deadlocks.

Most Operations Are Not Atomic

An atomic operation is one that always is observed to be either not started or already completed. Its state is never externally visible as "in progress." Consider, for example, this code fragment:

```
if (bankAccounts.Checking.Balance >= 1000.00m)
{
  bankAccounts.Checking.Balance -= 1000.00m;
  bankAccounts.Savings.Balance += 1000.00m;
}
```

This operation—checking for available funds, and then conditionally debiting one account and crediting another—needs to be atomic. In other words, for it to execute correctly, we must ensure that there is never a moment when the operation can be observed to be partially completed. Imagine, for example, that two threads are running in this code concurrently. It is possible that both threads verify that there are sufficient funds in the account, and then both threads do a transfer of funds, even if there are only sufficient funds in the account to do the transfer once. And, in fact, the situation is considerably worse: There are no operations in this code fragment that are atomic! Even operations like compound addition/subtraction or reading and writing a property of decimal type are nonatomic operations in C#. As such, they can all be observed to be "partially complete" in multithreaded scenarios—only partially incremented or decremented. The observation of inconsistent state due to partially completed nonatomic operations is a special case of a more general problem, called a race condition.

Uncertainty Caused by Race Conditions

As we discussed earlier, concurrency is often simulated by time slicing. In the absence of special control flow structures (which we will discuss in the next chapter in detail), the operating system can switch contexts between any two threads at any time of its choosing. As a consequence, when two threads are accessing the same object, which thread "wins the race" and gets to run first is unpredictable. If there are two threads running in the code fragment given previously, for example, it is possible that one thread might win the race and get all the way to the end before the second thread gets a chance to run. It is also possible that the context switch might happen after the first thread does the balance check, and the second thread might then win the race to get all the way to the end first.

The behavior of code that contains race conditions depends on the timing of context switches. This dependency introduces uncertainty concerning program execution. The order in which one instruction will execute relative to an instruction in a different thread is unknown. The worst of it is that often code containing race conditions will behave correctly 99.9 percent of the time, and then one time in a thousand a different thread wins the race due to an accident of timing. This unpredictability is what makes multithreaded programming so difficult.

Because such race conditions are difficult to replicate in the laboratory, much of the quality assurance of multithreaded code depends on long-running stress tests, specially designed code analysis tools, and a significant investment in code analysis and code review by experts.

The following chapter is about techniques for dealing with race conditions.

Memory Models Are Complex

The existence of race conditions, where two points of control can "race" through a piece of code at unpredictable and inconsistent speeds, is bad enough, but it gets worse. Consider two threads that are running on two different processors, but are accessing the same fields of some object. Modern processors do not actually access main memory every time you use a variable. Rather, they make a local copy in special "cache" memory on the processor; these caches are then periodically synchronized with main memory. This means that two threads that read and write the same location on two different processors can, in fact, be failing to observe each other's updates to that memory, or observing inconsistent results. Essentially what we have here is a race condition that depends on when processors choose to synchronize their caches.

Locking Leads to Deadlocks

Clearly there must exist mechanisms to make nonatomic operations into atomic operations, to instruct the operating system to schedule threads so as to avoid races, and to ensure that processor caches are synchronized when necessary. The primary mechanism used to solve all these problems in C# programs is the `lock` statement. This statement allows the developer to identify a section of code as "critical" code that only one thread may be in at one time; if multiple threads try to enter the critical section, the operating system will suspend all but one. The operating system also ensures that processor caches are synchronized properly upon encountering a lock.

However, locks introduce problems of their own. Most notably, if the order of lock acquisition between threads varies, a **deadlock** could occur such that threads freeze, each waiting for the other to release its lock.

For example:

Time	Thread A	Thread B
↓	Acquires a lock on a	Acquires a lock on b
↓	Requests a lock on b	Requests a lock on a
↓	Deadlocks, waiting for b	Deadlocks, waiting for a

At this point, each thread is waiting on the other thread before proceeding, so each thread is blocked, leading to an overall deadlock in the execution of that code.

We discuss various locking techniques in detail in Chapter 19.

Guidelines

DO NOT make an unwarranted assumption that any operation that is atomic in regular code will be atomic in multithreaded code.

DO NOT assume that all threads will observe all side effects of operations on shared memory in a consistent order.

DO ensure that code that concurrently holds multiple locks always acquires them in the same order.

AVOID all "race conditions"—that is, conditions where program behavior depends on how the operating system chooses to schedule threads.

Working with `System.Threading`

The Parallel Extensions library is extraordinarily useful because it allows you to manipulate a higher-level abstraction, the task, rather than working directly with threads. However, you might need to work with code written before the TPL and PLINQ were available (prior to .NET 4.0), or you might have a programming problem not directly addressed by them. In this section, we briefly cover some of the basic underlying APIs for directly manipulating threads.

Asynchronous Operations with `System.Threading.Thread`

The operating system implements threads and provides various unmanaged APIs to create and manage those threads. The CLR wraps these unmanaged threads and exposes them in managed code via the `System.Threading.Thread` class, an instance of which represents a "point of control" in the program. As mentioned earlier, you can think of a thread as a "worker" that independently follows the instructions that make up your program.

Listing 18.1 provides an example. The independent point of control is represented by an instance of `Thread` that runs concurrently. A thread needs to know which code to run when it starts up, so its constructor takes a delegate that refers to the code that is to be executed. In this case we convert a method group, `DoWork`, to the appropriate delegate type, `ThreadStart`. We then start the thread running by calling `Start()`. While the new thread is running, the main thread attempts to print 10,000 hyphens to the console. We instruct the main thread to then wait for the worker thread to complete its work by calling `Join()`. The result is shown in Output 18.1.

Listing 18.1: Starting a Method Using `System.Threading.Thread`

```
using System;
using System.Threading;

public class RunningASeparateThread
{
  public const int Repetitions = 1000;

  public static void Main()
  {
      ThreadStart threadStart = DoWork;
      Thread thread = new Thread(threadStart);
      thread.Start();
      for(int count = 0; count < Repetitions; count++)
      {
```

```
            Console.Write('-');
        }
        thread.Join();
    }

    public static void DoWork()
    {
        for(int count = 0; count < Repetitions; count++)
        {
            Console.Write('+');
        }
    }
}
```

Output 18.1

```
++++++++++++++++++++++++++++++++------------------------------------------------
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
--------------------------------------------------------------------------++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++---------------------------------------------------
--------------------------------------------------------------------------------
--------------------------------------------------------------------------------
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++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
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-------------------------------------------------------+++++++++++++++++++++++++
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
+++++++++++++++++++++++++++++++++++++++++++++
```

As you can see, the threads appear to be taking turns executing, each printing out a few hundred characters before the context switches. The two loops are running "in parallel," rather than the first one running to completion before the second one begins, as it would if the delegate had been executed synchronously.

For code to run under the context of a different thread, you need a delegate of type `ThreadStart` or `ParameterizedThreadStart` to identify the code to execute. (The latter allows for a single parameter of type `object`; both are found in the `System.Threading` namespace.) Given a `Thread` instance created using the thread-start delegate constructor, you can start the thread executing with a call to `thread.Start()`. (Listing 18.1 creates a variable of type `ThreadStart` explicitly to show the delegate type in the source code. The method group `DoWork` could have been passed directly to the thread constructor.) The call to `Thread.Start()` tells the operating system to begin concurrent execution of the new thread; control on the main thread immediately returns from the call and executes the `for` loop in the `Main()` method. The threads are now independent, and neither waits for the other until the call to `Join()`.

Thread Management

Threads include a number of methods and properties for managing their execution. Here are some of the basic ones:

- As we saw in Listing 18.1, you can cause one thread to wait for another with `Join()`. This tells the operating system to suspend execution of the current thread until the other thread is terminated. The `Join()` method is overloaded to take either an `int` or a `TimeSpan` to support a maximum time to wait for thread completion before continuing execution.
- By default, a new thread is a "foreground" thread; the operating system will terminate a process when all its foreground threads are complete. You can mark a thread as a "background" thread by setting the `IsBackground` property to `true`. The operating system will then allow the process to be terminated even if the background thread is still running. However, it is still a good idea to ensure that all threads are not aborted and instead to exit cleanly before the process exits; see the section on thread aborting later in this chapter for more details.
- Every thread has an associated priority, which you can change by setting the `Priority` property to a new `ThreadPriority` enum value. The possible values are `Lowest`, `BelowNormal`, `Normal`, `AboveNormal`, and `Highest`. The operating system prefers to schedule time slices to higher-priority threads. Be careful; if you set the priorities incorrectly, you can end up with "starvation" situations where one high-priority thread prevents many low-priority threads from ever running.

- If you simply want to know whether a thread is still "alive" or has finished all of its work, you can use the Boolean `IsAlive` property. A more informative picture of a thread's state is accessible through the `ThreadState` property. The `ThreadState` enum values are `Aborted`, `AbortRequested`, `Background`, `Running`, `Stopped`, `StopRequested`, `Suspended`, `SuspendRequested`, `Unstarted`, and `WaitSleepJoin`. These are flags; some of these values can be combined.

There are two commonly used, and commonly abused, methods for controlling threads that deserve to be discussed in their own sections: `Sleep()` and `Abort()`.

Do Not Put Threads to Sleep in Production Code

The static `Thread.Sleep()` method puts the current thread to sleep, essentially telling the operating system to not schedule any time slices to this thread until the given amount of time has passed. A single parameter—either a number of milliseconds or a `TimeSpan`—specifies how long the operating system will wait before continuing execution. While it is waiting, the operating system will, of course, schedule time slices for any other threads that might be waiting their turn to execute. This might sound like a sensible thing to do, but it is a "bad code smell" that indicates the design of the program could probably be better.

Threads are often put to sleep to try to synchronize a thread with some event in time. However, the operating system does not guarantee any level of precision in its timing. That is, if you say, "Put me to sleep for 123 milliseconds," the operating system will put the thread to sleep for *at least* 123 milliseconds, and possibly much longer. The actual amount of time between the thread going to sleep and then waking up again is not deterministic and can be arbitrarily long. Do not attempt to use `Thread.Sleep()` as a high-precision timer, because it is not.

Worse, `Thread.Sleep()` is often used as a "poor man's synchronization system." That is, if you have some unit of asynchronous work, and the current thread cannot proceed until that work is done, you might be tempted to put the thread to sleep for much longer than you think the asynchronous work will take, in the hopes that it will be finished when the current thread wakes up. This is a bad idea: Asynchronous work, by its very nature, can take longer than you think. Use proper thread synchronization mechanisms, described in the next chapter, to synchronize threads. (We'll give an example of this sort of abuse in Listing 18.2.)

Putting a thread to sleep is also a bad programming practice because it means that the sleeping thread is, obviously, unresponsive to attempts to run code on it. If you put the main thread of a Windows application to sleep, that thread will no longer be processing messages from the user interface, and will therefore appear to be hung.

More generally, putting a thread to sleep is a bad programming practice because the whole point of allocating an expensive resource like a thread is to get work out of that resource. You wouldn't pay an employee to sleep, so do not pay the price of allocating an expensive thread only to put it to sleep for millions or billions of processor cycles.

That said, there are some valid uses of `Thread.Sleep()`. First, putting a thread to sleep with a time delay of zero tells the operating system "the current thread is politely giving up the rest of its quantum to another thread if there is one that can use it." The polite thread will then be scheduled normally, without any further delay. Second, `Thread.Sleep()` is commonly used in test code to simulate a thread that is working on some high-latency operation without actually having to burn a processor doing some pointless arithmetic. Other uses in production code should be reviewed carefully to ensure that there is not a better way to obtain the desired effect.

In task-based asynchronous programming in C# 5, you can use the `await` operator on the result of the `Task.Delay()` method to introduce an asynchronous delay without blocking the current thread. See the "Timers" section in Chapter 19 for further detail.

Guidelines

AVOID calling `Thread.Sleep()` in production code.

Do Not Abort Threads in Production Code

The `Thread` object has an `Abort()` method that, when executed, attempts to destroy the thread. It does so by causing the runtime to throw a `ThreadAbortException` in the thread; this exception can be caught, but even if it is caught and ignored, it is automatically rethrown to try to ensure that the thread is, in fact, destroyed. There are many reasons why it is a very bad idea to attempt to abort a thread. Here are some of them:

- The method promises only to *try* to abort the thread; there is no guarantee that it will succeed. For example, the runtime will not attempt to cause a `ThreadAbortException` if the point of control of the thread is currently inside a finally block (because critical cleanup code could be running right now and should not be interrupted) or is in unmanaged code (because doing so could corrupt the CLR itself). Rather, the CLR defers throwing the exception until control leaves the finally block or returns to managed code. But there is no guarantee that this ever happens. The thread being aborted might contain an infinite loop inside a finally block. (Ironically, the fact that the thread has an infinite loop might be the reason you are attempting to abort it in the first place.)
- The aborted thread might be in critical code protected by a `lock` statement. (See Chapter 19 for details.) Unlike a finally block, a `lock` will not prevent the exception. The critical code will be interrupted halfway through by the exception, and the `lock` object will be automatically released, allowing other code that is waiting on the `lock` object to enter the critical section and observe the state of the halfway-executed code. The whole point of locking is to prevent that scenario, so aborting a thread can transform what looks like thread-safe code into dangerously incorrect code.
- The CLR guarantees that its internal data structures will never be corrupted if a thread is aborted, but the BCL does not make this guarantee. Aborting a thread can leave any of your data structures or the BCL's data structures in an arbitrarily bad state if the exception is thrown at the wrong time. Code running on other threads, or in the finally blocks of the aborted thread, can see this corrupted state and crash or behave badly.

In short, you should never abort a thread unless you are doing so as a last resort; ideally you should abort a thread only as part of a larger emergency shutdown whereby the entire AppDomain or the entire process is being destroyed. Fortunately, task-based asynchrony uses a more robust and safe cooperative cancellation pattern to terminate a "thread" whose results are no longer needed, as discussed in the next major section, "Asynchronous Tasks."

Guidelines

AVOID aborting a thread in production code; doing so will yield unpredictable results and can destabilize a program.

Thread Pooling

As we discussed earlier, in the Beginner Topic titled "Performance Considerations," it is possible for an excess of threads to negatively impact performance. Threads are expensive resources, thread context switching is not free, and running two jobs in simulated parallelism via time slicing can be hugely slower than running them one after the other.

To mitigate these problems, the BCL provides a thread pool. Instead of allocating threads directly, you can tell the thread pool which work you want to perform. When the work is finished, rather than the thread terminating and being destroyed, it is returned to the pool, saving on the cost of allocating a new thread when more work comes along. Listing 18.2 shows how to do the same thing as Listing 18.1, but this time with a pooled thread.

Listing 18.2: Using ThreadPool Instead of Instantiating Threads Explicitly

```
using System;
using System.Threading;

public class Program
{
  public const int Repetitions = 1000;
  public static void Main()
  {
      ThreadPool.QueueUserWorkItem(DoWork, '+');

      for(int count = 0; count < Repetitions; count++)
      {
          Console.Write('-');
      }

      // Pause until the thread completes.
      // This is for illustrative purposes; do not
      // use Thread.Sleep for synchronization in
      // production code.
      Thread.Sleep(1000);
  }
  public static void DoWork(object state)
  {
      for(int count = 0; count < Repetitions; count++)
```

```
            {
                Console.Write(state);
            }
        }
    }
```

The output of Listing 18.2 is similar to Output 18.1—that is, an intermingling of periods and hyphens. If we had a lot of different jobs to perform asynchronously, this pooling technique would provide more efficient execution on single-processor and multiprocessor computers. The efficiency is achieved by reusing threads over and over, rather than reconstructing them for every asynchronous call. Unfortunately, thread pool use is not without its pitfalls: There are still performance and synchronization problems to consider when using a thread pool.

To make efficient use of processors, the thread pool assumes that all the work you schedule on the thread pool will finish in a timely manner so that the thread can be returned to the thread pool and reused by another task. The thread pool also assumes that all the work will be of a relatively short duration (that is, consuming milliseconds or seconds of processor time, not hours or days). By making this assumption, it can ensure that each processor is working full out on a task, and not inefficiently time-slicing multiple tasks, as described in the Beginner Topic on performance. The thread pool attempts to prevent excessive time slicing by ensuring that thread creation is "throttled" so that no one processor is "oversubscribed" with too many threads. Of course, that then means that consuming all threads within the pool can delay execution of queued-up work. If all the threads in the pool are consumed by long-running or I/O bound work, the queued-up work will be delayed.

Unlike `Thread` and `Task`, which are objects that you can manipulate directly, the thread pool does not provide a reference to the thread used to execute a given piece of work. This prevents the calling thread from synchronizing with, or controlling, the worker thread via the thread management functions described earlier in the chapter. In Listing 18.2 we use the "poor man's synchronization" that we earlier discouraged; this would be a bad idea in production code because we do not actually know how long the work will take to complete.

In short, the thread pool does its job well, but that job does not include providing services to deal with long-running jobs or jobs that need to be synchronized with the main thread or with one another. What we really need to do is build a higher-level abstraction that can use threads and thread pools as an implementation detail; that abstraction is implemented by the Task Parallel Library, which is the topic of most of the rest of this chapter.

For more details on other techniques for managing worker threads that were commonly used prior to .NET 4, see the Essential C# 3.0 multithreading chapters at IntelliTect.com/EssentialCSharp.

Guidelines

DO use the thread pool to efficiently assign processor time to processor-bound tasks.

AVOID allocating a pooled worker thread to a task that is I/O bound or long-running; use TPL instead.

Asynchronous Tasks

Begin 4.0

Multithreaded programming includes the following complexities:

1. *Monitoring an asynchronous operation state for completion:* This includes determining when an asynchronous operation has completed, preferably not by polling the thread's state or by blocking and waiting.
2. *Thread pooling:* This avoids the significant cost of starting and tearing down threads. In addition, thread pooling avoids the creation of too many threads, such that the system spends more time switching threads than running them.
3. *Avoiding deadlocks:* This involves preventing the occurrence of deadlocks while attempting to protect the data from simultaneous access by two different threads.
4. *Providing atomicity across operations and synchronizing data access:* Adding synchronization around groups of operations ensures that operations execute as a single unit and that they are appropriately interrupted by another thread. Locking is provided so that two different threads do not access the data simultaneously.

Furthermore, anytime a method is long-running, multithreaded programming will probably be required—that is, invoking the long-running method asynchronously. As developers write more multithreaded code, a common set of scenarios and programming patterns for handling those scenarios emerges.

C# 5.0 enhanced the programmability of one such pattern—TAP—by leveraging the TPL from .NET 4.0 and enhancing the C# language with new constructs to support it. This and the following section delve into the details of the TPL on its own and then the TPL with the `async`/`await` contextual keywords that simplify TAP programming. In the second half of Chapter 19, we consider several additional multithreading patterns that are important to be familiar with if the TPL and C# 5.0 are not available or you are programming against a non–TPL-based API.

From Thread to Task

4.0

Creating a thread is a relatively expensive operation, and each thread consumes a large amount (1 megabyte, by default) of virtual memory. We saw earlier in this chapter that it is potentially more efficient to use a thread pool to allocate threads when needed, assign asynchronous work to the thread, run the work to completion, and then reuse the thread for subsequent asynchronous work, rather than destroying the thread when the work is complete and creating a new one later.

In .NET Framework 4, instead of creating an operating system thread each time asynchronous work is started, the TPL creates a `Task` and tells the **task scheduler** that there is asynchronous work to perform. A task scheduler might use many different strategies to fulfill this purpose, but by default it requests a worker thread from the thread pool. The thread pool, as we've seen already, might decide that it is more efficient to run the task later, after some currently executing tasks have completed, or might decide to schedule the task's worker thread to a particular processor. The thread pool determines whether it is more efficient to create an entirely new thread or to reuse an existing thread that previously finished executing.

By abstracting the concept of asynchronous work into the `Task` object, the TPL provides an object that represents asynchronous work and provides an object-oriented API for interacting with that work. Moreover, by providing an object that represents the unit of work, the TPL enables programmatically building up workflows by composing small tasks into larger ones, as we'll see.

A task is an object that encapsulates work that executes asynchronously. This should sound familiar: A delegate is also an object that represents code. The difference between a task and a delegate is that delegates are **synchronous** and tasks are **asynchronous.** Executing a delegate, say, an `Action`, immediately transfers the point of control of the current thread to the delegate's code; control does not return to the caller until the delegate is finished. By contrast, starting a task almost immediately returns control to the caller, no matter how much work the task has to perform. The task executes asynchronously, typically on another thread (though, as we will see later in this chapter, it is possible and even beneficial to execute tasks asynchronously with only one thread). A task essentially transforms a delegate from a synchronous to an asynchronous execution pattern.

Introducing Asynchronous Tasks

You know when a delegate is done executing on the current thread because the caller cannot do anything until the delegate is done. But how do you know when a task is done, and how do you get the result, if there is one? Consider the example of turning a synchronous delegate into an asynchronous task. We'll do the same thing we did with threads in Listing 18.1 and thread pools in Listing 18.2, but this time with tasks: The worker thread will write periods to the console, while the main thread writes hyphens. 4.0

Starting the task obtains a new thread from the thread pool, creating a second "point of control," and executes the delegate on that thread. The point of control on the main thread continues normally after the call to start the task (`Task.Run()`). The results of Listing 18.3 are almost identical to Output 18.1.

LISTING 18.3: Invoking an Asynchronous Task

```
using System;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      const int Repetitions = 10000;
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task task = Task.Run(() =>
          {
              for(int count = 0;
                  count < Repetitions; count++)
              {
                  Console.Write('-');
```

```
                }
            });
        for(int count = 0; count < Repetitions; count++)
        {
            Console.Write('+');
        }

        // Wait until the Task completes
        task.Wait();
    }
}
```

The code that is to run in a new thread is defined in the delegate (of type `Action` in this case) passed to the `Task.Run()` method. This delegate (in the form of a lambda expression) prints out dashes to the console repeatedly. The loop that follows the starting of the task is almost identical, except that it displays plus signs.

Notice that following the call to `Task.Run()` the `Action` passed as the argument immediately starts executing. The `Task` is said to be "hot," meaning that it has already been triggered to start executing—as opposed to a "cold" task, which needs to be explicitly started before the asynchronous work begins.

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Although a `Task` can also be instantiated in a "cold" state via the `Task` constructor, doing so is generally appropriate only as an implementation detail internal to an API that returns an already running ("hot") `Task`, one triggered by a call to `Task.Start()`.

Notice that the exact state of a "hot" task is indeterminate immediately following the call to `Run()`. The state is instead determined by the operating system and whether it chooses to run the task's worker thread immediately or delay it until additional resources are available. In fact, it is possible that the hot task is already finished by the time the code on the calling thread gets its turn to execute again. The call to `Wait()` forces the main thread to wait until all the work assigned to the task has completed executing. This is analogous to calling `Join()` on the worker thread, as we did in Listing 18.1.

In this scenario we have a single task, but it is also possible for many tasks to be running asynchronously. It is common to have a set of tasks where you want to wait for all of them to complete, or for any one of them to complete, before continuing execution of the current thread. The `Task.WaitAll()` and `Task.WaitAny()` methods do so.

So far, we've seen how a task can take an `Action` and run it asynchronously. But what if the work executed in the task returns a result? We can use the `Task<T>` type to run a `Func<T>` asynchronously. When executing a delegate synchronously, we know that control will not return until the result is available. When executing a `Task<T>` asynchronously, we can poll it from one thread to see if it is done, and fetch the result when it is.[3] Listing 18.4 demonstrates how to do so in a console application. Note that this sample uses a `PiCalculator.Calculate()` method that we will delve into further in the section "Executing Loop Iterations in Parallel."

LISTING 18.4: Polling a `Task<T>`

```
using System;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task<string> task =
          Task.Run<string>(
              () => PiCalculator.Calculate(100));

      foreach(
          char busySymbol in Utility.BusySymbols())
      {
          if(task.IsCompleted)
          {
              Console.Write('\b');
              break;
          }
          Console.Write(busySymbol);
      }

      Console.WriteLine();

      Console.WriteLine(task.Result);
      System.Diagnostics.Trace.Assert(
          task.IsCompleted);
  }
}
```

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3. Exercise caution when using this polling technique. When creating a task from a delegate, as we have here, the task will be scheduled to run on a worker thread from the thread pool. As a consequence, the current thread will loop until the work is complete on the worker thread. This technique works, but it might consume CPU resources unnecessarily. Such a polling technique is dangerously broken if, instead of scheduling the task to run on a worker thread, you schedule the task to execute in the future on the current thread. Since the current thread is in a loop polling the task, it will loop forever because the task will not complete until the current thread exits the loop.

```
public class PiCalculator
{
  public static string Calculate(int digits = 100)
  {
      // ...
  }
}
```

```
public class Utility
{
  public static IEnumerable<char> BusySymbols()
  {
      string busySymbols = @"-\|/-\|/";
      int next = 0;
      while(true)
      {
          yield return busySymbols[next];
          next = (next + 1) % busySymbols.Length;
          yield return '\b';
      }
  }
}
```

4.0

This listing shows that the data type of the task is `Task<string>`. The generic type includes a `Result` property from which to retrieve the value returned by the `Func<string>` that the `Task<string>` executes.

Note that Listing 18.4 does not make a call to `Wait()`. Instead, reading from the `Result` property automatically causes the current thread to block until the result is available, if it isn't already; in this case we know that it will already be complete when the result is fetched.

In addition to the `IsCompleted` and `Result` properties on `Task<T>`, there are several others worth noting:

- The `IsCompleted` property is set to `true` when a task completes, whether it completed normally or faulted (that is, ended because it threw an exception). More detailed information on the status of a task can be obtained by reading the `Status` property, which returns a value of type `TaskStatus`. Possible values are `Created`, `WaitingForActivation`, `WaitingToRun`, `Running`, `WaitingForChildrenToComplete`, `RanToCompletion`, `Canceled`, and `Faulted`. `IsCompleted` is `true` whenever the `Status` is `RanToCompletion`, `Canceled`, or `Faulted`. Of course, if the task is running on another thread and you read the status as "Running," the status could change to "Completed" at any time, including immediately after you read the value of the property. The same is true of many other states—even `Created` could potentially change if a different thread starts it. Only `RanToCompletion`, `Canceled`, and `Faulted` can be considered final states that can no longer be transitioned.

- A task can be uniquely identified by the value of the `Id` property. The static `Task.CurrentId` property provides the identifier for the currently executing `Task` (that is, the task that is executing the `Task.CurrentId` call). These properties are especially useful when debugging.
- You can use the `AsyncState` to associate additional data with a task. For example, imagine a `List<T>` whose values will be computed by various tasks. Each task could contain the index of the value in the `AsyncState` property. This way, when the task completes, the code can index into the list using the `AsyncState` (first casting it to an `int`).[4]

There are other useful properties that we will discuss later in this chapter, in the section on task cancellation.

Task Continuation

4.0

We've talked several times about the "control flow" of a program without ever saying what the most fundamental nature of control flow is: **Control flow determines what happens next.** When you have a simple control flow like `Console.WriteLine(x.ToString());`, the control flow tells you that when `ToString` completes normally, the next thing that will happen is a call to `WriteLine` with the value returned as the argument. The concept of "what happens next" is called **continuation;** each point in a control flow has a continuation. In our example, the continuation of `ToString` is `WriteLine` (and the continuation of `WriteLine` is whatever code runs in the next statement). The idea of continuation is so elementary to C# programming that most programmers don't even think about it; it's part of the invisible air that they breathe. The act of C# programming is the act of constructing continuation upon continuation until the control flow of the entire program is complete.

Notice that the continuation of a given piece of code in a normal C# program will be executed immediately upon the completion of that code.

4. Be careful when using tasks to asynchronously mutate collections. The tasks might be running on worker threads, and the collection might not be thread safe. It is safer to fill in the collection from the main thread after the tasks are completed.

When `ToString()` returns, the point of control on the current thread immediately does a synchronous call to `WriteLine`. Notice also that there are actually two possible continuations of a given piece of code: the "normal" continuation and the "exceptional" continuation that will be executed if the current piece of code throws an exception.

Asynchronous method calls, such as starting a `Task`, add an additional dimension to the control flow. With an asynchronous `Task` invocation, the control flow goes immediately to the statement after the `Task.Start()` while at the same time, it begins executing within the body of the `Task` delegate. In other words, "what happens next" when asynchrony is involved is multidimensional. Unlike with exceptions where the continuation is just a different path, with asynchrony continuation is an additional, parallel path.

Asynchronous tasks also allow composition of larger tasks out of smaller tasks by describing asynchronous continuations. Just as with regular control flow, a task can have different continuations to handle error situations, and tasks can be melded together by manipulating their continuations. There are several techniques for doing so, the most explicit of which is the `ContinueWith()` method (see Listing 18.5 and its corresponding output, Output 18.2).

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LISTING 18.5: Calling `Task.ContinueWith()`

```
using System;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      Console.WriteLine("Before");
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task taskA =
          Task.Run( () =>
               Console.WriteLine("Starting..."))
          .ContinueWith(antecedent =>
               Console.WriteLine("Continuing A..."));
      Task taskB = taskA.ContinueWith( antecedent =>
          Console.WriteLine("Continuing B..."));
      Task taskC = taskA.ContinueWith( antecedent =>
          Console.WriteLine("Continuing C..."));
      Task.WaitAll(taskB, taskC);
      Console.WriteLine("Finished!");
  }
}
```

Output 18.2

```
Before
Starting...
Continuing A...
Continuing C...
Continuing B...
Finished!
```

The `ContinueWith()` method enables "chaining" two tasks together, such that when the predecessor task—the **antecedent task**—completes, the second task—the **continuation task**—is automatically started asynchronously. In Listing 18.5, for example, `Console.WriteLine("Starting...")` is the antecedent task body and `Console.WriteLine("Continuing A...")` is its continuation task body. The continuation task takes a `Task` as its argument (`antecedent`), thereby allowing the continuation task's code to access the antecedent task's completion state. When the antecedent task is completed, the continuation task starts automatically, asynchronously executing the second delegate, and passing the just-completed antecedent task as an argument to that delegate. Furthermore, since the `ContinueWith()` method returns a `Task` as well, that `Task` can be used as the antecedent of yet another `Task`, and so on, forming a continuation chain of `Tasks` that can be arbitrarily long.

If you call `ContinueWith()` twice on the same antecedent task (as Listing 18.5 shows with `taskB` and `taskC` representing continuation tasks for `taskA`), the antecedent task (`taskA`) has two continuation tasks and when the antecedent task completes, both continuation tasks will be executed asynchronously. Notice that the order of execution of the continuation tasks from a single antecedent is indeterminate at compile time. Output 18.2 happens to show `taskC` executing before `taskB`, but in a second execution of the program, the order might be reversed. However, `taskA` will always execute before `taskB` and `taskC` because the latter are continuation tasks of `taskA` and, therefore, can't start before `taskA` completes. Similarly, the `Console.WriteLine("Starting...")` delegate will always execute to completion before `taskA` (`Console.WriteLine("Continuing A...")`) because the latter is a continuation task of the former. Furthermore, "Finished!" will always appear last because of the call to `Task.WaitAll(taskB, taskC)` that blocks the control flow from continuing until both `taskB` and `taskC` complete.

Many different overloads of `ContinueWith()` are possible, and some of them take a `TaskContinuationOptions` value to tweak the behavior of the continuation chain. These values are flags, so they can be combined using the logical OR operator (|). A brief description of some of the possible flag values appears in Table 18.1; see the online MSDN documentation[5] for more details.

Table 18.1: List of Available `TaskContinuationOptions` Enums

Enum	Description
`None`	This is the default behavior. The continuation task will be executed when the antecedent task completes, regardless of its task status.
`PreferFairness`	If two tasks were both asynchronously started, one before the other, there is no guarantee that the one that was started first actually gets to run first. This flag asks the task scheduler to try to increase the likelihood that the first task started is the first task to execute—something that is particularly relevant when the two tasks you describe are created from different thread pool threads.
`LongRunning`	This tells the task scheduler that the task is likely to be an I/O-bound high-latency task. The scheduler can then allow other queued work to be processed rather than starved because of the long-running task. This option should be used sparingly.
`AttachedToParent`	This specifies that a task should attempt to attach to a parent task within the task hierarchy.
`DenyChildAttach` (.NET 4.5)	This throws an exception if creation of a child task is attempted. If code within the continuation tries to use `AttachedToParent`, it will behave as if there was no parent.
`NotOnRanToCompletion*`	This specifies that the continuation task should not be scheduled if its antecedent ran to completion. This option is not valid for multitask continuations.
`NotOnFaulted*`	This specifies that the continuation task should not be scheduled if its antecedent threw an unhandled exception. This option is not valid for multitask continuations.
`OnlyOnCanceled*`	This specifies that the continuation task should be scheduled only if its antecedent was canceled. This option is not valid for multitask continuations.

4.0

5. MSDN.NET Framework Developer Center, http://msdn.microsoft.com/en-us/library/system.threading.tasks.taskcontinuationoptions(v=vs.110).aspx.

Table 18.1: List of Available **TaskContinuationOptions** Enums (*continued*)

Enum	Description
`NotOnCanceled*`	This specifies that the continuation task should not be scheduled if its antecedent was canceled. This option is not valid for multitask continuations.
`OnlyOnFaulted*`	This specifies that the continuation task should be scheduled only if its antecedent threw an unhandled exception. This option is not valid for multitask continuations.
`OnlyOnRanToCompletion*`	This specifies that the continuation task should be scheduled only if its antecedent ran to completion. This option is not valid for multitask continuations.
`ExecuteSynchronously`	This specifies that the continuation task should be executed synchronously. With this option specified, the continuation the schedule will attempt to execute the work on is the same thread that causes the antecedent task to transition into its final state. If the antecedent is already complete when the continuation is created, the continuation will run on the thread creating the continuation.
`HideScheduler` (.NET 4.5)	This prevents the ambient scheduler from being seen as the current scheduler in the created task. This means that operations like `Run`/`StartNew` and `ContinueWith` that are performed in the created task will see `TaskScheduler.Default` (`null`) as the current scheduler. This is useful when continuation should run on a particular scheduler, but the continuation is calling out to additional code that should not schedule work on the same scheduler.
`LazyCancellation` (.NET 4.5)	This causes the continuation to delay monitoring the supplied cancellation token for a cancellation request until the antecedent has completed. Consider tasks t1, t2, and t3 where the latter is a continuation of the former. If t2 is canceled before t1 completes, it is possible that t3 could start before t1 completes. Setting `LazyCancellation` avoids this.
`RunContinuationAsynchronously` (.NET 4.6)	This specifies that the continuation task should be run asynchronously. This option has precedence over `TaskContinuationOptions.ExecuteSynchronously`.

4.0

The items denoted with a star (*) indicate under which conditions the continuation task will be executed; thus they are particularly useful for creating continuations that act like event handlers for the antecedent task's behavior. Listing 18.6 demonstrates how an antecedent task can be given multiple continuations that execute conditionally, depending on how the antecedent task completed.

LISTING 18.6: Registering for Notifications of Task Behavior with `ContinueWith()`

```
using System;
using System.Threading.Tasks;
using System.Diagnostics;
using AddisonWesley.Michaelis.EssentialCSharp.Shared;

public class Program
{
  public static void Main()
  {
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task<string> task =
          Task.Run<string>(
              () => PiCalculator.Calculate(10));

      Task faultedTask = task.ContinueWith(
          (antecedentTask) =>
          {
              Trace.Assert(antecedentTask.IsFaulted);
              Console.WriteLine(
                  "Task State: Faulted");
          },
          TaskContinuationOptions.OnlyOnFaulted);

      Task canceledTask = task.ContinueWith(
          (antecedentTask) =>
          {
              Trace.Assert(antecedentTask.IsCanceled);
              Console.WriteLine(
                  "Task State: Canceled");
          },
          TaskContinuationOptions.OnlyOnCanceled);

      Task completedTask = task.ContinueWith(
          (antecedentTask) =>
          {
              Trace.Assert(antecedentTask.IsCompleted);
              Console.WriteLine(
                  "Task State: Completed");
          },  TaskContinuationOptions.
                  OnlyOnRanToCompletion);
```

4.0

```
        completedTask.Wait();
    }
}
```

In this listing, we effectively register “listeners” for “events” on the antecedent’s task so that when the task completes normally or abnormally, the particular “listening” task will begin executing. This is a powerful capability, particularly if the original task is a “fire and forget” task—that is, a task that we start, hook up to continuation tasks, and then never refer to again.

In Listing 18.6, notice that the final `Wait()` call is on `completedTask`, not on `task`—the original antecedent task created with `Task.Run()`. Although each delegate’s `antecedentTask` is a reference to the parent (antecedent) task (`task`), from outside the delegate listeners we can effectively discard the reference to the original `task`. We can then rely solely on the continuation tasks that begin executing asynchronously without any need for follow-up code that checks the status of the original `task`.

In this case, we call `completedTask.Wait()` so that the main thread does not exit the program before the completed output appears (see Output 18.3).

4.0

Output 18.3

```
Task State: Completed.
```

In this case, invoking `completedTask.Wait()` is somewhat contrived because we know that the original task will complete successfully. However, invoking `Wait()` on `canceledTask` or `faultedTask` will result in an exception. Those continuation tasks run only if the antecedent task is canceled or throws an exception; given that will not happen in this program, those tasks will never be scheduled to run, and waiting for them to complete would throw an exception. The continuation options in Listing 18.3 happen to be mutually exclusive, so when the antecedent task runs to completion and the task associated with `completedTask` executes, the task scheduler automatically cancels the tasks associated with `canceledTask` and `faultedTask`. The canceled tasks end with their state set to `Canceled`. Therefore, calling `Wait()` (or any other invocation that would cause the current thread to wait for a task completion) on either of these tasks will throw an exception indicating that they are canceled.

A less contrived approach might be to call `Task.WaitAny(completedTask, canceledTask, faultedTask)`, which will throw an `AggregateException` that then needs to be handled.

Unhandled Exception Handling on Task with AggregateException

When calling a method synchronously, we can wrap it in a try block with a catch clause to identify to the compiler which code we want to execute when an exception occurs. This does not work with an asynchronous call, however. We cannot simply wrap a try block around a call to `Start()`to catch an exception, because control immediately returns from the call, and control will then leave the try block, possibly long before the exception occurs on the worker thread. One solution is to wrap the body of the task delegate with a try/catch block. Exceptions thrown on and subsequently caught by the worker thread will consequently not present problems, as a try block will work normally on the worker thread. This is not the case, however, for unhandled exceptions—those that the worker thread does not catch.

4.0 Generally (starting with version 2.0[6] of the CLR), unhandled exceptions on any thread are treated as fatal, trigger the Windows Error Reporting dialog, and cause the application to terminate abnormally. All exceptions on all threads must be caught, and if they are not, the application is not allowed to continue to run. (For some advanced techniques for dealing with unhandled exceptions, see the upcoming Advanced Topic titled "Dealing with Unhandled Exceptions on a `Thread`.") Fortunately, this is not the case, however, for unhandled exceptions in an asynchronously running task. Rather, the task scheduler inserts a "catchall" exception handler around the delegate so that if the task throws an otherwise unhandled exception, the catchall handler will catch it and record the details of the exception in the task, avoiding any trigger of the CLR automatically terminating the process.

As we saw in Listing 18.6, one technique for dealing with a faulted task is to explicitly create a continuation task that is the "fault handler" for that

---

6. In version 1.0 of the CLR, an unhandled exception on a worker thread terminated the thread but not the application. As a result, it was possible for a buggy program to have all its worker threads die, but the main thread would continue to run, even though the program was no longer doing any work. This is a confusing situation for users to be in; it is better to signal to the user that the application is in a bad state and terminate it before it can do any more harm.

it detects that the antecedent task threw an unhandled exception. If no such handler is present, however, and `Wait()` (or an attempt to get the `Result`) executes on a faulted task, an `AggregateException` will be thrown (see Listing 18.7 and Output 18.4).

LISTING 18.7: Handling a Task's Unhandled Exception

```
using System;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task task = Task.Run(() =>
      {
          throw new InvalidOperationException();
      });

      try
      {
          task.Wait();
      }
      catch(AggregateException exception)
      {
          exception.Handle(eachException =>
            {
                Console.WriteLine(
                    $"ERROR: { eachException.Message }");
                return true;
            });
      }
  }
}
```

4.0

OUTPUT 18.4

```
ERROR: Operation is not valid due to the current state of the object.
```

The aggregate exception is so-called because it may contain many exceptions collected from one or more faulted tasks. Imagine, for example, asynchronously executing ten tasks in parallel and five of them throwing exceptions. To report all five exceptions and have them handled in a single catch block, the framework uses the `AggregateException` as a means of collecting the exceptions and reporting them as a single exception. Furthermore, since it is unknown at compile time whether a worker task will throw one or more exceptions, an unhandled faulted task will always throw an `AggregateException`. Listing 18.7 and Output 18.4 demonstrate this behavior. Even though the unhandled exception thrown on the worker thread was of type `InvalidOperationException`, the type of the exception caught on the main thread is still an `AggregateException`. Also, as expected, to catch the exception requires an `AggregateException` catch block.

A list of the exceptions contained within an `AggregateException` is available from the `InnerExceptions` property. As a result, you can iterate over this property to examine each exception and determine the appropriate course of action. Alternatively, and as shown in Listing 18.7, you can use the `AggregateException.Handle()` method, specifying an expression to execute against each individual exception contained within the `AggregateException`. One important characteristic of the `Handle()` method to consider, however, is that it is a predicate. As such, the predicate should return `true` for any exceptions that the `Handle()` delegate successfully addresses. If any exception handling invocation returns `false` for an exception, the `Handle()` method will throw a new `AggregateException` that contains the composite list of such corresponding exceptions.

4.0

You can also observe the state of a faulted task without causing the exception to be rethrown on the current thread by simply looking at the `Exception` property of the task. Listing 18.8 demonstrates this approach by waiting for the completion of a fault continuation of a task[7] that we know will throw an exception.

LISTING 18.8: Observing Unhandled Exceptions on a Task Using `ContinueWith()`

```
using System;
using System.Diagnostics;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      bool parentTaskFaulted = false;
```

7. As we discussed earlier, waiting for a fault continuation to complete is a strange thing to do because most of the time it will never be scheduled to run in the first place. This code is provided for illustrative purposes only.

```
        Task task = new Task(() =>
            {
                throw new InvalidOperationException();
            });
        Task continuationTask = task.ContinueWith(
            (antecedentTask) =>
            {
                parentTaskFaulted =
                    antecedentTask.IsFaulted;
            }, TaskContinuationOptions.OnlyOnFaulted);
        task.Start();
        continuationTask.Wait();
        Trace.Assert(parentTaskFaulted);
        Trace.Assert(task.IsFaulted);
        task.Exception.Handle(eachException =>
        {
            Console.WriteLine(
                $"ERROR: { eachException.Message }");
            return true;
        });
    }
}
```

Notice that to retrieve the unhandled exception on the original task, we use the `Exception` property. The result is output identical to Output 18.4.

4.0

If an exception that occurs within a task goes entirely unobserved—that is, (1) it isn't caught from within the task; (2) the completion of the task is never observed, via `Wait()`, `Result`, or accessing the `Exception` property, for example; and (3) the faulted `ContinueWith()` is never observed—then the exception is likely to go unhandled entirely, resulting in a process-wide unhandled exception. In .NET 4.0, such a faulted task would get rethrown by the finalizer thread and likely crash the process. In contrast, in .NET 4.5, the crashing has been suppressed (although the CLR can be configured for the crashing behavior if preferred).

In either case, you can register for an unhandled task exception via the `TaskScheduler.UnobservedTaskException` event.

ADVANCED TOPIC

Dealing with Unhandled Exceptions on a Thread

As we discussed earlier, an unhandled exception on any thread by default causes the application to shut down. An unhandled exception is a fatal, unexpected bug, and the exception may have occurred because a crucial data structure is corrupt. You therefore have no idea what the program could possibly be doing, so the safest thing to do is to shut down the whole thing immediately.

Ideally, no programs would ever throw unhandled exceptions on any thread; programs that do so have bugs, and the best course of action is to find and fix the bug before the software is shipped to customers. However, rather than shutting down an application as soon as possible when an unhandled exception occurs, it is often desirable to save any working data and/or log the exception for error reporting and future debugging. This requires a mechanism to register notifications of unhandled exceptions.

Every AppDomain provides such a mechanism, and to observe the unhandled exceptions that occur in an AppDomain, you must add a handler to the `UnhandledException` event. The `UnhandledException` event will fire for all unhandled exceptions on threads within the application domain, whether it is the main thread or a worker thread. Note that the purpose of this mechanism is notification; it does not permit the application to recover from the unhandled exception and continue executing. After the event handlers run, the application will display the Window Error Reporting dialog and then the application will exit. (For console applications, the exception details will also appear on the console.)

4.0

In Listing 18.9, we show how to create a second thread that throws an exception, which is then handled by the application domain's unhandled exception event handler. For demonstration purposes, to ensure that thread timing issues do not come into play, we insert some artificial delays using `Thread.Sleep`. Output 18.5 shows the results.

LISTING 18.9: Registering for Unhandled Exceptions

```
using System;
using System.Diagnostics;
using System.Threading;

public class Program
{
  public static Stopwatch clock = new Stopwatch();
  public static void Main()
  {
    try
    {
      clock.Start();
      // Register a callback to receive notifications
      // of any unhandled exception.
```

```
        AppDomain.CurrentDomain.UnhandledException +=
          (s, e) =>
            {
              Message("Event handler starting");
              Delay(4000);
            };

        Thread thread = new Thread(() =>
        {
          Message("Throwing exception.");
          throw new Exception();
        });
        thread.Start();

        Delay(2000);
      }
      finally
      {
        Message("Finally block running.");
      }
    }

    static void Delay(int i)
    {
      Message($"Sleeping for {i} ms");
      Thread.Sleep(i);
      Message("Awake");
    }

    static void Message(string text)
    {
      Console.WriteLine("{0}:{1:0000}:{2}",
        Thread.CurrentThread.ManagedThreadId,
        clock.ElapsedMilliseconds, text);
    }
  }
```

Output 18.5

```
3:0047:Throwing exception.
3:0052:Unhandled exception handler starting.
3:0055:Sleeping for 4000 ms
1:0058:Sleeping for 2000 ms
1:2059:Awake
1:2060:Finally block running.
3:4059:Awake
Unhandled Exception: System.Exception: Exception of type 'System.
Exception' was thrown.
```

As you can see in Output 18.5, the new thread is assigned thread ID 3 and the main thread is assigned thread ID 1. The operating system schedules thread 3 to run for a while; it throws an unhandled exception, the event handler is invoked, and it goes to sleep. Soon thereafter, the operating system realizes that thread 1 can be scheduled, but its code immediately puts it to sleep. Thread 1 wakes up first and runs the finally block, and then 2 seconds later thread 3 wakes up, and the unhandled exception finally crashes the process.

This sequence of events—the event handler executing, and the process crashing after it is finished—is typical, but not guaranteed. The moment there is an unhandled exception in your program, all bets are off; the program is now in an unknown and potentially very unstable state, so its behavior can be unpredictable. In this case, as you can see, the CLR allows the main thread to continue running and executes its finally block, even though it knows by the time that control gets to the finally block, another thread is in the AppDomain's unhanded exception event handler.

To emphasize this fact, try changing the delays so that the main thread sleeps longer than the event handler. In that scenario, the finally block will never execute! The process will be destroyed by the unhandled exception before thread 1 wakes up. You can also get different results depending on
4.0
whether the exception-throwing thread is or is not created by the thread pool. The best practice, therefore, is to avoid all possible unhandled exceptions, whether they occur in worker threads or in the main thread.

How does this pertain to tasks? What if there are unfinished tasks hanging around the system when you want to shut it down? We'll look at task cancellation in the next section.

Guidelines

AVOID writing programs that produce unhandled exceptions on any thread.

CONSIDER registering an unhandled exception event handler for debugging, logging, and emergency shutdown purposes.

DO cancel unfinished tasks, rather than allowing them to run during application shutdown.

Canceling a Task

Earlier in this chapter, we described why it's a bad idea to rudely abort a thread so as to cancel a task being performed by that thread. The TPL uses **cooperative cancellation,** a far more polite, robust, and reliable technique for safely canceling a task that is no longer needed. A task that supports cancellation monitors a `CancellationToken` object (found in the `System.Threading` namespace) by periodically polling it to see if a cancellation request has been issued. Listing 18.10 demonstrates both the cancellation request and the response to the request. Output 18.6 shows the results.

LISTING 18.10: Canceling a Task Using `CancellationToken`

```
using System;
using System.Threading;
using System.Threading.Tasks;
using AddisonWesley.Michaelis.EssentialCSharp.Shared;

public class Program
{
  public static void Main()
  {
      string stars =
          "*".PadRight(Console.WindowWidth-1, '*');
      Console.WriteLine("Push ENTER to exit.");

      CancellationTokenSource cancellationTokenSource=
          new CancellationTokenSource();
      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task task = Task.Run(
          () =>
              WritePi(cancellationTokenSource.Token),
                  cancellationTokenSource.Token);

      // Wait for the user's input
      Console.ReadLine();

      cancellationTokenSource.Cancel();
      Console.WriteLine(stars);
      task.Wait();
      Console.WriteLine();
  }

  private static void WritePi(
      CancellationToken cancellationToken)
  {
      const int batchSize = 1;
      string piSection = string.Empty;
      int i = 0;

      while(!cancellationToken.IsCancellationRequested
          || i == int.MaxValue)
```

4.0

```
        {
            piSection = PiCalculator.Calculate(
                batchSize, (i++) * batchSize);
            Console.Write(piSection);
        }
    }
}
```

Output 18.6

```
Push ENTER to exit.
3.141592653589793238462643383279502884197169399375105820974944592307816
40628620899862803482534211706798214808651328230664709384460955058223172
53594081284811174 50
***********************************************************************
2
```

After starting the task, a `Console.Read()` blocks the main thread. At the same time, the task continues to execute, calculating the next digit of pi and printing it out. Once the user presses Enter, the execution encounters a call to `CancellationTokenSource.Cancel()`. In Listing 18.10, we split the call to `task.Cancel()` from the call to `task.Wait()` and print out a line of asterisks in between. The purpose of this step is to show that quite possibly an additional iteration will occur before the cancellation token is observed—hence the additional `2` in Output 18.6 following the stars. The `2` appears because the `CancellationTokenSource.Cancel()` doesn't rudely stop the task from executing. The task keeps on running until it checks the token, and politely shuts down when it sees that the owner of the token is requesting cancellation of the task.

4.0

The `Cancel()` call effectively sets the `IsCancellationRequested` property on all cancellation tokens copied from `CancellationTokenSource.Token`. There are a few things to note, however:

- A `CancellationToken`, not a `CancellationTokenSource`, is given to the asynchronous task. A `CancellationToken` enables polling for a cancellation request; the `CancellationTokenSource` provides the token and signals it when it is canceled (see Figure 18.2). By passing the `CancellationToken` rather than the `CancellationTokenSource`, we don't have to worry about thread synchronization issues on the `CancellationTokenSource` because the latter remains accessible to only the original thread.

- A `CancellationToken` is a struct, so it is copied by value. The value returned by `CancellationTokenSource.Token` produces a copy of the token. For this reason `CancellationToken` is thread safe—it is available only from within the `WritePi()` method.

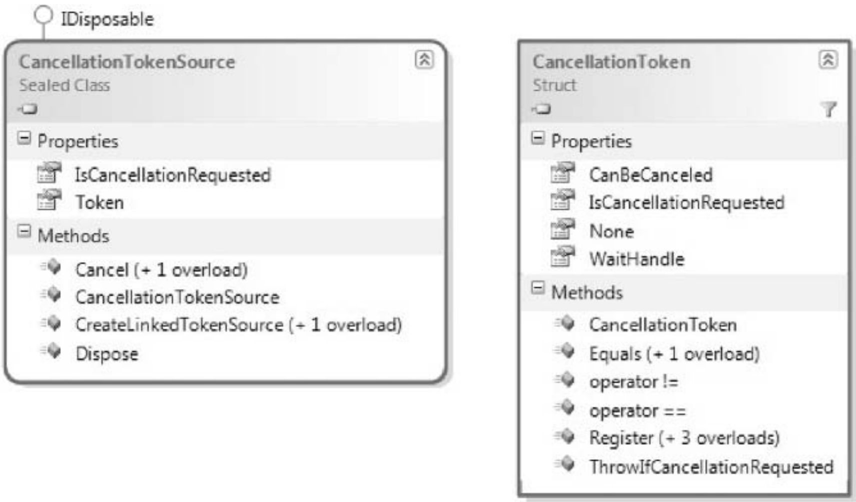

FIGURE 18.2: **`CancellationTokenSource`** and **`CancellationToken`** Class Diagrams

To monitor the `IsCancellationRequested` property, a copy of the `CancellationToken` (retrieved from `CancellationTokenSource.Token`) is passed to the task. In Listing 18.9, we then occasionally check the `IsCancellationRequested` property on the `CancellationToken` parameter; in this case, we check after each digit calculation. If `IsCancellationRequested` returns `true`, the `while` loop exits. Unlike a thread abort, which would throw an exception at essentially a random point, we exit the loop using normal control flow. We guarantee that the code is responsive to cancellation requests by polling frequently.

One other point to note about the `CancellationToken` is the overloaded `Register()` method. Via this method, you can register an action that will be invoked whenever the token is canceled. In other words, calling the `Register()` method subscribes to a listener delegate on the corresponding `CancellationTokenSource`'s `Cancel()`.

Given that canceling before completing is the expected behavior in this program, the code in Listing 18.9 does not throw a `System.Threading`

.Tasks.TaskCanceledException. As a consequence, task.Status will return TaskStatus.RanToCompletion—providing no indication that the work of the task was, in fact, canceled. In this example, there is no need for such an indication; however, the TPL does include the capability to do this. If the cancel call were disruptive in some way—preventing a valid result from returning, for example—throwing a TaskCanceledException (which derives from System.OperationCanceledException) would be the TPL pattern for reporting it. Instead of throwing the exception explicitly, CancellationToken includes a ThrowIfCancellationRequested() method to report the exception more easily, assuming an instance of CancellationToken is available.

If you attempt to call Wait() (or obtain the Result) on a task that threw TaskCanceledException, the behavior is the same as if any other exception had been thrown in the task: The call will throw an AggregateException. The exception is a means of communicating that the state of execution following the task is potentially incomplete. Unlike a successfully completed task in which all expected work executed successfully, a canceled task potentially has partially completed work—the state of the work is untrusted.

4.0

This example demonstrates how a long-running processor-bound operation (calculating pi almost indefinitely) can monitor for a cancellation request and respond if one occurs. There are some cases, however, when cancellation can occur without explicitly coding for it within the target task. For example, the Parallel class discussed later in the chapter offers such a behavior by default.

Begin 5.0

Task.Run(): A Shortcut and Simplification to Task.Factory.StartNew()

In .NET 4.0, the general practice for obtaining a task was to call Task.Factory.StartNew(). In .NET 4.5, a simpler calling structure was provided in Task.Run(). Like Task.Run(), Task.Factory.StartNew() could be used in C# 4.0 scenarios to invoke CPU-intensive methods that require an additional thread to be created.

Given .NET 4.5, Task.Run() should be used by default unless it proves insufficient. For example, if you need to control the task with TaskCreationOptions, if you need to specify an alternative scheduler, or if, for performance reasons, you want to pass in object state, you should consider using Task.Factory.StartNew(). Only in rare cases, where you need to separate creation from scheduling, should constructor instantiation followed by a call to `Start()` be considered.

Listing 18.11 provides an example of using `Task.Factory.StartNew()`.

Listing 18.11: Using Task.Factory.StartNew()

```
public Task<string> CalculatePiAsync(int digits)
{
  return Task.Factory.StartNew<string>(
      () => CalculatePi(digits));
}

private string CalculatePi(int digits)
{
    // ...
}
```

End 5.0

Long-Running Tasks

As we discussed earlier in the commentary on Listing 18.2, the thread pool assumes that work items will be processor-bound and relatively short-lived; it makes these assumptions to effectively throttle the number of threads created. This prevents both overallocation of expensive thread resources and oversubscription of processors that would lead to excessive context switching and time slicing.

4.0

But what if the developer knows that a task will be long-running and, therefore, will hold on to an underlying thread resource for a long time? In this case, the developer can notify the scheduler that the task is unlikely to complete its work anytime soon. This has two effects. First, it hints to the scheduler that perhaps a dedicated thread ought to be created specifically for this task, rather than attempting to use a thread from the thread pool. Second, it hints to the scheduler that perhaps this would be a good time to allow more tasks to be scheduled than there are processors to handle them. This will cause more time slicing to happen, which is a good thing. We do not want one long-running task to hog an entire processor and prevent shorter-running tasks from using it. The short-running tasks will be able to use their time slice to finish a large percentage of their work, and the long-running task is unlikely to notice the relatively slight delays caused by sharing a processor with other tasks. To accomplish this, use the `TaskCreationOptions.LongRunning` option when calling

StartNew(), as shown in Listing 18.12. (Task.Run() does not support a TaskCreationOptions parameter.)

Listing 18.12: Cooperatively Executing Long-Running Tasks

```
using System.Threading.Tasks;

// ...

      Task task = Task.Factory.StartNew(
          () =>
              WritePi(cancellationTokenSource.Token),
                  TaskCreationOptions.LongRunning);
// ...
```

Guidelines

DO inform the task factory that a newly created task is likely to be long-running so that it can manage it appropriately.

DO use TaskCreationOptions.LongRunning sparingly.

4.0

Tasks Are Disposable

Note that Task also supports IDisposable. This is necessary because Task may allocate a WaitHandle when waiting for it to complete; since WaitHandle supports IDisposable, Task also supports IDisposable in accordance with best practices. However, readers will note that the preceding code samples do not include a Dispose() call, nor do they rely on such a call implicitly via the using statement. The listings instead rely on an automatic WaitHandle finalizer invocation when the program exits.

This approach leads to two notable results. First, the handles live longer and hence consume more resources than they ought to. Second, the garbage collector is slightly less efficient because finalized objects survive into the next generation. However, both of these concerns are inconsequential in the Task case unless an extraordinarily large number of tasks are being finalized. Therefore, even though technically speaking all code should be disposing of tasks, you needn't bother to do so unless performance metrics require it and it's easy—that is, if you're certain that Tasks have completed and no other code is using them.

The Task-Based Asynchronous Pattern

As we've seen so far, tasks provide a better abstraction for the manipulation of asynchronous work than threads do. Tasks are automatically scheduled to the right number of threads and large tasks can be composed by chaining together small tasks, just as large programs can be composed from multiple small methods.

However, there are some drawbacks to tasks. The principal difficulty with tasks is that they turn your program logic "inside out." To illustrate this, we first consider a synchronous method that is blocked on an I/O-bound, high-latency operation—a web request. Next, we compare it to an asynchronous version prior to C# 5.0 and the Task-based Asynchronous Pattern (TAP). Lastly, we revise the same example by using C# 5.0 (and higher) and the `async`/`await` contextual keywords.

Synchronously Invoking a High-Latency Operation

In Listing 18.13, the code uses a `WebRequest` to download a web page and display its size. If the operation fails, an exception is thrown.

LISTING 18.13: A Synchronous Web Request

```
using System;
using System.IO;
using System.Net;
using System.Linq;

public class Program
{
  public static void Main(string[] args)
  {
      string url = "http://www.IntelliTect.com";
      if(args.Length > 0)
      {
          url = args[0];
      }

      try
      {
          Console.Write(url);
          WebRequest webRequest =
              WebRequest.Create(url);

          WebResponse response =
              webRequest.GetResponse();

          Console.Write(".....");
```

```
                using(StreamReader reader =
                    new StreamReader(
                        response.GetResponseStream()))
                {
                    string text =
                        reader.ReadToEnd();
                    Console.WriteLine(
                        FormatBytes(text.Length));
                }
            }
            catch(WebException)
            {
                // ...
            }
            catch(IOException )
            {
                // ...
            }
            catch(NotSupportedException )
            {
                // ...
            }
        }

        static public string FormatBytes(long bytes)
        {
            string[] magnitudes =
                new string[] { "GB", "MB", "KB", "Bytes" };
            long max =
                (long)Math.Pow(1024, magnitudes.Length);

            return string.Format("{1:##.##} {0}",
                magnitudes.FirstOrDefault(
                    magnitude =>
                        bytes > (max /= 1024)) ?? "0 Bytes",
                    (decimal)bytes / (decimal)max);
        }
    }
```

4.0

The logic in Listing 18.13 is relatively straightforward—using common C# idioms like try/catch blocks and `return` statements to describe the control flow. Given a `WebRequest`, this code calls `GetResponse()` to download the page. To gain stream access to the page, it calls `GetResponseStream()` and assigns the result to a `StreamReader`. Finally, it reads to the end of the stream with `ReadToEnd()` to determine the size of the page and then print it out to the screen.

The problem with this approach is, of course, that the calling thread is blocked until the I/O operation completes; this is wasting a thread that could be doing useful work while the asynchronous operation executes. For this reason, we cannot, for example, execute any other code, such as code that indicates progress.

Asynchronously Invoking a High-Latency Operation Using the TPL

To address this problem, Listing 18.14 takes a similar approach but instead uses task-based asynchrony with the TPL.

LISTING 18.14: An Asynchronous Web Request

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading.Tasks;
using System.Runtime.ExceptionServices;

public class Program
{
  public static void Main(string[] args)
  {
      string url = "http://www.IntelliTect.com";
      if(args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);

      Task task = WriteWebRequestSizeAsync(url);

      try
      {
          while(!task.Wait(100))
          {
              Console.Write(".");
          }
      }
      catch(AggregateException exception)
      {
          exception = exception.Flatten();
          try
          {
              exception.Handle(innerException =>
              {
                  // Rethrowing rather than using
                  // if condition on the type.
                  ExceptionDispatchInfo.Capture(
                      exception.InnerException)
                      .Throw();
```

4.0

```
                    return true;
                });
            }
            catch(WebException)
            {
                // ...
            }
            catch(IOException )
            {
                // ...
            }
            catch(NotSupportedException )
            {
                // ...
            }
        }
    }


    private static Task WriteWebRequestSizeAsync(
        string url)
    {
        StreamReader reader = null;
        WebRequest webRequest =
             WebRequest.Create(url);

        Task task =
            webRequest.GetResponseAsync()
        .ContinueWith( antecedent =>
        {
            WebResponse response =
               antecedent.Result;

            reader =
                new StreamReader(
                    response.GetResponseStream());
            return reader.ReadToEndAsync();
        })
        .Unwrap()
        .ContinueWith(antecedent =>
        {
            if(reader != null) reader.Dispose();
            string text = antecedent.Result;
            Console.WriteLine(
                FormatBytes(text.Length));
        });

        return task;
    }

    // ...
}
```

4.0

Unlike Listing 18.13, when Listing 18.14 executes, it prints periods to the console while the page is downloading. The result is that instead of simply printing four periods ("....") to the console, Listing 18.14 is able to continuously print periods for as long as it takes to download the file, read it from the stream, and determine its size.

Unfortunately, this asynchrony comes at the cost of complexity. Interspersed throughout the code is TPL-related code that interrupts the flow. Rather than simply following the `WebRequest.GetResponseAsync()` call with steps to retrieve the `StreamReader` and call `ReadToEndAsync()`, the asynchronous version of the code requires `ContinueWith()` statements. The first `ContinueWith()` statement identifies what to execute after the `WebRequest.GetResponseAsync()`. Notice that the `return` statement in the first `ContinueWith()` expression returns `StreamReader.ReadToEndAsync()`, which returns another `Task`.

Without the `Unwrap()` call, therefore, the antecedent in the second `ContinueWith()` statement is a `Task<Task<string>>`, which alone indicates the complexity. As a result, it is necessary to call `Result` twice—once on the `antecedent` directly and a second time on the `Task<string>.Result` property `antecedent.Result` returned, with the latter blocking subsequent execution until the `ReadToEnd()` operation completes. To avoid the `Task<Task<TResult>>` structure, we preface the call to `ContinueWith()` with a call to `Unwrap()`, thereby shedding the outer `Task` and appropriately handling any errors or cancellation requests.

The complexity doesn't stop with `Tasks` and `ContinueWith()`, however: The exception handling adds an entirely new dimension to the complexity. As mentioned earlier, the TPL generally throws an `AggregateException` exception because of the possibility that an asynchronous operation could encounter multiple exceptions. However, because we are calling the `Result` property from within `ContinueWith()` blocks, it is possible that inside the worker thread we might also throw an `AggregateException`.

As you learned earlier in the chapter, there are multiple ways to handle these exceptions:

1. We can add continuation tasks to all `*Async` methods that return a task along with each `ContinueWith()` method call. However, doing so would prevent us from using the fluid API in which the `ContinueWith()` statements are chained together one after the other. Furthermore, this

would force us to deeply embed error-handling logic into the control flow rather than simply relying on exception handling.

2. We can surround each delegate body with a try/catch block so that no exceptions go unhandled from the task. Unfortunately, this approach is less than ideal as well. First, some exceptions (like those triggered when calling `antecedent.Result`) will throw an `AggregateException` from which we will need to unwrap the `InnerException`(s) to handle them individually. Upon unwrapping them, we either rethrow them so as to catch a specific type or conditionally check for the type of the exception separately from any other catch blocks (even catch blocks for the same type). Second, each delegate body will require its own separate try/catch handler, even if some of the exception types between blocks are the same. Third, `Main`'s call to `task.Wait()` could still throw an exception because `WebRequest.GetResponseAsync()` could potentially throw an exception, and there is no way to surround it with a try/catch block. Therefore, there is no way to eliminate the try/catch block in `Main` that surrounds `task.Wait()`.

4.0

3. We can ignore all exception handling from within `WriteWebRequestSizeAsync()` and instead rely solely on the try/catch block that surrounds `Main`'s `task.Wait()`. Given that we know the exception will be an `AggregateException`, we can have a catch for only that exception. Within the catch block, we can handle the exception by calling `Aggregate-Exception.Handle()` and throwing each exception using the `Exception-Dispatch-Info` object so as not to lose the original stack trace. These exceptions are then caught by the expected exception handles and addressed accordingly. Notice, however, that before handling the `Aggregate-Exception`'s `InnerExceptions`, we first call `AggregateException.Flatten()`. This step addresses the issue of an `AggregateException` wrapping inner exceptions that are also of type `AggregateException` (and so on). By calling `Flatten()`, we ensure that all exceptions are moved to the first level and all contained `AggregateExceptions` are removed.

As shown in Listing 18.14, option 3 is probably the preferred approach because it keeps the exception handling outside the control flow for the most part. This doesn't eliminate the error-handling complexity entirely;

rather, it simply minimizes the occasions on which it is interspersed within the regular control flow.

Although the asynchronous version in Listing 18.14 has almost the same logical control flow as the synchronous version in Listing 18.13, both versions attempt to download a resource from a server and, if the download succeeds, the result is returned. (If the download fails, the exception's type is interrogated to determine the right course of action.) However, it is clear that the asynchronous version of Listing 18.14 is significantly more difficult to read, understand, and change than the corresponding synchronous version in Listing 18.13. Unlike the synchronous version, which uses standard control flow statements, the asynchronous version is forced to create multiple lambda expressions to express the continuation logic in the form of delegates.

And this is a fairly simple example! Imagine what the asynchronous code would look like if, for example, the synchronous code contained a loop that retried the operation three times if it failed, if it tried to contact multiple different servers, if it took a collection of resources rather than a single one, or if all of these possible features occurred together. Adding those features to the synchronous version would be straightforward, but it is not at all clear how to do so in the asynchronous version. Rewriting synchronous methods into asynchronous methods by explicitly specifying the continuation of each task gets very complicated very quickly even if the synchronous continuations are what appear to be very simple control flows.

The Task-Based Asynchronous Pattern with `async` and `await`

Fortunately, it turns out that it is actually not too difficult to write a computer program that does these complex code transformations for you. The designers of the C# language realized this need would crop up, and they have added such a capability to the C# 5.0 compiler. Starting with C# 5.0, you can rewrite the synchronous program given earlier into an asynchronous program much more easily using the Task-based Asynchronous Pattern (TAP); the C# compiler then does the tedious work of transforming your method into a series of task continuations. Listing 18.15 shows how to rewrite Listing 18.13 into an asynchronous method without the major structural changes of Listing 18.14.

LISTING 18.15: An Asynchronous Web Request Using the Task-Based Asynchronous Pattern

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading.Tasks;

public class Program
{
  private static async Task WriteWebRequestSizeAsync(
      string url)
  {
      try
      {
          WebRequest webRequest =
              WebRequest.Create(url);
          WebResponse response =
              await webRequest.GetResponseAsync();
          using(StreamReader reader =
              new StreamReader(
                  response.GetResponseStream()))
          {
              string text =
                  await reader.ReadToEndAsync();
              Console.WriteLine(
                  FormatBytes(text.Length));
          }
      }
      catch(WebException)
      {
          // ...
      }
      catch(IOException )
      {
          // ...
      }
      catch(NotSupportedException )
      {
          // ...
      }
  }

  public static void Main(string[] args)
  {
      string url = "http://www.IntelliTect.com";
      if(args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);
```

4.0

```
            Task task = WriteWebRequestSizeAsync(url);

            while(!task.Wait(100))
            {
                Console.Write(".");
            }
        }

        // ...

    }
```

Notice the small differences between Listing 18.13 and Listing 18.15. First, we refactor the body of the web request functionality into a new method (`WriteWebRequestSizeAsync()`) and add the new contextual keyword `async` to the method's declaration. A method decorated with this keyword must return `Task`, `Task<T>`, or `void`. In this case, since there is no data returned by the body of the method but we still want the capability of returning information about the asynchronous activity to the caller, `WriteWebRequestSizeAsync()` returns `Task`. Notice the method name suffix is `Async`; this is not necessary, but it is conventional to mark asynchronous methods this way so as to identify their asynchronous behavior. Finally, everywhere there is an asynchronous equivalent for the synchronous method, we insert the new contextual keyword `await` before invoking the asynchronous version.

4.0

Notice that nothing else changes between Listings 18.13 and 18.15. The asynchronous method versions seemingly still return the same data types as before—despite the fact that each actually returns a `Task<T>`. This is not via some magical implicit cast, either. `GetResponseAsync()` is declared as follows:

```
public virtual Task<WebResponse> GetResponseAsync() { ... }
```

At the call site, we assign the return value to `WebResponse`:

```
WebResponse response = await webRequest.GetResponseAsync()
```

The `async` contextual keyword plays a critical role by signaling to the compiler that it should rewrite the expression into a state machine that represents all the control flow we saw in Listing 18.14 (and more).

Also notice the try/catch logic improvements over Listing 18.14 that appear in Listing 18.15. In Listing 18.15, there is no need to catch an `AggregateException`. The `catch` clause continues to catch the exact type of exception expected, with no unwrapping of the inner exceptions required. Rather, the compiler's rewrite seemingly ensures that the `AggregateException` in the task is processed just as if it was a normal, synchronously thrown exception. In reality, the `AggregateException` (and its internal exception collection) continue to operate as expected only when you await the task, at which point the rewrite pulls the first exception from the collection and throws it. The aim is to make the asynchronous code look as much as possible like the synchronous code.

To better understand the control flow, Table 18.2 shows each task in a separate column along with the execution that occurs on each task.

There are a couple of important misconceptions that the table helps to dismiss:

4.0

- **Misconception #1: A method decorated with the `async` keyword is automatically executed on a worker thread when called.** This is absolutely not true; the method is executed normally, on the calling thread, and if the implementation doesn't await any incomplete awaitable tasks, it will complete synchronously on the same thread. It's the method's implementation that is responsible for starting any asynchronous work. Just using the `async` keyword does not change where the method's code executes. Also, there is nothing unusual about a call to an `async` method from the caller's perspective; it is a method typed as returning a `Task`, it is called normally, and it returns an object of its return type normally.
- **Misconception #2: The `await` keyword causes the current thread to block until the awaited task is completed.** That is also absolutely not true. If you want the current thread to block until the task completes, call the `Wait()` method, as we have already described. In fact, the `Main` thread does so repeatedly while waiting for the other tasks to complete. However, the `while(!task.Wait(100)) { }` call executes concurrently with the other tasks—not synchronously. The `await` keyword evaluates the expression that follows it, which is usually of type `Task` or `Task<T>`, adds a continuation to the resultant task, and then *immediately* returns control to the caller. The creation of the task has started asynchronous work; the `await` keyword means that the developer wishes the caller of this method to continue executing its work on this thread while the asynchronous work is processed. At some point after that asynchronous work is complete, execution will resume at the point of control following the `await` expression.

Table 18.2: Control Flow within Each Task

Description	Main() Thread/	GetResponseAsync() Task	ReadToEndAsync() Task

1. Execution flows normally into `Main` and up through the first `Console.Write(url)` statement.
2. A call is made to `WriteWebRequestSizeAsync()`, so control flows into that method as it would normally.
3. Instructions within `WriteWebRequestSizeAsync()` execute normally (still on the `Main()` thread), including the call to `WebRequest.Create(url)`.
	`string url =`
	`  "http://www.IntelliTect.com";`
	`if(args.Length > 0)`
	`{`
	`  url = args[0];`
	`}`
	
	`Console.Write(url);`
	
	`Task task =`
	`  WriteWebRequestSizeAsync(url);`
	`WebRequest webRequest =`
	`  WebRequest.Create(url);`		

4. The first `await` modifier begins, generating a new `Task` on which the `GetResponseAsync()` can execute. Assuming it didn't execute almost instantaneously, the control flow returns to `Main()` and begins executing the while loop.
5. Once the `GetResponseAsync()` task completes, execution within the same task continues with the implicit assignment of the said task's result to the response variable. Then the `StreamReader` is instantiated from the response.
	`while(!task.Wait(100))`
	`{`
	`  Console.Write(".");`
	`}`
		`WebResponse response =`
		`  await webRequest.GetResponseAsync();`
		`StreamReader reader =`
		`  new StreamReader(`
		`  response.GetResponseStream()));`	

6. Upon the occurrence of another await, another task is created, this time to execute `ReadToEndAsync()`. (All the while, `Main`'s while loop continues executing.)
7. Upon completion of the `ReadToEndAsync()` task, the result is assigned to `text`, whose `Length` is then displayed on the console.
8. Finally, `task.Wait()` returns `true` and the process executes.
			`string text =`
			`  (await reader.ReadToEndAsync());`
			`Console.WriteLine(`
			`  FormatBytes(text.Length));`

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In fact, the principal reasons why the async keyword exists in the first place are twofold. First, it makes it crystal clear to the reader of the code that the method that follows will be automatically rewritten by the compiler. Second, it informs the compiler that usages of the await contextual keyword in the method are to be treated as asynchronous control flow, and not as an ordinary identifier.

Asynchronous Lambdas

Just as a lambda expression converted to a delegate can be used as a concise syntax for declaring a normal method, so C# 5.0 (and later) also allows lambdas containing await expressions to be converted to delegates. To do so, just precede the lambda expression with the async keyword. In Listing 18.16, we rewrite the GetResourceAsync() method from Listing 18.15 from an async method to an async lambda.

LISTING 18.16: An Asynchronous Client-Server Interaction As a Lambda Expression

4.0

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading.Tasks;

public class Program
{

  public static void Main(string[] args)
  {
      string url = "http://www.IntelliTect.com";
      if(args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);

      Func<string, Task> writeWebRequestSizeAsync =
          async (string webRequestUrl) =>
          {
              // Error handling ommitted for
              // elucidation.
              WebRequest webRequest =
                 WebRequest.Create(url);

              WebResponse response =
                  await webRequest.GetResponseAsync();
              using(StreamReader reader =
                  new StreamReader(
```

```
                    response.GetResponseStream()))
                {
                    string text =
                        (await reader.ReadToEndAsync());
                    Console.WriteLine(
                        FormatBytes(text.Length));
                }
            };

        Task task = writeWebRequestSizeAsync(url);

        while (!task.Wait(100))
        {
            Console.Write(".");
        }
    }

    // ...

  }
```

Note that an `async` lambda expression has the exact same restrictions as the named `async` method:

4.0

- An `async` lambda expression must be converted to a delegate whose return type is `void`, `Task`, or `Task<T>`.
- The lambda is rewritten so that `return` statements become signals that the task returned by the lambda has completed with the given result.
- Execution within the lambda expression occurs synchronously until the first `await` on an incomplete awaitable is executed.
- All instructions following the `await` will execute as continuations on the return from the invoked asynchronous method (or, if the awaitable is already complete, will be simply executed synchronously rather than as continuations).
- An `async` lambda expression can be invoked with an `await` (not shown in Listing 18.16).

ADVANCED TOPIC

Implementing a Custom Asynchronous Method

Implementing an asynchronous method by relying on other asynchronous methods (which, in turn, rely on more asynchronous methods) is relatively easy with the await keyword. However, at some point in the call hierarchy it becomes necessary to write a "leaf" asynchronous Task-returning method. Consider, for example, an asynchronous method for running a command-line program with the eventual goal that the output could be accessed. Such a method would be declared as follows:

```
static public Task<Process> RunProcessAsync(string filename)
```

The simplest implementation would, of course, be to rely on Task.Run() again and call both the System.Diagnostics.Process's Start() and WaitForExit() methods. However, creating an additional thread in the current process is unnecessary when the invoked process itself will have its own collection of one or more threads. To implement the RunProcessAsync() method and return to the caller's synchronization context when the invoked process completes, we can rely on a TaskCompletionSource<T> object, as shown in Listing 18.17.

LISTING 18.17: Implementing a Custom Asynchronous Method

4.0

```
using System.Diagnostics;
using System.Threading;
using System.Threading.Tasks;
class Program
{
  static public Task<Process> RunProcessAsync(
      string fileName,
      string arguments = null,
      CancellationToken cancellationToken =
          default(CancellationToken))
  {
      TaskCompletionSource<Process> taskCS =
          new TaskCompletionSource<Process>();

      Process process = new Process()
      {
          StartInfo = new ProcessStartInfo(fileName)
          {
              UseShellExecute = false,
              Arguments = arguments
          },
          EnableRaisingEvents = true
      };

      process.Exited += (sender, localEventArgs) =>
      {
          taskCS.SetResult(process);
      };
```

```
            cancellationToken
                .ThrowIfCancellationRequested();

            process.Start();

            cancellationToken.Register(() =>
            {
                process.CloseMainWindow();
            });

            return taskCS.Task;
        }

      // ...
    }
```

Ignore the highlighting for the moment and instead focus on the pattern of using an event for notification when the process completes. Since `System.Diagnostics.Process` includes a notification upon exit, we register for this notification and use it as a callback from which we can invoke `TaskCompletionSource.SetResult()`. The code in Listing 18.17 follows a fairly common pattern that you can use to create an asynchronous method without having to resort to `Task.Run()`.

4.0

Another important characteristic that an `async` method might require is cancellation. TAP relies on the same methods for cancellation as the TPL does—namely, a `System.Threading.CancellationToken`. Listing 18.17 highlights the code necessary to support cancellation. In this example, we allow for canceling before the process ever starts, as well as an attempt to close the application's main window (if there is one). A more aggressive approach would be to call `Process.Kill()`, but this could potentially cause problems for the program that is executing.

Notice that we don't register for the cancellation event until after the process is started. This avoids any race conditions that might occur if cancellation is triggered before the process actually begins.

One last feature to consider supporting is a progress update. Listing 18.18 is the full version of `RunProcessAsync()` with just such an update.

Listing 18.18: Implementing a Custom Asynchronous Method with Progress Support

```
using System;
using System.Diagnostics;
using System.Threading;
using System.Threading.Tasks;
class Program
```

4.0

```
{
  static public Task<Process> RunProcessAsync(
      string fileName,
      string arguments = null,
      CancellationToken cancellationToken =
          default(CancellationToken),
      IProgress<ProcessProgressEventArgs> progress =
          null,
      object objectState = null)
  {
      TaskCompletionSource<Process> taskCS =
          new TaskCompletionSource<Process>();

      Process process = new Process()
      {
          StartInfo = new ProcessStartInfo(fileName)
          {
              UseShellExecute = false,
              Arguments = arguments,
              RedirectStandardOutput =
                  progress != null
          },
          EnableRaisingEvents = true
      };

      process.Exited += (sender, localEventArgs) =>
      {
          taskCS.SetResult(process);
      };

      if(progress != null)
      {
          process.OutputDataReceived +=
              (sender, localEventArgs) =>
          {
              progress.Report(
                  new ProcessProgressEventArgs(
                      localEventArgs.Data,
                      objectState));
          };
      }

      if(cancellationToken.IsCancellationRequested)
      {
          cancellationToken
              .ThrowIfCancellationRequested();
      }

      process.Start();

      if(progress != null)
      {
          process.BeginOutputReadLine();
      }
```

```
        cancellationToken.Register(() =>
        {
            process.CloseMainWindow();
            cancellationToken
                .ThrowIfCancellationRequested();
        });

        return taskCS.Task;
    }
  // ...
}
```

```
class ProcessProgressEventArgs
{
  // ...
}
```

ADVANCED TOPIC

Awaiting Non-Task<T> Values

4.0

Generally, the expression that follows the `await` keyword is of either type `Task` or type `Task<T>`. In the examples of `await` shown so far in this chapter, the expressions that follow the keyword have all returned `Task<T>`. From a syntax perspective, an `await` operating on type `Task` is essentially the equivalent of an expression that returns `void`. In fact, because the compiler does not even know whether the task has a result, much less which type it is, such an expression is classified in the same way as a call to a `void`-returning method; that is, you can use it only in a statement context. Listing 18.19 shows some `await` expressions used as statement expressions.

LISTING 18.19: An await Expression May Be a Statement Expression

```
async Task<int> DoStuffAsync()
{
  await DoSomethingAsync();
  await DoSomethingElseAsync();
  return await GetAnIntegerAsync() + 1;
}
```

Here we presume that the first methods return a `Task`, rather than a `Task<T>`. Since there is no result value associated with the first two tasks, awaiting them produces no value; thus the expression must appear as a statement. The third task is presumably of type `Task<int>`, and its value can be used in the computation of the value of the task returned by `DoStuffAsync()`.

This Advanced Topic begins with the word Generally—a deliberate injection of incertitude. In fact, the exact rule regarding the return type that `await` requires is more generic than just `Task` or `Task<T>`. Rather, it requires that the type support a `GetAwaiter`. This method produces an object that has certain properties and methods needed by the compiler's rewriting logic. This makes the system extensible by third parties.[8] If you want to design your own non-`Task`-based asynchrony system that uses some other type to represent asynchronous work, however, you can do so and still use the `await` syntax.

Note that it is not possible to make `async` methods return something other than `void`, `Task`, or `Task<T>`, no matter which type is awaited inside the method.

4.0

Wrapping your head around precisely what is happening in an `async` method can be difficult, but it is far less difficult than trying to figure out what asynchronous code written with explicit continuations in lambdas is doing. The key points to remember are as follows:

- When control reaches an `await` keyword, the expression that follows it produces a task.[9] Control then returns to the caller so that it can continue to do work while the task completes asynchronously.
- Some time after the task completes, control resumes at the point following the `await`. If the awaited task produces a result, that result is then obtained. If it faulted, the exception is thrown.
- A `return` statement in an `async` method causes the task associated with the method invocation to become completed; if the `return` statement has a value, the value returned becomes the result of the task.

---

8. This technique of allowing third-party extension by looking for a particular method by its signature is used in two other C# features: LINQ looks for methods like `Select()` and `Where()` by name to implement the `select` and `where` contextual keywords, and the `foreach` loop does not require that the collection implement `IEnumerable`, just that it have an appropriate `GetEnumerator()` method.

9. Technically, it is an awaitable type as described in the Advanced Topic titled "Awaiting Non-`Task<T>` Values."

Task Schedulers and the Synchronization Context

On occasion, this chapter has mentioned the task scheduler and its role in determining how to assign work to threads efficiently. Programmatically, the task scheduler is an instance of the `System.Threading.Tasks.TaskScheduler`. This class, by default, uses the thread pool to schedule tasks appropriately, determining how to safely and efficiently execute them—when to reuse them, dispose them, or create additional ones.

It is possible to create your own task scheduler that makes different choices about how to schedule tasks by deriving a new type from the `TaskScheduler` class. You can obtain a `TaskScheduler` that will schedule a task to the current thread (or, more precisely, to the **synchronization context** associated with the current thread), rather than to a different worker thread, by using the static `FromCurrentSynchronizationContext()` method.[10]

The **synchronization context** under which a task executes and, in turn, the continuation task(s) execute(s), is important because the awaiting task consults the synchronization context (assuming there is one) so that a task can execute efficiently and safely. Listing 18.20 (along with Output 18.7) is similar to Listing 18.5 except that it also prints out the thread ID when it displays the message.

4.0

Listing 18.20: Calling `Task.ContinueWith()`

```
using System;
using System.Threading;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      DisplayStatus("Before");
      Task taskA =
          Task.Run(() =>
               DisplayStatus("Starting..."))
          .ContinueWith( antecedent =>
               DisplayStatus("Continuing A..."));
      Task taskB = taskA.ContinueWith( antecedent =>
          DisplayStatus("Continuing B..."));
      Task taskC = taskA.ContinueWith( antecedent =>
          DisplayStatus("Continuing C..."));
```

10. For an example, see Listing C.8 in *Multithreading Patterns Prior to C# 5.0*, available at IntelliTect.com/EssentialCSharp.

```
        Task.WaitAll(taskB, taskC);
        DisplayStatus("Finished!");
    }

    private static void DisplayStatus(string message)
    {
        string text = string.Format(
                $@"{ Thread.CurrentThread.ManagedThreadId
                    }: { message }");
        Console.WriteLine(text);
    }
}
```

Output 18.7

```
1: Before
3: Starting...
4: Continuing A...
3: Continuing C...
4: Continuing B...
1: Finished!
```

4.0

What is noteworthy about this output is that the thread ID changes sometimes and gets repeated at other times. In this kind of plain console application, the synchronization context (accessible from `SynchronizationContext.Current`) is null—the default synchronization context causes the thread pool to handle thread allocation instead. This explains why the thread ID changes between tasks: Sometimes the thread pool determines that it is more efficient to use a new thread, and sometimes it decides that the best course of action is to reuse an existing thread.

Fortunately, the synchronization context gets set automatically for types of applications where that is critical. For example, if the code creating tasks is running in a thread created by ASP.NET, the thread will have a synchronization context of type `AspNetSynchronizationContext` associated with it. In contrast, if your code is running in a thread created in a Windows UI application (WPF or Windows Forms), the thread will have an instance of `DispatcherSynchronizationContext` associated with it. (For console applications, there is no synchronization context by default.) Since the TPL consults the synchronization context and the synchronization context varies depending on the circumstances of the execution, the TPL is able to schedule continuations executing in contexts that are both efficient and safe.

To modify the code so that the synchronization context is leveraged instead, you must (1) set the synchronization context and (2) use `async/await` so that the synchronization context is consulted.[11]

It is possible to define custom synchronization contexts, and to work with existing synchronization contexts to improve their performance in some specific scenarios. However, describing how to do so is beyond the scope of this text.

async/await with the Windows UI

One place where synchronization is especially important is in the context of UI and Web programming. With the Windows UI, for example, a message pump processes messages such as mouse click and move events. Furthermore, the UI is single-threaded, so that interaction with any UI components (a text box, for example) must always occur from the single UI thread. One of the key advantages of the `async/await` pattern is that it leverages the synchronization context to ensure that continuation work—work that appears after the `await` statement—will always execute on the same synchronization task that invoked the `await` statement. This approach is of significant value because it eliminates the need to explicitly switch back to the UI thread to update a control.

4.0

To better appreciate this benefit, consider the example of a UI event for a button click in WPF, as shown in Listing 18.21.

Listing 18.21: Synchronous High-Latency Invocation in WPF

```
using System;

private void PingButton_Click(
  object sender, RoutedEventArgs e)
{
  StatusLabel.Content = "Pinging…";
  UpdateLayout();
  Ping ping = new Ping();
  PingReply pingReply =
      ping.Send("www.IntelliTect.com");
  StatusLabel.Text = pingReply.Status.ToString();
}
```

11. For a simple example of how to set the synchronization context of a thread, and how to use a task scheduler to schedule a task to that thread, see Listing C.8 in *Multithreading Patterns Prior to C# 5.0*, available at IntelliTect.com/EssentialCSharp.

Given that `StatusLabel` is a WPF `System.Windows.Controls.TextBlock` control and we have updated the `Content` property twice within the `PingButton_Click()` event subscriber, it would be a reasonable assumption that first "Pinging…" would be displayed until `Ping.Send()` returned, and then the label would be updated with the status of the `Send()` reply. As those experienced with Windows UI frameworks well know, this is not, in fact, what happens. Rather, a message is posted to the Windows message pump to update the content with "Pinging…" but, because the UI thread is busy executing the `PingButton_Click()` method, the Windows message pump is not processed. By the time the UI thread frees up to look at the Windows message pump, a second `Text` property update request has been queued and the only message that the user is able to observe is the final status.

To fix this problem using TAP, we change the code highlighted in Listing 18.22.

LISTING 18.22: Synchronous High-Latency Invocation in WPF Using `await`

4.0

```
using System;
async private void PingButton_Click(
  object sender, RoutedEventArgs e)
{
  StatusLabel.Content = "Pinging...";
  UpdateLayout();
  Ping ping = new Ping();
  PingReply pingReply =
      await ping.SendPingAsync("www.IntelliTect.com");
  StatusLabel.Text = pingReply.Status.ToString();
}
```

This change offers two advantages. First, the asynchronous nature of the ping call frees up the caller thread to return to the Windows message pump caller's synchronization context, and processes the update to `StatusLabel.Content` so that "Pinging…" appears to the user. Second, when awaiting `ping.SendTaskAsync()` completes, it will always execute on the same synchronization context as the caller. Also, because the synchronization context is specifically appropriate for Windows UI, it is single-threaded and, therefore, the return will always be to the same thread—the UI thread. In other words, rather than immediately executing the continuation task, the TPL consults the synchronization context, which instead posts a message regarding the continuation work to the message pump. Next, because the UI thread monitors the message pump, upon picking up the continuation work message, it invokes the code following the `await` call. (As a result, the invocation of the continuation code is on the same thread as the caller that processed the message pump.)

There is a key code readability feature built into the TAP language pattern. Notice in Listing 18.22 that the call to return `pingReply.Status` appears to flow naturally after the `await`, providing a clear indication that it will execute immediately following the previous line. However, writing what really happens from scratch would be far less understandable for multiple reasons.

`await` Operators

There is no limitation on the number of times that `await` can be placed into a single method. In fact, such statements are not limited to appearing one after another. Rather, `await` statements can be placed into loops and processed consecutively one after the other, thereby following a natural control flow the way code appears. Consider the example in Listing 18.23.

Listing 18.23: Iterating over an Await Operation

4.0

```
async private void PingButton_Click(
  object sender, RoutedEventArgs e)
{
  List<string> urls = new List<string>()
      {
          "www.habitat-spokane.org",
          "www.partnersintl.org",
          "www.iassist.org",
          "www.fh.org",
          "www.worldvision.org"
      };
  IPStatus status;

  Func<string, Task<IPStatus>> func =
      async (localUrl) =>
      {
          Ping ping = new Ping();
          PingReply pingReply =
              await ping.SendPingAsync(localUrl);
          return pingReply.Status;
      };

  StatusLabel.Content = "Pinging…";

  foreach(string url in urls)
  {
      status = await func(url);
```

```
        StatusLabel.Text =
            $@"{ url }: { status.ToString() } ({
                Thread.CurrentThread.ManagedThreadId })";
    }
}
```

Regardless of whether the `await` statements occur within an iteration or as separate entries, they will execute serially, one after the other and in the same order they were invoked from the calling thread. The underlying implementation is to string them together in the semantic equivalent of `Task.ContinueWith()`, except that all of the code between the `await` operators will execute in the caller's synchronization context.

Support for TAP from the UI is one of the key scenarios that led to TAP's creation. A second scenario takes place on the server, when a request comes in from a client to query an entire table's worth of data from the database. As querying the data could be time-consuming, a new thread should be created rather than consuming one from the limited number allocated to the thread pool. The problem with this approach is that the work to query from the database is executing entirely on another machine. There is no reason to block an entire thread given that the thread is generally not active anyway.

4.0

To summarize, TAP was created to address these key problems:

- There is a need to allow long-running activities to occur without blocking the UI thread.
- Creating a new thread (or `Task`) for non–CPU-intensive work is relatively expensive when you consider that all the thread is doing is waiting for the activity to complete.
- When the activity completes (either by using a new thread or via a callback), it is frequently necessary to make a thread synchronization context switch back to the original caller that initiated the activity.
- TAP provides a new pattern that works for both CPU-intensive and non–CPU-intensive asynchronous invocations—one that all .NET languages support explicitly.

Executing Loop Iterations in Parallel

Consider the following `for` loop statement and associated code (see Listing 18.24 and the corresponding output, Output 18.8). The Listing calls a method for calculating a section of the decimal expansion of pi, where the parameters are the number of digits and the digit to start with. The actual calculation is not germane to the discussion. What is interesting about this calculation is that it is **embarrassingly parallelizable;** that is, it is almost embarrassing how easy it is to split up a large task—say, computing 1 million decimal digits of pi—into any desired number of smaller tasks that can all be run in parallel. These types of computations are the easiest ones to speed up by adding parallelism.

LISTING 18.24: For Loop Synchronously Calculating Pi in Sections

```
using System;
using AddisonWesley.Michaelis.EssentialCSharp.Shared;

class Program
{
  const int TotalDigits = 100;
  const int BatchSize = 10;

  static void Main()
  {
      string pi = null;
      const int iterations = TotalDigits / BatchSize;
      for(int i = 0; i < iterations; i++)
      {
          pi += PiCalculator.Calculate(
              BatchSize, i * BatchSize);
      }

      Console.WriteLine(pi);
  }
}
```

```
using System;

class PiCalculator
{
  public static string Calculate(
      int digits, int startingAt)
  {
     // ...
  }

    // ...
}
```

4.0

Output 18.8

```
>3.141592653589793238462643383279502884197169399375105820974944592307816
406286208998628034825342117067982148086513282306647093844609550582231
725359408128481117450284102701938521105559644622948954930381964428810975
665933446128475648233786783165271201909145648566923460348610454326648213
393607260249141273724587006606315588174881520920962829254091715364367892
590360011330530548820466521384146951941511609433057270365759591953092186
117381932611793105118548074462379962749567351885752724891227938183011949
12
```

The for loop executes each iteration synchronously and sequentially. However, because the pi calculation algorithm splits the pi calculation into independent pieces, it is not necessary to compute the pieces sequentially just as long as the results are appended in the right order. Imagine what would happen if you could have all the iterations of this loop run concurrently: Each processor could take a single iteration and execute it in parallel with other processors executing other iterations. Given the simultaneous execution of iterations, we could decrease the execution time more and more based on the number of processors.

4.0

The TPL provides a convenient method, `Parallel.For()`, that does precisely that. Listing 18.25 shows how to modify the sequential, single-threaded program in Listing 18.24 to use the helper method.

Listing 18.25: For Loop Calculating Pi in Sections in Parallel

```
using System;
using System.Threading.Tasks;
using AddisonWesley.Michaelis.EssentialCSharp.Shared;

// ...

class Program
{
  static void Main()
  {
        string pi = null;
        const int iterations = TotalDigits / BatchSize;
        string[] sections = new string[iterations];
        Parallel.For(0, iterations, (i) =>
        {
            sections[i] = PiCalculator.Calculate(
                BatchSize, i * BatchSize);
        });
        pi = string.Join("", sections);
        Console.WriteLine(pi);
}
```

The output for Listing 18.25 is identical to Output 18.8; however, the execution time is significantly faster if you have multiple CPUs (and possibly slower if you do not). The `Parallel.For()` API is designed to look similar to a standard `for` loop. The first parameter is the `fromInclusive` value, the second is the `toExclusive` value, and the last is the `Action<int>` to perform as the loop body. When using an expression lambda for the action, the code looks similar to a `for` loop statement except that now each iteration may execute in parallel. As with the `for` loop, the call to `Parallel.For()` will not complete until all iterations are complete. In other words, by the time execution reaches the `string.Join()` statement, all sections of pi will have been calculated.

Note that the code for combining the various sections of pi no longer occurs inside the iteration (`action`) in Listing 18.25. As sections of the pi calculation will very likely not complete sequentially, appending a section whenever an iteration completes will likely append them out of order. Even if sequence was not a problem, there is still a potential race condition because the `+=` operator is not atomic. To address both of these problems, each section of pi is stored into an array and no two or more iterations will access a single element within the array simultaneously. Only once all sections of pi are calculated does `string.Join()` combine them. In other words, we postpone concatenating the sections until after the `Parallel.For()` loop has completed. This avoids any race condition caused by sections not yet calculated or sections concatenating out of order.

4.0

The TPL uses the same sorts of thread pooling techniques that it uses for task scheduling to ensure good performance of the parallel loop: It will try to ensure that CPUs are not overscheduled, and so on.

Guidelines

DO use parallel loops when the computations performed can be easily split up into many mutually independent processor-bound computations that can be executed in any order on any thread.

The TPL also provides a similar parallel version of the `foreach` statement, as shown in Listing 18.26.

LISTING 18.26: Parallel Execution of a foreach Loop

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Threading.Tasks;

class Program
{
  // ...
  static void EncryptFiles(
      string directoryPath, string searchPattern)
  {
      IEnumerable<string> files = Directory.EnumerateFiles(
          directoryPath, searchPattern,
          SearchOption.AllDirectories);

      Parallel.ForEach(files, (fileName) =>
      {
          Encrypt(fileName);
      });
  }
  // ...
}
```

4.0

In this example, we call a method that encrypts each file within the `files` collection. It does so in parallel, executing as many threads as the TPL determines is efficient.

ADVANCED TOPIC

How the TPL Tunes Its Own Performance

The default scheduler within the TPL targets the thread pool, resulting in a variety of heuristics to try to ensure that the right number of threads are executing at any one time. Two of the heuristics it uses are **hill climbing** and **work stealing.**

The hill climbing algorithm involves creating threads to run tasks, and then monitoring the performance of those tasks to try to experimentally determine the point at which adding more threads begins making performance worse. Once that point is reached, the number of threads can then be decreased back to the number that produced the best performance.

The TPL associates "top-level" tasks that are waiting to be executed with no particular thread. If, however, a task running on a thread itself creates another task, the newly created task is associated with that thread automatically. When the new "child" task is eventually scheduled to run, it usually runs on the same thread as the task that created it. The work stealing algorithm identifies threads that have an unusually large or unusually small amount of pending work; a thread that has too few tasks associated with it will sometimes "steal" not-yet-executed tasks from threads that have too many tasks waiting to run.

The key feature of these algorithms is that they enable the TPL to dynamically tune its own performance to mitigate processor overscheduling and underscheduling, and to balance the work among the available processors.

The TPL generally does a good job of tuning its own performance, but you can help it do a better job by providing hints about the best course of action. Specifying the TPL `TaskCreationOptions.LongRunning` option described earlier in the section "Long-Running Tasks" is an example of such a hint. You can also explicitly tell the task scheduler how many threads you think would be best to service a parallel loop; see the Advanced Topic titled "Parallel Loop Options" for more details.

4.0

BEGINNER TOPIC

Parallel Loop Exception Handling with AggregateException

We know already that the TPL catches and saves exceptions associated with tasks in an `AggregateException`, because a given task might have several exceptions obtained from its subtasks. This is also the case with parallel execution of loops: Each iteration could have produced an exception, so the exceptions need to be gathered up into one aggregating exception. Consider the example in Listing 18.27 and its output in Output 18.9.

Listing 18.27: Unhandled Exception Handling for Parallel Iterations

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Threading;
using System.Threading.Tasks;

class Program
{
  // ...
  static void EncryptFiles(
      string directoryPath, string searchPattern)
  {
```

```
            IEnumerable<string> files = Directory.EnumerateFiles(
                directoryPath, searchPattern,
                SearchOption.AllDirectories);
            try
            {
                Parallel.ForEach(files, (fileName) =>
                {
                    Encrypt(fileName);
                });
            }
            catch(AggregateException exception)
            {
                Console.WriteLine(
                    "ERROR: {0}:",
                    exception.GetType().Name);
                foreach(Exception item in
                    exception.InnerExceptions)
                {
                    Console.WriteLine("  {0} - {1}",
                        item.GetType().Name, item.Message);
                }
            }
        }
        // ...
    }
```

4.0

Output 18.9

```
ERROR: AggregateException:
  UnauthorizedAccessException - Attempted to perform an unauthorized
operation.
  UnauthorizedAccessException - Attempted to perform an unauthorized
operation.
  UnauthorizedAccessException - Attempted to perform an unauthorized
operation.
```

Output 18.9 shows that three exceptions occurred while executing the `Parallel.ForEach<T>(...)` loop. However, in the code, there is only one catch of type `System.AggregateException`. The `UnauthorizedAccessExceptions` were retrieved from the `InnerExceptions` property on the `AggregateException`. With a `Parallel.ForEach<T>()` loop, each iteration could potentially throw an exception, so the `System.AggregateException` thrown by the method call will contain each of those exceptions within its `InnerExceptions` property.

Canceling a Parallel Loop

Unlike a task, which requires an explicit call if it is to block until it completes, a parallel loop executes iterations in parallel but does not itself return until the entire parallel loop completes. Canceling a parallel loop, therefore, generally involves invocation of the cancellation request from a thread other than the one executing the parallel loop. In Listing 18.28, we invoke `Parallel.ForEach<T>()` using `Task.Run()`. In this manner, not only does the query execute in parallel, but it also executes asynchronously, allowing the code to prompt the user to "Push ENTER to exit."

LISTING 18.28: Canceling a Parallel Loop

```
using System;
using System.Collections.Generic;
using System.IO;
using System.Threading;
using System.Threading.Tasks;

public class Program
{
      // ...

  static void EncryptFiles(
      string directoryPath, string searchPattern)
  {

      string stars =
          "*".PadRight(Console.WindowWidth-1, '*');

      IEnumerable<string> files = Directory.GetFiles(
         directoryPath, searchPattern,
         SearchOption.AllDirectories);

      CancellationTokenSource cts =
          new CancellationTokenSource();
      ParallelOptions parallelOptions =
          new ParallelOptions
              { CancellationToken = cts.Token };
      cts.Token.Register(
          () => Console.WriteLine("Cancelling..."));

      Console.WriteLine("Push ENTER to exit.");

      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task task = Task.Run(() =>
          {
              try
              {
```

4.0

```
                Parallel.ForEach(
                    files, parallelOptions,
                    (fileName, loopState) =>
                        {
                            Encrypt(fileName);
                        });
            }
            catch(OperationCanceledException){}
        });

        // Wait for the user's input
        Console.Read();

        // Cancel the query
        cts.Cancel();
        Console.Write(stars);
        task.Wait();
    }
}
```

The parallel loops use the same cancellation token pattern that tasks use. The token obtained from a `CancellationTokenSource` is associated with the parallel loop by calling an overload of the `ForEach()` method that has a parameter of type `ParallelOptions`. This object contains the cancellation token.

4.0

Note that if you cancel a parallel loop operation, any iterations that have not started yet are prevented from starting by checking the `IsCancellationRequested` property. Existing executing iterations will run to their respective termination points. Furthermore, calling `Cancel()` even after all iterations have completed will still cause the registered cancel event (via `cts.Token.Register()`) to execute.

The only means by which the `ForEach()` method is able to acknowledge that the loop has been canceled is via the `OperationCanceledException`. Given that cancellation in this example is expected, the exception is caught and ignored, allowing the application to display “Canceling...”, followed by a line of stars before exiting.

ADVANCED TOPIC

Parallel Loop Options

Although not generally necessary, it is possible to control the maximum degree of parallelism (that is, the number of threads that are scheduled to run at the same time) via the `ParallelOptions` parameter on overloads of both the `Parallel.For()` and `Parallel.ForEach<T>()` loops. In some specific cases, the developer may know more about the particular algorithm or circumstance such that changing the maximum degree of parallelism makes sense. These circumstances include the following:

- Scenarios where you want to disable parallelism to make debugging or analysis easier. Setting the maximum degree of parallelism to 1 ensures that the loop iterations do not run concurrently.
- Scenarios where you know ahead of time that the degree of parallelism will be gated on an external factor such as a hardware constraint. For example, if your parallel operation involves using multiple USB ports, it is possible that there is no point in creating more threads than there are available ports.
- Scenarios with really long-running loop iterations (for example, minutes or hours). The thread pool can't distinguish long-running iterations from blocked operations, so it could end up introducing many new threads, all of which will be consumed by the `for` loop. This can result in incremental thread growth over time, resulting in a huge number of threads in the process.

4.0

And so on. To control the maximum degree of parallelism, use the `MaxDegreeOfParallelism` property on the `ParallelOptions` object.

You can also use the `ParallelOptions` object's `TaskScheduler` property to specify a custom task scheduler to use to schedule the tasks associated with each iteration. For example, you might have an asynchronous event handler that responds to the user's click of a "Next" button. If the user clicks the button several times, you might want to use a custom task scheduler that prioritizes the most recently created task, rather than prioritizing the task that has waited the longest. The task scheduler provides a means of specifying how the tasks will execute in relation to one another.

The `ParallelOptions` object also has a `CancellationToken` property that provides a mechanism to communicate to the loop that no further iterations should start. Additionally, the body of an iteration can watch the cancellation token to determine if an early exit from the iteration is in order.

ADVANCED TOPIC

Breaking a Parallel Loop

Like a standard `for` loop, the `Parallel.For()` loop supports the concept of "breaking" to exit the loop and canceling any further iterations. In the context of parallel `for` execution, however, a break signifies that no new iterations following the breaking iteration should start. All currently executing iterations, however, will run to completion.

To break a parallel loop, you can provide a cancellation token and cancel it on another thread, as described in the preceding Advanced Topic. You can also use an overload of the `Parallel.For()` method whose body delegate takes two parameters: the index, and a `ParallelLoopState` object. An iteration that wishes to "break" the loop can call the `Break()` or `Stop()` method on the loop state object passed to the delegate. The `Break()` method indicates that no more iterations with index values higher than the current value need to execute; the `Stop()` method indicates that no more iterations need to run at all.

4.0

For example, suppose you have a `Parallel.For()` loop that is performing ten iterations in parallel. Some of those iterations might run faster than others, and the task scheduler does not guarantee that they will run in any particular order. Suppose the first iteration has completed; iterations 3, 5, 7, and 9 are "in flight," scheduled to four different threads; and iterations 5 and 7 both call `Break()`. In this scenario, iterations 6 and 8 will never start, but iterations 2 and 4 will still be scheduled to run. Iterations 3 and 9 will run to completion because they were already started when the break happened.

The `Parallel.For()` and `Parallel.ForEach<T>()` methods return a reference to a `ParallelLoopResult` object that contains useful information about what happened during the loop. This result object has the following properties:

- `IsCompleted` returns a Boolean indicating whether all iterations started.
- `LowestBreakIteration` identifies the lowest iteration that executed a break. The value is of type `long?`, where a value of null indicates no break statement was encountered.

Returning to the ten-iteration example, the `IsCompleted` property will return `false` and the `LowestBreakIteration` will return a value of 5.

Running LINQ Queries in Parallel

Just as it is possible to execute a loop in parallel using `Parallel.For()`, so it is also possible to execute LINQ queries in parallel using the Parallel LINQ API (PLINQ, for short). An example of a simple nonparallel LINQ expression is shown in Listing 18.29; in Listing 18.30, we modify it to run in parallel.

LISTING 18.29: LINQ `Select()`

```
using System.Collections.Generic;
using System.Linq;

class Cryptographer
{
  // ...
  public List<string>
    Encrypt(IEnumerable<string> data)
  {
      return data.Select(
          item => Encrypt(item)).ToList();
  }
  // ...
}
```

4.0

In Listing 18.29, a LINQ query uses the `Select()` standard query operator to encrypt each string within a sequence of strings, and convert the resultant sequence to a list. This seems like an "embarrassingly parallel" operation; each encryption is likely to be a high-latency processor-bound operation that could be farmed out to a worker thread on another CPU.

Listing 18.30 shows how to modify Listing 18.29 so that the code that encrypts the strings is executed in parallel.

LISTING 18.30: `Parallel LINQ Select()`

```
using System.Linq;

class Cryptographer
{
  // ...
  public List<string> Encrypt (IEnumerable<string> data)
  {
      return data.AsParallel().Select(
          item => Encrypt(item)).ToList();
  }
  // ...
}
```

As Listing 18.30 shows, the change to enable parallel support is extremely small! All that it uses is a .NET Framework 4.0–introduced standard query operator, `AsParallel()`, which can be found on the static class `System.Linq.ParallelEnumerable`. This simple extension method tells the runtime that it can execute the query in parallel. The result is that on machines with multiple available CPUs, the total time taken to execute the query can be significantly shorter.

`System.Linq.ParallelEnumerable` includes a superset of the query operators available on `System.Linq.Enumerable`, resulting in possible performance improvements for all of the common query operators, including those used for sorting, filtering (`Where()`), projecting (`Select()`), joining, grouping, and aggregating. Listing 18.31 shows how to do a parallel sort.

LISTING 18.31: Parallel LINQ with Standard Query Operators

4.0

```
// ...
      OrderedParallelQuery<string> parallelGroups =
          data.AsParallel().OrderBy(item => item);

      // Show the total count of items still
      // matches the original count
      System.Diagnostics.Trace.Assert(
          data.Count == parallelGroups.Sum(
              item => item.Count()));
// ...
```

As Listing 18.31 shows, invoking the parallel version simply involves a call to the `AsParallel()` extension method. Notice that the type of the result returned by the parallel standard query operators is either `ParallelQuery<T>` or `OrderedParallelQuery<T>`; both inform the compiler that it should continue to use the parallel versions of the standard query operations that are available.

Given that query expressions are simply a syntactic sugar for the method call form of the query used in Listings 18.30 and 18.31, you can just as easily use `AsParallel()` with the expression form. Listing 18.32 shows an example of executing a grouping operation in parallel using query expression syntax.

LISTING 18.32: Parallel LINQ with Query Expressions

```
// ...
      ParallelQuery<IGrouping<char, string>> parallelGroups;
      parallelGroups =
          from text in data.AsParallel()
            orderby text
            group text by text[0];
```

```
        // Show the total count of items still
        // matches the original count
        System.Diagnostics.Trace.Assert(
            data.Count == parallelGroups.Sum(
                item => item.Count()));
  // ...
```

As you saw in the previous examples, converting a query or iteration loop to execute in parallel is simple. There is one significant caveat, however: As we will discuss in depth in Chapter 19, you must take care not to allow multiple threads to inappropriately access and modify the same memory simultaneously. Doing so will cause a race condition.

As we saw earlier in this chapter, the `Parallel.For()` and `Parallel.ForEach<T> 4()` methods will gather up any exceptions thrown during the parallel iterations and then throw one aggregating exception containing all of the original exceptions. PLINQ operations are no different. That is, they also have the potential of returning multiple exceptions for the exact same reason: When the query logic is run on each element in parallel, the code executing on each element can independently throw an exception. Unsurprisingly, PLINQ deals with this situation in exactly the same way as do parallel loops and the TPL: Exceptions thrown during parallel queries are accessible via the `InnerExceptions` property of the `AggregateException`. Therefore, wrapping a PLINQ query in a try/catch block with the exception type of `System.AggregateException` will successfully handle any exceptions within each iteration that were unhandled. 4.0

Canceling a PLINQ Query

As expected, the cancellation request pattern is also available on PLINQ queries. Listing 18.33 (with Output 18.10) provides an example. Like the parallel loops, canceled PLINQ queries will throw a `System.OperationCanceledException`. Also like the parallel loops, executing a PLINQ query is a synchronous operation on the invoking thread. Thus, a common technique is to wrap the parallel query in a task that runs on another thread so that the current thread can cancel it if necessary—the same solution used in Listing 18.28.

Listing 18.33: Canceling a PLINQ Query

```
  using System;
  using System.Collections.Generic;
  using System.Linq;
```

```
using System.Threading;
using System.Threading.Tasks;

public class Program
{

  public static List<string> ParallelEncrypt(
      List<string> data,
      CancellationToken cancellationToken)
  {
      return data.AsParallel().WithCancellation(
          cancellationToken).Select(
              (item) => Encrypt(item)).ToList();
  }

  public static void Main()
  {
      ConsoleColor originalColor = Console.ForegroundColor;
      List<string> data = Utility.GetData(100000).ToList();

      CancellationTokenSource cts =
          new CancellationTokenSource();

      Console.WriteLine("Push ENTER to Exit.");

      // Use Task.Factory.StartNew<string>() for
      // TPL prior to .NET 4.5
      Task task = Task.Run(() =>
      {
          data = ParallelEncrypt(data, cts.Token);
      }, cts.Token);

      // Wait for the user's input
      Console.Read();

      if (!task.IsCompleted)
      {
          cts.Cancel();
          try { task.Wait(); }
          catch (AggregateException exception)
          {
              Console.ForegroundColor = ConsoleColor.Red;
              TaskCanceledException taskCanceledException =
                  (TaskCanceledException)exception.Flatten()
                  .InnerExceptions
                 .FirstOrDefault(
                  innerException =>
                      innerException.GetType() ==
                      typeof(TaskCanceledException));
              if(taskCanceledException != null){
                  Console.WriteLine($@"Cancelled: {
                      taskCanceledException.Message }");
```

4.0

```
                }
                else
                {
                    // ...
                }
            }
        }
        else
        {
            task.Wait();
            Console.ForegroundColor = ConsoleColor.Green;
            Console.Write("Completed successfully");
        }
        Console.ForegroundColor = originalColor;
    }
}
```

Output 18.10

```
Cancelled: A task was canceled.
```


As with a parallel loop or task, canceling a PLINQ query requires a `CancellationToken`, which is available from a `CancellationTokenSource`. However, rather than overloading every PLINQ query to support the cancellation token, the `ParallelQuery<T>` object returned by `IEnumerable`'s `AsParallel()` method includes a `WithCancellation()` extension method that simply takes a `CancellationToken`. As a result, calling `Cancel()` on the `CancellationTokenSource` object will request the parallel query to cancel—because it checks the `IsCancellationRequested` property on the `CancellationToken`.

As mentioned, canceling a PLINQ query will throw an exception in place of returning the complete result. One common technique for dealing with a possibly canceled PLINQ query is to wrap the query in a try block and catch the `OperationCanceledException`. A second common technique, used in Listing 18.33, is to pass the `CancellationToken` both to `ParallelEncrypt()` and as a second parameter on `Run()`. This will cause `task.Wait()` to throw an `AggregateException` whose `InnerException` property will be set to a `TaskCanceledException`. The aggregating exception can then be caught, just as you would catch any other exception from a parallel operation.

SUMMARY

In this chapter, we started by examining the basic parts of multithreaded programs: the `Thread` class, which represents an independent "point of control" in a program, and the `ThreadPool`, which encourages efficient allocation and scheduling of threads to multiple CPUs. However, these APIs are low-level entities that are difficult to work with directly. Starting with Version 4.0, the .NET Framework provides the Parallel Extensions library, which includes the Task Parallel Library (TPL) and Parallel LINQ (PLINQ). Both provide new APIs for creating and scheduling units of work represented by `Task` objects, executing loops in parallel using `Parallel.For()` and `Parallel.ForEach()`, and automatically parallelizing LINQ queries with `AsParallel()`.

We also discussed how C# 5.0 makes programming complex workflows with `Task` objects much easier by automatically rewriting your programs to manage the continuation "wiring" that composes larger tasks out of smaller tasks.

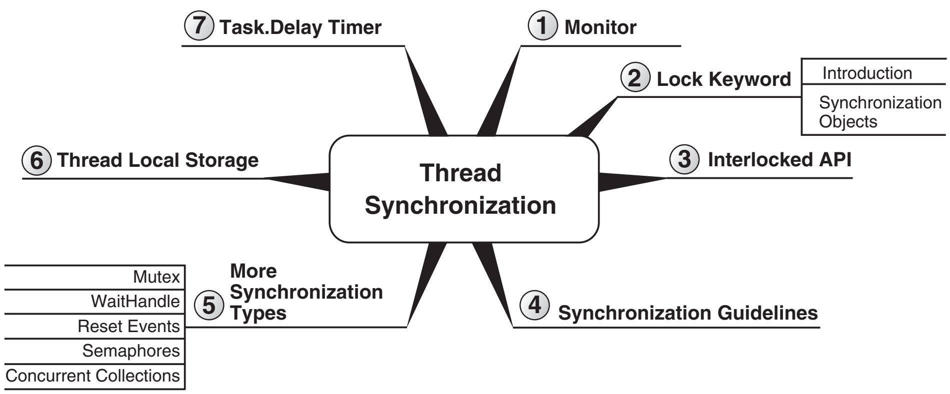
At the beginning of this chapter, we briefly glossed over some of the difficult problems that developers often face when writing multithreaded programs: atomicity problems, deadlocks, and other "race conditions" that introduce uncertainty and bad behavior into multithreaded programs. The standard way to avoid these problems is to carefully write code that uses "locks" to synchronize access to shared resources; this is the topic of the next chapter.

End 4.0

19

Thread Synchronization

IN CHAPTER 18, WE DISCUSSED the details of multithreaded programming using the Task Parallel Library (TPL) and Parallel LINQ (PLINQ). One topic we specifically avoided, however, was thread synchronization, which prevents race conditions while avoiding deadlocks. Thread synchronization is the topic of this chapter.



We begin with a multithreaded example with no thread synchronization around shared data—resulting in a race condition in which data integrity is lost. This discussion serves as the introduction for why we need thread synchronization. It is followed by coverage of a myriad of mechanisms and best practices for doing it.

Prior editions of this book included a significant section on additional multithreading patterns and another on various timer callback mechanisms. With the introduction of the async/await pattern, however, those approaches have essentially been replaced unless you are programming with frameworks prior to C# 5.0/.NET 4.5. However, pre-C# 5.0 material still available from this book's website—http://www.IntelliTect.com/EssentialCSharp.

This entire chapter uses the TPL, so the samples cannot be compiled on frameworks prior to .NET Framework 4. However, unless specifically identified as a .NET Framework 4 API, the only reason for the .NET Framework 4 restriction is the use of the `System.Threading.Tasks.Task` class to execute the asynchronous operation. Modifying the code to instantiate a `System.Threading.Thread` and use a `Thread.Join()` to wait for the thread to execute will allow the vast majority of samples to compile on earlier frameworks.

That being said, the specific API for starting tasks throughout this chapter is the .NET 4.5–specific `System.Threading.Tasks.Task.Run()`. As we discussed in Chapter 18, this method is preferred over `System.Threading.Tasks.Task.Factory.StartNew()` because it is simpler and sufficient for the majority of scenarios. Those readers limited to .NET 4 can replace `Task.Run()` with `Task.Factory.StartNew()` without any additional modifications. (For this reason the chapter does not explicitly highlight such code as .NET 4.5–specific code when only this method is used.)

Furthermore, Microsoft has released the Reactive Extensions to .NET (Rx), a separate download that adds support for the TPL and PLINQ within the .NET 3.5 Framework.[1] This framework also includes the concurrent and synchronization types introduced in this chapter. For this reason, code listings that depend on `Task` or that introduce C# 4.0 synchronization classes are, in fact, available from .NET 3.5 using the functionality backported to the .NET 3.5 Framework via Rx and a reference to the `System.Threading.dll` assembly. Reactive Extensions also includes functionality for leveraging LINQ with delegates. The full library is now available via open source at https://github.com/Reactive-Extensions/Rx.NET.

In summary, most of the samples in the chapter will require only minor modification to work with .NET prior to .NET 4.5, either by using

1. See http://bit.ly/Rx3point5

`Task.Factory.StartNew()` or by relying on `Thread.Start()` if the TPL is not available.

Why Synchronization?

Running a new thread is a relatively simple programming task. What makes multithreaded programming difficult, however, is identifying which data multiple threads can safely access simultaneously. The program must synchronize such data to prevent simultaneous access, thereby creating the "safety." Consider Listing 19.1.

LISTING 19.1: Unsynchronized State

```
using System;
using System.Threading.Tasks;

public class Program
{
    const int _Total = int.MaxValue;
    static long _Count = 0;

    public static void Main()
    {
        // Use Task.Factory.StartNew for .NET 4.0
        Task task = Task.Run(()=>Decrement());

        // Increment
        for(int i = 0; i < _Total; i++)
        {
            _Count++;
        }

        task.Wait();
        Console.WriteLine("Count = {0}", _Count);
    }

    static void Decrement()
    {
        // Decrement
        for(int i = 0; i < _Total; i++)
        {
            _Count--;
        }
    }
}
```

One possible result of Listing 19.1 appears in Output 19.1.

OUTPUT 19.1

```
Count = 113449949
```

The important thing to note about Listing 19.1 is that the output is not `0`. It would have been if `Decrement()` was called directly (sequentially). However, when calling `Decrement()` asynchronously, a race condition occurs because the individual steps within `_Count++` and `_Count--` statements intermingle. (As discussed in the Beginner Topic titled "Multithreading Jargon" in Chapter 18, a single statement in C# will likely involve multiple steps.) Consider the sample execution in Table 19.1.

TABLE 19.1: Sample Pseudocode Execution

Main Thread	Decrement Thread	Count
...	...	...
Copy the value `0` out of `_Count`.		0
Increment the copied value (`0`), resulting in `1`.		0
Copy the resultant value (`1`) into `_Count`.		1
Copy the value `1` out of `_Count`.		1
	Copy the value `1` out of `_Count`.	1
Increment the copied value (`1`), resulting in `2`.		1
Copy the resultant value (`2`) into `_Count`.		2
	Decrement the copied value (`1`), resulting in `0`.	2
	Copy the resultant value (`0`) into `_Count`.	0
...	...	...

Table 19.1 shows a parallel execution (or a thread context switch) by the transition of instructions appearing from one column to the other. The value

of `_Count` after a particular line has completed appears in the last column. In this sample execution, `_Count++` executes twice and `_Count--` occurs once. However, the resultant `_Count` value is `0`, not `1`. Copying a result back to `_Count` essentially wipes out any `_Count` value changes that have occurred since the read of `_Count` on the same thread.

The problem in Listing 19.1 is a race condition, where multiple threads have simultaneous access to the same data elements. As this sample execution demonstrates, allowing multiple threads to access the same data elements is likely to undermine data integrity, even on a single-processor computer. To remedy this potential problem, the code needs synchronization around the data. Code or data synchronized for simultaneous access by multiple threads is **thread-safe.**

There is one important point to note about atomicity of reading and writing to variables. The runtime guarantees that a type whose size is no bigger than a native (pointer-size) integer will not be read or written partially. With a 64-bit operating system, therefore, reads and writes to a `long` (64 bits) will be atomic. However, reads and writes to a 128-bit variable such as `decimal` may not be atomic. Therefore, write operations to change a `decimal` variable may be interrupted after copying only 32 bits, resulting in the reading of an incorrect value, known as a **torn read.**

BEGINNER TOPIC

Multiple Threads and Local Variables

Note that it is not necessary to synchronize local variables. Local variables are loaded onto the stack and each thread has its own logical stack. Therefore, each local variable has its own instance for each method call. By default, local variables are not shared across method calls; likewise, they are not shared among multiple threads.

However, this does not mean local variables are entirely without concurrency issues—after all, code could easily expose the local variable to multiple threads.[2] A parallel `for` loop that shares a local variable between iterations, for example, will expose the variable to concurrent access and a race condition (see Listing 19.2).

2. While at the C# level it's a local, at the IL level it's a field—and fields can be accessed from multiple threads.

Listing 19.2: Unsynchronized Local Variables

```
using System;
using System.Threading.Tasks;

public class Program
{
  public static void Main()
  {
      int x = 0;
      Parallel.For(0, int.MaxValue, i =>
          {
              x++;
              x--;
          });
      Console.WriteLine("Count = {0}", x);
  }
}
```

In this example, `x` (a local variable) is accessed within a parallel `for` loop, so multiple threads will modify it simultaneously, creating a race condition very similar to that in Listing 19.1. The output is unlikely to yield the value `0` even though `x` is incremented and decremented the same number of times.

Begin 5.0

BEGINNER TOPIC

Task Return with No await

In Listing 19.1, although `Task.Run(()=>Decrement())` returns a `Task`, the `await` operator is not used. The reason for this is that `await` is allowed only in an `async`-decorated method and `Main()` doesn't support the use of `async`. Refactoring the code outside of `Main()` would allow it to easily leverage the `await`/`async` pattern, as shown in Listing 19.3.

Listing 19.3: Unsynchronized Local Variables

```
using System;
using System.Threading.Tasks;

public class Program
{
    const int _Total = int.MaxValue;
    static long _Count = 0;

  public static async void CountAsync()
```

```
    {
        // Use Task.Factory.StartNew for .NET 4.0
        Task task = Task.Run(()=>Decrement());

        // Increment
        for(int i = 0; i < _Total; i++)
        {
            _Count++;
        }

        await task;
        Console.WriteLine($"Count = {_Count}");
    }
}
```

End 5.0

Synchronization Using Monitor

To synchronize multiple threads so that they cannot execute particular sections of code simultaneously, you can use a **monitor** to block the second thread from entering a protected code section before the first thread has exited that section. The monitor functionality is part of a class called `System.Threading.Monitor`, and the beginning and end of protected code sections are marked with calls to the static methods `Monitor.Enter()` and `Monitor.Exit()`, respectively.

Listing 19.4 demonstrates synchronization using the `Monitor` class explicitly. As this listing shows, it is important that all code between calls to `Monitor.Enter()` and `Monitor.Exit()` be surrounded with a try/finally block. Without this block, an exception could occur within the protected section and `Monitor.Exit()` may never be called, thereby blocking other threads indefinitely.

Listing 19.4: Synchronizing with a Monitor Explicitly

Begin 4.0

```
using System;
using System.Threading;
using System.Threading.Tasks;

public class Program
{
    readonly static object _Sync = new object();
    const int _Total = int.MaxValue;
    static long _Count = 0;

    public static void Main()
    {
```

```
            // Use Task.Factory.StartNew for .NET 4.0
            Task task = Task.Run(()=>Decrement());

            // Increment
            for(int i = 0; i < _Total; i++)
            {
                bool lockTaken = false;
                try
                {
                    Monitor.Enter(_Sync, ref lockTaken);
                    _Count++;
                }
                finally
                {
                    if (lockTaken)
                    {
                        Monitor.Exit(_Sync);
                    }
                }
            }

            task.Wait();
            Console.WriteLine($"Count = {_Count}");
        }

        static void Decrement()
        {
            for(int i = 0; i < _Total; i++)
            {
                bool lockTaken = false;
                try
                {
                    Monitor.Enter(_Sync, ref lockTaken);
                    _Count--;
                }
                finally
                {
                    if(lockTaken)
                    {
                        Monitor.Exit(_Sync);
                    }
                }
            }
        }
    }
```

4.0

The results of Listing 19.4 appear in Output 19.2.

Output 19.2

```
Count = 0
```

Note that calls to Monitor.Enter() and Monitor.Exit() are associated with each other by sharing the same object reference passed as the parameter (in this case, _Sync). The Monitor.Enter() overload method that takes the lockTaken parameter was added to the framework only in .NET 4.0. Before that, no such lockTaken parameter was available and there was no way to reliably catch an exception that occurred between the Monitor.Enter() and the try block. Placing the try block immediately following the Monitor.Enter() call was reliable in release code because the JIT prevented any such asynchronous exception from sneaking in. However, anything other than a try block immediately following the Monitor.Enter(), including any instructions that the compiler might have injected within debug code, could prevent the JIT from reliably returning execution within the try block. Therefore, if an exception did occur, it would leak the lock (the lock remained acquired) rather than executing the finally block and releasing it—likely causing a deadlock when another thread tried to acquire the lock. In summary, in versions of the framework prior to .NET 4.0, you should always follow Monitor.Enter() with a try/finally {Monitor.Exit(_Sync))} block.

Monitor also supports a Pulse() method for allowing a thread to enter the "ready queue," indicating it is up next for execution. This is a common means of synchronizing producer–consumer patterns so that no "consume" occurs until there has been a "produce." The producer thread that owns the monitor (by calling Monitor.Enter()) calls Monitor.Pulse() to signal the consumer thread (which may already have called Monitor.Enter()) that an item is available for consumption and that it should "get ready." For a single Pulse() call, only one thread (the consumer thread, in this case) can enter the ready queue. When the producer thread calls Monitor.Exit(), the consumer thread takes the lock (Monitor.Enter() completes) and enters the critical section to begin "consuming" the item. Once the consumer processes the waiting item, it calls Exit(), thus allowing the producer (currently blocked with Monitor.Enter()) to produce again. In this example, only one thread can enter the ready queue at a time, ensuring that there is no "consumption" without "production," and vice versa.

End 4.0

Using the lock Keyword

Because of the frequent need for synchronization using Monitor in multithreaded code, and because the try/finally block can easily be forgotten, C# provides a special keyword to handle this locking synchronization pattern. Listing 19.5 demonstrates the use of the `lock` keyword, and Output 19.3 shows the results.

Listing 19.5: Synchronization Using the lock Keyword

```
using System;
using System.Threading;
using System.Threading.Tasks;

public class Program
{
    readonly static object _Sync = new object();
    const int _Total = int.MaxValue;
    static long _Count = 0;

    public static void Main()
    {
        // Use Task.Factory.StartNew for .NET 4.0
        Task task = Task.Run(()=>Decrement());

        // Increment
        for(int i = 0; i < _Total; i++)
        {
            lock(_Sync)
            {
                _Count++;
            }
        }

        task.Wait();
        Console.WriteLine($"Count = {_Count}");
    }

    static void Decrement()
    {
        for(int i = 0; i < _Total; i++)
        {
            lock(_Sync)
            {
                _Count--;
            }
        }
    }
}
```

Output 19.3

```
Count = 0
```

By locking the section of code accessing `_Count` (using either `lock` or `Monitor`), you make the `Main()` and `Decrement()` methods thread-safe, meaning they can be safely called from multiple threads simultaneously. (Prior to C# 4.0, the concept was the same but the compiler-emitted code depended on the `lockTaken`-less `Monitor.Enter()` method and the `Monitor.Enter()` called was emitted before the try block.)

The price of synchronization is a reduction in performance. Listing 19.5, for example, takes an order of magnitude longer to execute than Listing 19.1 does, which demonstrates `lock`'s relatively slow execution compared to the execution of incrementing and decrementing the count.

Even when `lock` is insignificant in comparison with the work it synchronizes, programmers should avoid indiscriminate synchronization so as to avoid the possibility of deadlocks and unnecessary synchronization on multiprocessor computers that could instead be executing code in parallel. The general best practice for object design is to synchronize mutable static state and not any instance data. (There is no need to synchronize something that never changes.) Programmers who allow multiple threads to access a particular object must provide synchronization for the object. Any class that explicitly deals with threads is likely to want to make instances thread-safe to some extent.

Choosing a `lock` Object

Whether or not the `lock` keyword or the `Monitor` class is explicitly used, it is crucial that programmers carefully select the `lock` object.

In the previous examples, the synchronization variable, `_Sync`, is declared as both private and read-only. It is declared as read-only to ensure that the value is not changed between calls to `Monitor.Enter()` and `Monitor.Exit()`. This allows correlation between entering and exiting the synchronized block.

Similarly, the code declares `_Sync` as private so that no synchronization block outside the class can synchronize the same object instance, causing the code to block.

If the data is public, the synchronization object may be public so that other classes can synchronize using the same object instance. However, this makes it harder to avoid deadlock. Fortunately, the need for this pattern is rare. For public data, it is instead preferable to leave synchronization entirely outside the class, allowing the calling code to take locks with its own synchronization object.

It's important that the synchronization object not be a value type. If the `lock` keyword is used on a value type, the compiler will report an error. (In the case of accessing the `System.Threading.Monitor` class explicitly [not via `lock`], no such error will occur at compile time. Instead, the code will throw an exception with the call to `Monitor.Exit()`, indicating there was no corresponding `Monitor.Enter()` call.) The issue is that when using a value type, the runtime makes a copy of the value, places it in the heap (boxing occurs), and passes the boxed value to `Monitor.Enter()`. Similarly, `Monitor.Exit()` receives a boxed copy of the original variable. The result is that `Monitor.Enter()` and `Monitor.Exit()` receive different synchronization object instances so that no correlation between the two calls occurs.

Why to Avoid Locking on `this`, `typeof(type)`, and `string`

One common pattern is to lock on the `this` keyword for instance data in a class, and on the type instance obtained from `typeof(type)` (for example, `typeof(MyType)`) for static data. Such a pattern provides a synchronization target for all states associated with a particular object instance when `this` is used, and all static data for a type when `typeof(type)` is used. The problem is that the synchronization target that `this` (or `typeof(type)`) points to could participate in the synchronization target for an entirely different synchronization block created in an unrelated block of code. In other words, although only the code within the instance itself can block using the `this` keyword, the caller that created the instance can pass that instance to a synchronization lock.

The result is that two different synchronization blocks that synchronize two entirely different sets of data could block each other. Although perhaps unlikely, sharing the same synchronization target could have an unintended performance impact and, in extreme cases, could even cause a deadlock. Instead of locking on `this` or even `typeof(type)`, it is better to define a private, read-only field on which no one will block except for the class that has access to it.

Another lock type to avoid is `string` due to string interning. If the same `string` constant appears within multiple locations, it is likely that all locations will refer to the same instance, making the scope of the lock much broader than expected.

In summary, you should use a per-synchronization context instance of type `object` for the lock target.

Guidelines

AVOID locking on `this`, `typeof()`, or a `string`.

DO declare a separate, read-only synchronization variable of type `object` for the synchronization target.

ADVANCED TOPIC

Avoid Synchronizing with `MethodImplAttribute`

One synchronization mechanism that was introduced in .NET 1.0 was the `MethodImplAttribute`. Used in conjunction with the `MethodImplOptions.Synchronized` method, this attribute marks a method as synchronized so that only one thread can execute the method at a time. To achieve this, the just-in-time compiler essentially treats the method as though it was surrounded by `lock(this)` or, in the case of a static method, locks on the type. Such an implementation means that, in fact, the method and all other methods on the same class, decorated with the same attribute and enum parameter, are synchronized—rather than each method being synchronized relative to itself. In other words, given two or more methods on the same class decorated with the attribute, only one of them will be able to execute at a time and the one executing will block all calls by other threads to itself or to any other method in the class with the same decoration. Furthermore, since the synchronization is on `this` (or even worse, on the type), it suffers the same detriments as `lock(this)` (or worse, for the static) discussed in the preceding section. As a result, it is a best practice to avoid the attribute altogether.

Guidelines

AVOID using the `MethodImplAttribute` for synchronization.

Declaring Fields As `volatile`

On occasion, the compiler or CPU may optimize code in such a way that the instructions do not occur in the exact order they are coded, or some instructions are optimized out. Such optimizations are innocuous when code executes on one thread. However, with multiple threads, such optimizations may have unintended consequences because the optimizations may change the order of execution of a field's read or write operations relative to an alternate thread's access to the same field.

One way to stabilize this behavior is to declare fields using the `volatile` keyword. This keyword forces all reads and writes to the volatile field to occur at the exact location the code identifies instead of at some other location that the optimization produces. The `volatile` modifier identifies that the field is susceptible to modification by the hardware, operating system, or another thread. As such, the data is "volatile," and the keyword instructs the compilers and runtime to handle it more exactly. (See http://bit.ly/CSharpReorderingOptimizations for further details.)

In general, the use of the `volatile` modifier is rare and fraught with complications that will likely lead to incorrect usage. Using `lock` is preferred to the `volatile` modifier unless you are absolutely certain about the `volatile` usage.

Using the `System.Threading.Interlocked` Class

The mutual exclusion pattern described so far provides the minimum set of tools for handling synchronization within a process (application domain). However, synchronization with `System.Threading.Monitor` is a relatively expensive operation, and an alternative solution that the processor supports directly targets specific synchronization patterns.

Listing 19.6 sets `_Data` to a new value as long as the preceding value was `null`. As indicated by the method name, this pattern is the compare/exchange pattern. Instead of manually placing a lock around behaviorally equivalent compare and exchange code, the `Interlocked.CompareExchange()` method provides a built-in method for a synchronous operation that does the same check for a value (`null`) and updates the first parameter if the value is equal to the second parameter. Table 19.2 shows other synchronization methods supported by `Interlocked`.

Listing 19.6: Synchronization Using `System.Threading.Interlocked`

```
public class SynchronizationUsingInterlocked
{
    private static object _Data;

    // Initialize data if not yet assigned.
    static void Initialize(object newValue)
    {
        // If _Data is null, then set it to newValue.
        Interlocked.CompareExchange(
            ref _Data, newValue, null);
    }

    // ...
}
```

Table 19.2: `Interlocked`'s Synchronization-Related Methods

Begin 2.0

Method Signature	Description
`public static T CompareExchange<T>( T location, T value, T comparand );`	Checks `location` for the value in `comparand`. If the values are equal, it sets `location` to `value` and returns the original data stored in `location`.
`public static T Exchange<T>( T location, T value );`	Assigns `location` with `value` and returns the previous value.
`public static int Decrement( ref int location );`	Decrements `location` by one. It is equivalent to the `prefix --` operator, except `Decrement()` is thread-safe.
`public static int Increment( ref int location );`	Increments `location` by one. It is equivalent to the prefix `++` operator, except `Increment()` is thread-safe.
`public static int Add( ref int location, int value );`	Adds `value` to `location` and assigns `location` the result. It is equivalent to the `+=` operator.
`public static long Read( ref long location );`	Returns a 64-bit value in a single atomic operation.

End 2.0

Most of these methods are overloaded with additional data type signatures, such as support for `long`. Table 19.2 provides the general signatures and descriptions.

Note that you can use `Increment()` and `Decrement()` in place of the synchronized `++` and `--` operators from Listing 19.6, and doing so will yield better performance. Also note that if a different thread accessed `location` using a non-interlocked method, the two accesses would not be synchronized correctly.

Event Notification with Multiple Threads

One area where developers often overlook synchronization is when firing events. The unsafe thread code for publishing an event is similar to Listing 19.7.

Listing 19.7: Firing an Event Notification

```
// Not thread-safe
if(OnTemperatureChanged != null)
{
  // Call subscribers
  OnTemperatureChanged(
      this, new TemperatureEventArgs(value) );
}
```

This code is valid as long as there is no race condition between this method and the event subscribers. However, the code is not atomic, so multiple threads could introduce a race condition. It is possible that between the time when `OnTemperatureChange` is checked for `null` and the event is actually fired, `OnTemperatureChange` could be set to `null`, thereby throwing a `NullReferenceException`. In other words, if multiple threads could potentially access a delegate simultaneously, it is necessary to synchronize the assignment and firing of the delegate.

The C# 6.0 solution to this dilemma is trivial. All that is necessary is to use the null-conditional operator:

```
OnTemperature?.Invoke(
    this, new TemperatureEventArgs( value ) );
```

The null-conditional operator is specifically designed to be atomic, so this invocation of the delegate is, in fact, atomic. The key, obviously, is to remember to make use of the null-conditional operator.

Although it requires more code, thread-safe delegate invocation prior to C# 6.0 isn't especially difficult, either. This approach works because the operators for adding and removing listeners are thread-safe and static (operator overloading is done with static methods). To correct Listing 19.7 and make it thread-safe, assign a copy, check the copy for `null`, and fire the copy (see Listing 19.8).

LISTING 19.8: Thread-Safe Event Notification

```
// ...
TemperatureChangedHandler localOnChange =
    OnTemperatureChanged;
if(localOnChanged != null)
{
  // Call subscribers
  localOnChanged(
      this, new TemperatureEventArgs(value) );
}
// ...
```

Given that a delegate is a reference type, it is perhaps surprising that assigning a local variable and then firing with the local variable is sufficient for making the null check thread-safe. As `localOnChange` points to the same location that `OnTemperatureChange` points to, you might think that any changes in `OnTemperatureChange` would be reflected in `localOnChange` as well.

However, this is not the case: Any calls to `OnTemperatureChange += <listener>` will not add a new delegate to `OnTemperatureChange`, but rather will assign it an entirely new multicast delegate without having any effect on the original multicast delegate to which `localOnChange` also points. This makes the code thread-safe because only one thread will access the `localOnChange` instance, and `OnTemperatureChange` will be an entirely new instance if listeners are added or removed.

Synchronization Design Best Practices

Along with the complexities of multithreaded programming come several best practices for handling those complexities.

Avoiding Deadlock

With the introduction of synchronization comes the potential for deadlock. Deadlock occurs when two or more threads wait for one another to release a synchronization lock. For example, suppose Thread 1 requests a lock on `_Sync1`, and then later requests a lock on `_Sync2` before releasing the lock on `_Sync1`. At the same time, Thread 2 requests a lock on `_Sync2`, followed by a lock on `_Sync1`, before releasing the lock on `_Sync2`. This sets the stage for the deadlock. The deadlock actually occurs if both Thread 1 and Thread 2 successfully acquire their initial locks (`_Sync1` and `_Sync2`, respectively) before obtaining their second locks.

For a deadlock to occur, four fundamental conditions must be met:

1. *Mutual exclusion:* One thread (`ThreadA`) exclusively owns a resource such that no other thread (`ThreadB`) can acquire the same resource.
2. *Hold and wait:* One thread (`ThreadA`) with a mutual exclusion is waiting to acquire a resource held by another thread (`ThreadB`).
3. *No preemption:* The resource held by a thread (`ThreadA`) cannot be forcibly removed (`ThreadA` needs to release its own locked resource).
4. *Circular wait condition:* Two or more threads form a circular chain such that they lock on the same two or more resources and each waits on the resource held by the next thread in the chain.

Removing any one of these conditions will prevent the deadlock.

A scenario likely to cause a deadlock is when two or more threads request exclusive ownership on the same two or more synchronization targets (resources) and the locks are requested in different orders. This situation can be avoided when developers are careful to ensure that multiple lock acquisitions always occur in the same order. Another cause of a deadlock is locks that are not **reentrant.** When a lock from one thread can block the same thread—that is, when it re-requests the same lock—the lock is not reentrant. For example, if `ThreadA` acquires a lock and then re-requests the same lock but is blocked because the lock is already owned (by itself), the lock is not reentrant and the additional request will deadlock. Therefore, locks that are not reentrant can occur only with a single thread.

The code generated by the `lock` keyword (with the underlying `Monitor` class) is reentrant. However, as we shall see in the "More Synchronization Types" section, some lock types are not reentrant.

When to Provide Synchronization

As we discussed earlier, all static data should be thread-safe. Therefore, synchronization needs to surround static data that is mutable. Generally, programmers should declare private static variables and then provide public methods for modifying the data. Such methods should internally handle the synchronization if multithreaded access is possible.

In contrast, instance state is not expected to include synchronization. Synchronization may significantly decrease performance and increase the chance of a lock contention or deadlock. With the exception of classes that are explicitly designed for multithreaded access, programmers sharing objects across multiple threads are expected to handle their own synchronization of the data being shared.

Avoiding Unnecessary Locking

Without compromising data integrity, programmers should avoid unnecessary synchronization where possible. For example, you should use immutable types between threads so that no synchronization is necessary (this approach has proved invaluable in functional programming languages such as F#). Similarly, you should avoid locking on thread-safe operations such as simple reads and writes of values smaller than a native (pointer-size) integer, as such operations are automatically atomic.

Guidelines

DO NOT request exclusive ownership on the same two or more synchronization targets in different orders.

DO ensure that code that concurrently holds multiple locks always acquires them in the same order.

DO encapsulate mutable static data in public APIs with synchronization logic.

AVOID synchronization on simple reading or writing of values no bigger than a native (pointer-size) integer, as such operations are automatically atomic.

More Synchronization Types

In addition to `System.Threading.Monitor` and `System.Threading.Interlocked`, several more synchronization techniques are available.

Using `System.Threading.Mutex`

Begin 2.0

`System.Threading.Mutex` is similar in concept to the `System.Threading.Monitor` class (without the `Pulse()` method support), except that the `lock` keyword does not use it and `Mutex`es can be named so that they support synchronization across multiple processes. Using the `Mutex` class, you can synchronize access to a file or some other cross-process resource. Since `Mutex` is a cross-process resource, .NET 2.0 added support to allow for setting the access control via a `System.Security.AccessControl.MutexSecurity` object. One use for the `Mutex` class is to limit an application so that it cannot run multiple times simultaneously, as Listing 19.9 demonstrates.

End 2.0

Listing 19.9: Creating a Single Instance Application

```
using System;
using System.Threading;
using System.Reflection;

public class Program
{
  public static void Main()
  {
      // Indicates whether this is the first
      // application instance.
      bool firstApplicationInstance;

      // Obtain the mutex name from the full
      // assembly name.
      string mutexName =
          Assembly.GetEntryAssembly().FullName;

      using(Mutex mutex = new Mutex(false, mutexName,
          out firstApplicationInstance))
      {

          if(!firstApplicationInstance)
          {
              Console.WriteLine(
                  "This application is already running.");
          }
          else
          {
              Console.WriteLine("ENTER to shut down");
              Console.ReadLine();
          }
      }
  }
}
```

The results from running the first instance of the application appear in Output 19.4.

Output 19.4

```
ENTER to shut down
```

The results of the second instance of the application while the first instance is still running appear in Output 19.5.

Output 19.5

```
This application is already running.
```

In this case, the application can run only once on the machine, even if it is launched by different users. To restrict the instances to once per user, prefix `Assembly.GetEntryAssembly().FullName` with a combination of the `System.Environment.UserDomainName` and the `System.Environment.UserName`.

`Mutex` derives from `System.Threading.WaitHandle`, so it includes the `WaitAll()`, `WaitAny()`, and `SignalAndWait()` methods. These methods allow it to acquire multiple locks automatically—something `Monitor` does not support.

WaitHandle

The base class for `Mutex` is a `System.Threading.WaitHandle`. This is a fundamental synchronization class used by the `Mutex`, `EventWaitHandle`, and `Semaphore` synchronization classes. The key methods on a `WaitHandle` are the `WaitOne()` methods. These methods block execution until the `WaitHandle` instance is signaled or set. The `WaitOne()` methods include several overloads allowing for an indefinite wait: `void WaitOne()`, a millisecond-timed wait; `bool WaitOne(int milliseconds)`; and `bool WaitOne(TimeSpan timeout)`, a `TimeSpan` wait. The versions that return a Boolean will return a value of `true` whenever the `WaitHandle` is signaled before the timeout.

In addition to the `WaitHandle` instance methods, there are two key static members: `WaitAll()` and `WaitAny()`. Like their instance cousins, these static members support timeouts. In addition, they take a collection of `WaitHandles`, in the form of an array, so that they can respond to signals coming from within the collection.

Note that `WaitHandle` contains a handle (of type `SafeWaitHandle`) that implements `IDisposable`. As such, care is needed to ensure that `WaitHandles` are disposed when they are no longer needed.

Begin 4.0

Reset Events: ManualResetEvent and ManualResetEventSlim

One way to control uncertainty about when particular instructions in a thread will execute relative to instructions in another thread is with reset events. In spite of the term events, reset events have nothing to do with C# delegates and events. Instead, reset events are a way to force code to wait for the execution of another thread until the other thread signals. They are especially useful for testing multithreaded code because it is possible to wait for a particular state before verifying the results.

The reset event types are `System.Threading.ManualResetEvent` and the .NET Framework 4–added lightweight version, `System.Threading.ManualResetEventSlim`. (As discussed in the upcoming Advanced Topic, there is a third type, `System.Threading.AutoResetEvent`, but programmers should avoid it in favor of one of the first two—see the Advanced Topic, "Favor `ManualResetEvent` and Semaphores over `AutoResetEvent`.") The key methods on the reset events are `Set()` and `Wait()` (called `WaitOne()` on `ManualResetEvent`). Calling the `Wait()` method will cause a thread to block until a different thread calls `Set()`, or until the wait period times out. Listing 19.10 demonstrates how this works, and Output 19.6 shows the results.

LISTING 19.10: Waiting for `ManualResetEventSlim`

```
using System;
using System.Threading;
using System.Threading.Tasks;

public class Program
{
  static ManualResetEventSlim MainSignaledResetEvent;
  static ManualResetEventSlim DoWorkSignaledResetEvent;

  public static void DoWork()
  {
      Console.WriteLine("DoWork() started....");
      DoWorkSignaledResetEvent.Set();
      MainSignaledResetEvent.Wait();
      Console.WriteLine("DoWork() ending....");
  }

  public static void Main()
  {
```

```
            using(MainSignaledResetEvent =
                new ManualResetEventSlim())
            using (DoWorkSignaledResetEvent =
                new ManualResetEventSlim())
            {
                Console.WriteLine(
                    "Application started....");
                Console.WriteLine("Starting task....");

                // Use Task.Factory.StartNew for .NET 4.0.
                Task task = Task.Run(()=>DoWork());

                // Block until DoWork() has started.
                DoWorkSignaledResetEvent.Wait();
                Console.WriteLine(
                    " Waiting while thread executes...");
                MainSignaledResetEvent.Set();
                task.Wait();
                Console.WriteLine("Thread completed");
                Console.WriteLine(
                    "Application shutting down....");
            }
        }
    }
```


Output 19.6

```
Application started....
Starting thread....
DoWork() started....
Waiting while thread executes...
DoWork() ending....
Thread completed
Application shutting down....
```

Listing 19.10 begins by instantiating and starting a new `Task`. Table 19.3 on the next page shows the execution path in which each column represents a thread. In cases where code appears on the same row, it is indeterminate which side executes first.

Calling a reset event's `Wait()` method (for a `ManualResetEvent`, it is called `WaitOne()`) blocks the calling thread until another thread signals and allows the blocked thread to continue. Instead of blocking indefinitely, `Wait()`/`WaitOne()` overrides include a parameter, either in milliseconds or as a `TimeSpan` object, for the maximum amount of time to block. When specifying a timeout period, the return from `WaitOne()` will be `false` if the timeout occurs before the reset event is signaled. `ManualResetEvent.Wait()`

Table 19.3: Execution Path with ManualResetEvent Synchronization

Main()	DoWork()
...	
Console.WriteLine("Application started....");	
Task task = new Task(DoWork);	
Console.WriteLine("Starting thread....");	
task.Start();	
DoWorkSignaledResetEvent.Wait();	Console.WriteLine("DoWork() started....");
	DoWorkSignaledResetEvent.Set();
Console.WriteLine("Thread executing...");	MainSignaledResetEvent.Wait();
MainSignaledResetEvent.Set();	
task.Wait();	Console.WriteLine("DoWork() ending....");
Console.WriteLine("Thread completed");	
Console.WriteLine("Application exiting....");	

4.0

also includes a version that takes a cancellation token, allowing for cancellation requests as discussed in Chapter 18.

The difference between `ManualResetEventSlim` and `ManualResetEvent` is the fact that the latter uses kernel synchronization by default whereas the former is optimized to avoid trips to the kernel except as a last resort. Thus, `ManualResetEventSlim` is more performant even though it could possibly use more CPU cycles. For this reason, you should use `ManualResetEventSlim` in general unless waiting on multiple events or across processes is required.

Notice that reset events implement `IDisposable`, so they should be disposed when they are no longer needed. In Listing 19.10, we do this via a `using` statement. (`CancellationTokenSource` contains a `ManualResetEvent`, which is why it, too, implements `IDisposable`.)

Although not exactly the same, `System.Threading.Monitor`'s `Wait()` and `Pulse()` methods provide similar functionality to reset events in some circumstances.

ADVANCED TOPIC

Favor ManualResetEvent and Semaphores over AutoResetEvent

There is a third reset event, `System.Threading.AutoResetEvent`, that, like `ManualResetEvent`, allows one thread to signal (with a call to `Set()`) another thread that this first thread has reached a certain location in the code. The difference is that the `AutoResetEvent` unblocks only one thread's `Wait()` call: After the first thread passes through the auto-reset gate, it goes back to locked. With the auto-reset event, it is all too easy to mistakenly code the producer thread with more iterations than the consumer thread. Therefore, use of `Monitor`'s `Wait()`/`Pulse()` pattern or use a semaphore (if fewer than *n* threads can participate in a particular block) is generally preferred.

In contrast to an `AutoResetEvent`, the `ManualResetEvent` won't return to the unsignaled state until `Reset()` is called explicitly.

4.0

Semaphore/SemaphoreSlim and CountdownEvent

`Semaphore` and `SemaphoreSlim` have the same performance differences as `ManualResetEvent` and `ManualResetEventSlim`. Unlike `ManualResetEvent`/`ManualResetEventSlim`, which provide a lock (like a gate) that is either open or closed, semaphores restrict only *N* calls to pass within a critical section simultaneously. The semaphore essentially keeps a count of the pool of resources. When this count reaches zero, it blocks any further access to the pool until one of the resources is returned, making it available for the next blocked request that is queued.

`CountdownEvent` is much like a semaphore, except it achieves the opposite synchronization. That is, rather than protecting further access to a pool of resources that are all used up, the `CountdownEvent` allows access only once the count reaches zero. Consider, for example, a parallel operation that downloads a multitude of stock quotes. Only when all of the quotes are downloaded can a particular search algorithm execute. The `CountdownEvent` may be used for synchronizing the search algorithm, decrementing the count as each stock is downloading, and then releasing the search to start once the count reaches zero.

Begin 5.0

End 5.0

Notice that SemaphoreSlim and CountdownEvent were introduced with .NET Framework 4. In .NET 4.5, the former includes a SemaphoreSlim .WaitAsync() method so that TAP can be used when waiting to enter the semaphore.

Concurrent Collection Classes

Another series of classes introduced with .NET Framework 4 is the concurrent collection classes. These classes are especially designed to include built-in synchronization code so that they can support simultaneous access by multiple threads without concern for race conditions. A list of the concurrent collection classes appears in Table 19.4.

A common pattern enabled by concurrent collections is support for thread-safe access by producers and consumers. Classes that implement IProducerConsumerCollection<T> (identified by * in Table 19.4) are specifically designed to provide such support. This enables one or more classes to be pumping data into the collection while a different set reads it out, removing it. The order in

4.0

TABLE 19.4: Concurrent Collection Classes

Collection Class	Description
BlockingCollection<T>	Provides a blocking collection that enables producer/consumer scenarios in which producers write data into the collection while consumers read the data. This class provides a generic collection type that synchronizes add and remove operations without concern for the backend storage (whether a queue, stack, list, and so on). BlockingCollection<T> provides blocking and bounding support for collections that implement the IProducerConsumerCollection<T> interface.
*ConcurrentBag<T>	A thread-safe unordered collection of T type objects.
ConcurrentDictionary<TKey, TValue>	A thread-safe dictionary; a collection of keys and values.
*ConcurrentQueue<T>	A thread-safe queue supporting first in, first out (FIFO) semantics on objects of type T.
*ConcurrentStack<T>	A thread-safe stack supporting first in, last out (FILO) semantics on objects of type T.

* Collection classes that implement IProducerConsumerCollection<T>.

which data is added and removed is determined by the individual collection classes that implement the `IProducerConsumerCollection<T>` interface.

Although it is not built into the out-of-the-box .NET Framework, an additional immutable collection library is available, called `System.Collections.Immutable`. The advantage of the immutable collection is that it can be passed freely between threads without concern for either deadlocks or interim updates. As immutable collections cannot be modified, interim updates won't occur; thus such collections are automatically thread-safe (so there is no need to lock access). For more information, see http://bit.ly/SystemCollectionsImmutable.

Thread Local Storage

In some cases, using synchronization locks can lead to unacceptable performance and scalability restrictions. In other instances, providing synchronization around a particular data element may be too complex, especially when it is added after the original coding.

One alternative solution to synchronization is isolation, and one method for implementing isolation is **thread local storage.** With thread local storage, each thread has its own dedicated instance of a variable. As a result, there is no need for synchronization, as there is no point in synchronizing data that occurs within only a single thread's context. Two examples of thread local storage implementations are `ThreadLocal<T>` and `ThreadStaticAttribute`. 4.0

ThreadLocal<T>

Use of thread local storage with .NET Framework 4 involves declaring a field (or variable, in the case of closure by the compiler) of type `ThreadLocal<T>`. The result is a different instance of the field for each thread, as demonstrated in Listing 19.11 and Output 19.7. Note that a different instance exists even if the field is static.

LISTING 19.11: Using ThreadLocal<T> for Thread Local Storage

```
using System;
using System.Threading;

public class Program
{
  static ThreadLocal<double> _Count =
      new ThreadLocal<double>(() => 0.01134);
```

```
    public static double Count
    {
        get { return _Count.Value; }
        set { _Count.Value = value; }
    }

    public static void Main()
    {
        Thread thread = new Thread(Decrement);
        thread.Start();

        // Increment
        for(double i = 0; i < short.MaxValue; i++)
        {
            Count++;
        }

        thread.Join();
        Console.WriteLine("Main Count = {0}", Count);
    }

    static void Decrement()
    {
        Count = -Count;
        for (double i = 0; i < short.MaxValue; i++)
        {
            Count--;
        }
        Console.WriteLine(
            "Decrement Count = {0}", Count);
    }
}
```

Output 19.7

```
Decrement Count = -32767.01134
Main Count = 32767.01134
```

As Output 19.7 demonstrates, the value of `Count` for the thread executing `Main()` is never decremented by the thread executing `Decrement()`. For `Main()`'s thread, the initial value is `0.01134` and the final value is `32767.01134`. `Decrement()` has similar values, except that they are negative. As `Count` is based on the static field of type `ThreadLocal<T>`, the thread running `Main()` and the thread running `Decrement()` have independent values stored in `_Count.Value`.

End 4.0

Thread Local Storage with ThreadStaticAttribute

Decorating a static field with a `ThreadStaticAttribute`, as in Listing 19.12, is a second way to designate a static variable as an instance per thread. This technique has a few caveats relative to `ThreadLocal<T>`, but it also has the advantage of being available prior to .NET Framework 4. (Also, since `ThreadLocal<T>` is based on the `ThreadStaticAttribute`, it would consume less memory and give a slight performance advantage given frequently enough repeated small iterations.)

Listing 19.12: Using ThreadStaticAttribute for Thread Local Storage

```
using System;
using System.Threading;

public class Program
{
    [ThreadStatic]
    static double _Count = 0.01134;
    public static double Count
    {
        get { return Program._Count; }
        set { Program._Count = value; }
    }

    public static void Main()
    {
        Thread thread = new Thread(Decrement);
        thread.Start();

        // Increment
        for(int i = 0; i < short.MaxValue; i++)
        {
            Count++;
        }

        thread.Join();
        Console.WriteLine("Main Count = {0}", Count);
    }

    static void Decrement()
    {
        for(int i = 0; i < short.MaxValue; i++)
        {
            Count--;
        }
        Console.WriteLine("Decrement Count = {0}", Count);
    }
}
```

The results of Listing 19.12 appear in Output 19.8.

Output 19.8

```
Decrement Count = -32767
Main Count = 32767.01134
```

As in Listing 19.11, the value of `Count` for the thread executing `Main()` is never decremented by the thread executing `Decrement()`. For `Main()`'s thread, the initial value is a negative `_Total` and the final value is `0`. In other words, with `ThreadStaticAttribute` the value of `Count` for each thread is specific to the thread and not accessible across threads.

Notice that unlike with Listing 19.11, the value displayed for the "Decrement Count" does not have any decimal digits, indicating it was never initialized to `0.01134`. Although the value of `_Count` is assigned during declaration—`private double _Count = 0.01134` in this example—only the thread static instance associated with the thread running the static constructor will be initialized. In Listing 19.12, only the thread executing `Main()` will have a thread local storage variable initialized to `0.01134`. The value of `_Count` that `Decrement()` decrements will always be initialized to `0` (`default(double)` since `_Count` is a `double`). Similarly, if a constructor initializes a thread local storage field, only the constructor calling that thread will initialize the thread local storage instance. For this reason, it is a good practice to initialize a thread local storage field within the method that each thread initially calls. However, this is not always reasonable, especially in connection with `async`, in which different pieces of computation might run on different threads, resulting in unexpectedly differing thread local storage values on each piece.

The decision to use thread local storage requires some degree of cost–benefit analysis. For example, consider using thread local storage for a database connection. Depending on the database management system, database connections are relatively expensive, so creating a connection for every thread could be costly. Similarly, locking a connection so that all database calls are synchronized places a significantly lower ceiling on scalability. Each pattern has its costs and benefits, and the best choice depends largely on the individual implementation.

Another reason to use thread local storage is to make commonly needed context information available to other methods without explicitly passing the data via parameters. For example, if multiple methods in the call stack require user security information, you can pass the data using thread local storage fields instead of as parameters. This keeps APIs cleaner while still making the information available to methods in a thread-safe manner. Such an approach requires that you ensure the thread local data is always set—a step that is especially important on `Tasks` or other thread pool threads because the underlying threads are reused.

Timers

Begin 5.0

On occasion, it is necessary to delay code execution for a specific period of time or to register for a notification after a specific period of time. Examples include refreshing the screen at a specific period rather than immediately when frequent data changes occur. One approach to implementing timers is to leverage the async/await pattern of C# 5.0 and the `Task.Delay()` method added in .NET 4.5. As we pointed out in Chapter 18, one key feature of TAP is that the code executing after an async call will continue in a supported thread context, thereby avoiding any UI cross-threading issues. Listing 19.13 provides an example of how to use the `Task.Delay()` method.

LISTING 19.13: Using `Task.Delay()` As a Timer

```
using System;
using System.Threading.Tasks;

public class Pomodoro
{
  // ...

  private static async Task TickAsync(
      System.Threading.CancellationToken token)
  {
      for(int minute = 0; minute < 25; minute++)
      {
          DisplayMinuteTicker(minute);
          for(int second = 0; second < 60; second++)
          {
              await Task.Delay(1000);
              if(token.IsCancellationRequested) break;
              DisplaySecondTicker();
          }
          if(token.IsCancellationRequested) break;
      }
  }
}
```

The call to `Task.Delay(1000)` will set a countdown timer that triggers after 1 second and executes the continuation code that appears after it.

Fortunately, in C# 5.0, TAP's use of the synchronization context specifically addressed executing UI-related code exclusively on the UI thread. Prior to that, it was necessary to use specific timer classes that were UI-thread-safe—or could be configured as such. Timers such as `System.Windows.Forms.Timer`, `System.Windows.Threading.DispatcherTimer`, and `System.Timers.Timer` (if configured appropriately) are UI-thread-friendly. Others, such as `System.Threading.Timer`, are optimized for performance.

End 5.0

ADVANCED TOPIC

Controlling the COM Threading Model with the STAThreadAttribute

With COM, four different apartment-threading models determine the threading rules relating to calls between COM objects. Fortunately, these rules—and the complexity that accompanied them—have disappeared from .NET as long as the program invokes no COM components. The general approach to handling COM interoperability issues is to place all .NET components within the main, single-threaded apartment by decorating a process's `Main` method with the `System.STAThreadAttribute`. In so doing, it is not necessary to cross apartment boundaries to invoke the majority of COM components. Furthermore, apartment initialization does not occur, unless a COM interop call is made. The caveat to this approach is that all other threads (including those of `Task`) will default to using a Multithreaded Apartment (MTA). In turn, care needs to be taken when invoking COM components from other threads besides the main one.

COM interop is not necessarily an explicit action by the developer. Microsoft implemented many of the components within the .NET Framework by creating a runtime callable wrapper (RCW) rather than rewriting all the COM functionality within managed code. As a result, COM calls are often made unknowingly. To ensure that these calls are always made from a single-threaded apartment, it is generally a good practice to decorate the main method of all Windows Forms executables with the `System.STAThreadAttribute`.

SUMMARY

In this chapter, we looked at various synchronization mechanisms and saw how a variety of classes are available to protect against race conditions. Coverage included the `lock` keyword, which leverages `System.Threading.Monitor` under the covers. Other synchronization classes include `System.Threading.Interlocked`, `System.Threading.Mutext`, `System.Threading.WaitHandle`, reset events, semaphores, and the concurrent collection classes.

In spite of all the progress made in improving multithreaded programming between early versions of .NET and today, synchronization of multithreaded programming remains complicated with numerous pitfalls. To avoid these sand traps, several best practices have been identified. They include consistently acquiring synchronization targets in the same order and wrapping static members with synchronization logic.

Before closing the chapter, we considered the `Task.Delay()` method, a .NET 4.5 introduced API for implementing a timer based on TAP.

The next chapter investigates another complex .NET technology: that of marshalling calls out of .NET and into unmanaged code using P/Invoke. In addition, it introduces a concept known as unsafe code, which C# uses to access memory pointers directly, as unmanaged code does (for example, C++).

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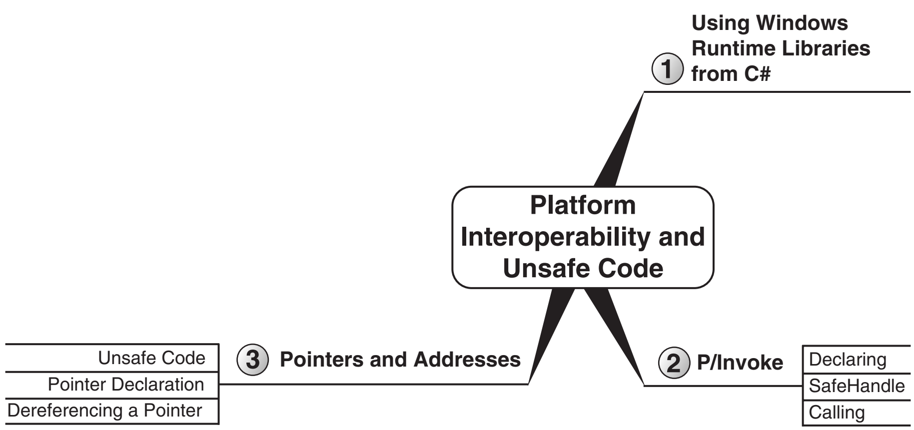
20

Platform Interoperability and Unsafe Code

C# HAS GREAT CAPABILITIES, PARTICULARLY WHEN paired with the .NET libraries. Sometimes, however, you do need to escape out of all the safety that C# provides and step back into the world of memory addresses and pointers. C# supports this action in four ways. The first option is to go through Platform Invoke (P/Invoke) and calls into APIs exposed by unmanaged DLLs. The second way is through **unsafe code,** which enables access to memory pointers and addresses. The third approach—although specific to Windows 8 or newer—is through the Windows Runtime (WinRT) API, which is exposing more and more of the operating system functions and making them directly available in C# 5.0 or higher. The last way, which is not covered in this text, is through COM interoperability.



The majority of the chapter discusses interoperability with unmanaged code, and the use of unsafe code. This discussion culminates with a small program that determines whether the computer is a virtual computer. The code requires that you do the following:

1. Call into an operating system DLL and request allocation of a portion of memory for executing instructions.
2. Write some assembler instructions into the allocated area.
3. Inject an address location into the assembler instructions.
4. Execute the assembler code.

Aside from the P/Invoke and unsafe constructs covered here, the full listing demonstrates the full power of C# and the fact that the capabilities of unmanaged code are still accessible from C# and managed code. We end this chapter by briefly discussing WinRT so developers are aware of some of its distinguishing characteristics before using it.

Platform Invoke

Whether a developer is trying to call a library of existing unmanaged code, accessing unmanaged code in the operating system not exposed in any managed API, or trying to achieve maximum performance for a particular algorithm by avoiding the runtime overhead of type checking and garbage collection, at some point there must be a call into unmanaged code. The CLI provides this capability through P/Invoke. With P/Invoke, you can make API calls into exported functions of unmanaged DLLs.

All of the APIs invoked in this section are Windows APIs. Although the same APIs are not available on other platforms, developers can still use P/Invoke for APIs native to their platform, or for calls into their own DLLs. The guidelines and syntax are the same.

Declaring External Functions

Once the target function is identified, the next step of P/Invoke is to declare the function with managed code. Just as with all regular methods that belong to a class, you need to declare the targeted API within the context of a class, but by using the `extern` modifier. Listing 20.1 demonstrates how to do this.

Listing 20.1: Declaring an External Method

```
using System;
using System.Runtime.InteropServices;
class VirtualMemoryManager
{
  [DllImport("kernel32.dll", EntryPoint="GetCurrentProcess")]
  internal static extern IntPtr GetCurrentProcessHandle();
}
```

In this case, the class is `VirtualMemoryManager`, because it will contain functions associated with managing memory. (This particular function is available directly off the `System.Diagnostics.Processor` class, so there is no need to declare it in real code.) Note that the method returns an `IntPtr`; this type is explained in the next section.

The `extern` methods never include any body and are (almost) always static. Instead of a method body, the `DllImport` attribute, which accompanies the method declaration, points to the implementation. At a minimum, the attribute needs the name of the DLL that defines the function. The runtime determines the function name from the method name, although you can override this default using the `EntryPoint` named parameter to provide the function name. (The .NET platform will automatically attempt calls to the Unicode [...W] or ASCII [...A] API version.)

It this case, the external function, `GetCurrentProcess()`, retrieves a pseudohandle for the current process that you will use in the call for virtual memory allocation. Here's the unmanaged declaration:

```
HANDLE GetCurrentProcess();
```

Parameter Data Types

Assuming the developer has identified the targeted DLL and exported function, the most difficult step is identifying or creating the managed data types that correspond to the unmanaged types in the external function.[1] Listing 20.2 shows a more difficult API.

Listing 20.2: The `VirtualAllocEx()` API

```
LPVOID VirtualAllocEx(
    HANDLE hProcess,   // The handle to a process. The
```

1. One particularly helpful resource for declaring Win32 APIs is www.pinvoke.net. It provides a great starting point for many APIs, helping you avoid some of the subtle problems that can arise when coding an external API call from scratch.

```
                           // function allocates memory within
                           // the virtual address space of this
                           // process.
       LPVOID lpAddress,   // The pointer that specifies a
                           // desired starting address for the
                           // region of pages that you want to
                           // allocate. If lpAddress is NULL,
                           // the function determines where to
                           // allocate the region.
       SIZE_T dwSize,      // The size of the region of memory to
                           // allocate, in bytes. If lpAddress
                           // is NULL, the function rounds dwSize
                           // up to the next page boundary.
       DWORD flAllocationType, // The type of memory allocation.
       DWORD flProtect);   // The type of memory allocation.
```

`VirtualAllocEx()` allocates virtual memory that the operating system specifically designates for execution or data. To call it, you need corresponding definitions in managed code for each data type; although common in Win32 programming, `HANDLE`, `LPVOID`, `SIZE_T`, and `DWORD` are undefined in the CLI managed code. The declaration in C# for `VirtualAllocEx()`, therefore, is shown in Listing 20.3.

LISTING 20.3: Declaring the `VirtualAllocEx()` API in C#

```
using System;
using System.Runtime.InteropServices;
class VirtualMemoryManager
{
  [DllImport("kernel32.dll")]
  internal static extern IntPtr GetCurrentProcess();

  [DllImport("kernel32.dll", SetLastError = true)]
  private static extern IntPtr VirtualAllocEx(
      IntPtr hProcess,
      IntPtr lpAddress,
      IntPtr dwSize,
      AllocationType flAllocationType,
      uint flProtect);
}
```

One distinct characteristic of managed code is that primitive data types such as `int` do not change their size based on the processor. Whether the processor is 16, 32, or 64 bits, `int` is always 32 bits. In unmanaged code, however, memory pointers will vary depending on the processor. Therefore, instead of mapping types such as `HANDLE` and `LPVOID` simply to `int`s, you need to map to `System.IntPtr`, whose size will vary depending on the processor memory layout. This example also uses an `AllocationType` enum, which we discuss in the section "Simplifying API Calls with Wrappers" later in this chapter.

An interesting point to note about Listing 20.3 is that `IntPtr` is not just useful for pointers; that is, it is useful for other things such as quantities. `IntPtr` does not mean just "pointer stored in an integer"; it also means "integer that is the size of a pointer." An `IntPtr` need not contain a pointer, but simply needs to contain something the size of a pointer. Lots of things are the size of a pointer but are nevertheless not pointers.

Using ref Rather Than Pointers

Frequently, unmanaged code uses pointers for pass-by-reference parameters. In these cases, P/Invoke doesn't require that you map the data type to a pointer in managed code. Instead, you map the corresponding parameters to `ref` (or `out`, depending on whether the parameter is `in/out` or just `out`). In Listing 20.4, `lpflOldProtect`, whose data type is `PDWORD`, is an example that returns the "pointer to a variable that receives the previous access protection of the first page in the specified region of pages."[2]

LISTING 20.4: Using ref and out Rather Than Pointers

```
class VirtualMemoryManager
{
  // ...
  [DllImport("kernel32.dll", SetLastError = true)]
  static extern bool VirtualProtectEx(
      IntPtr hProcess, IntPtr lpAddress,
      IntPtr dwSize, uint flNewProtect,
      ref uint lpflOldProtect);
}
```

Despite the fact that `lpflOldProtect` is documented as `[out]` (even though the signature doesn't enforce it), the description goes on to mention that the parameter must point to a valid variable and not `NULL`. This inconsistency is confusing, but commonly encountered. The guideline is to use `ref` rather than `out` for P/Invoke type parameters since the callee can always ignore the data passed with `ref`, but the converse will not necessarily succeed.

The other parameters are virtually the same as `VirtualAllocEx()`, except that the `lpAddress` is the address returned from `VirtualAllocEx()`. In

2. MSDN documentation.

addition, `flNewProtect` specifies the exact type of memory protection: page execute, page read-only, and so on.

Using StructLayoutAttribute for Sequential Layout

Some APIs involve types that have no corresponding managed type. Calling these types requires redeclaration of the type in managed code. You declare the unmanaged `COLORREF` struct, for example, in managed code (see Listing 20.5).

Listing 20.5: Declaring Types from Unmanaged Structs

```
[StructLayout(LayoutKind.Sequential)]
struct ColorRef
{
  public byte Red;
  public byte Green;
  public byte Blue;
  // Turn off warning about not accessing Unused.
  #pragma warning disable 414
  private byte Unused;
  #pragma warning restore 414

  public ColorRef(byte red, byte green, byte blue)
  {
      Blue = blue;
      Green = green;
      Red = red;
      Unused = 0;
  }
}
```

Various Microsoft Windows color APIs use `COLORREF` to represent RGB colors (that is, levels of red, green, and blue).

The key in this declaration is `StructLayoutAttribute`. By default, managed code can optimize the memory layouts of types, so layouts may not be sequential from one field to the next. To force sequential layouts so that a type maps directly and can be copied bit for bit (blitted) from managed to unmanaged code, and vice versa, you add the `StructLayoutAttribute` with the `LayoutKind.Sequential` enum value. (This is also useful when writing data to and from filestreams where a sequential layout may be expected.)

Since the unmanaged (C++) definition for `struct` does not map to the C# definition, there is not a direct mapping of unmanaged struct to managed struct. Instead, developers should follow the usual C# guidelines about whether the type should behave like a value or a reference type, and whether the size is small (approximately less than 16 bytes).

Error Handling

One inconvenient aspect of Win32 API programming is the fact that the APIs frequently report errors in inconsistent ways. For example, some APIs return a value (`0`, `1`, `false`, and so on) to indicate an error, whereas others set an `out` parameter in some way. Furthermore, the details of what went wrong require additional calls to the `GetLastError()` API and then an additional call to `FormatMessage()` to retrieve an error message corresponding to the error. In summary, Win32 error reporting in unmanaged code seldom occurs via exceptions.

Fortunately, the P/Invoke designers provided a mechanism for error handling. To enable it, if the `SetLastError` named parameter of the `DllImport` attribute is `true`, it is possible to instantiate a `System.ComponentModel.Win32Exception()` that is automatically initialized with the Win32 error data immediately following the P/Invoke call (see Listing 20.6).

LISTING 20.6: Win32 Error Handling

```
class VirtualMemoryManager
{
  [DllImport("kernel32.dll", ", SetLastError = true)]
  private static extern IntPtr VirtualAllocEx(
      IntPtr hProcess,
      IntPtr lpAddress,
      IntPtr dwSize,
      AllocationType flAllocationType,
      uint flProtect);

  // ...
  [DllImport("kernel32.dll", SetLastError = true)]
  static extern bool VirtualProtectEx(
      IntPtr hProcess, IntPtr lpAddress,
      IntPtr dwSize, uint flNewProtect,
      ref uint lpflOldProtect);

  [Flags]
  private enum AllocationType : uint
  {
      // ...
  }

  [Flags]
  private enum ProtectionOptions
```

```
    {
        // ...
    }

    [Flags]
    private enum MemoryFreeType
    {
        // ...
    }

    public static IntPtr AllocExecutionBlock(
        int size, IntPtr hProcess)
    {
        IntPtr codeBytesPtr;
        codeBytesPtr = VirtualAllocEx(
            hProcess, IntPtr.Zero,
            (IntPtr)size,
            AllocationType.Reserve | AllocationType.Commit,
            (uint)ProtectionOptions.PageExecuteReadWrite);

        if (codeBytesPtr == IntPtr.Zero)
        {
            throw new System.ComponentModel.Win32Exception();
        }

        uint lpflOldProtect = 0;
        if (!VirtualProtectEx(
            hProcess, codeBytesPtr,
            (IntPtr)size,
            (uint)ProtectionOptions.PageExecuteReadWrite,
            ref lpflOldProtect))
        {
            throw new System.ComponentModel.Win32Exception();
        }
        return codeBytesPtr;
    }

    public static IntPtr AllocExecutionBlock(int size)
    {
        return AllocExecutionBlock(
            size, GetCurrentProcessHandle());
    }
}
```

This code enables developers to provide the custom error checking that each API uses while still reporting the error in a standard manner.

Listing 20.1 and Listing 20.3 declared the P/Invoke methods as internal or private. Except for the simplest of APIs, wrapping methods in public wrappers that reduce the complexity of the P/Invoke API calls is a good guideline that increases API usability and moves toward object-oriented type structure. The `AllocExecutionBlock()` declaration in Listing 20.6 provides a good example of this approach.

> ### Guidelines
>
> **DO** create public managed wrappers around unmanaged methods that use the conventions of managed code, such as structured exception handling.

Using SafeHandle

Begin 2.0

Frequently, P/Invoke involves a resource, such as a window handle, that code needs to clean up after using. Instead of requiring developers to remember this step is necessary and manually code it each time, it is helpful to provide a class that implements `IDisposable` and a finalizer. In Listing 20.7, for example, the address returned after `VirtualAllocEx()` and `VirtualProtectEx()` requires a follow-up call to `VirtualFreeEx()`. To provide built-in support for this process, you define a `VirtualMemoryPtr` class that derives from `System.Runtime.InteropServices.SafeHandle`.

Listing 20.7: Managed Resources Using SafeHandle

```
public class VirtualMemoryPtr :
  System.Runtime.InteropServices.SafeHandle
{
  public VirtualMemoryPtr(int memorySize) :
      base(IntPtr.Zero, true)
  {
      ProcessHandle =
          VirtualMemoryManager.GetCurrentProcessHandle();
      MemorySize = (IntPtr)memorySize;
      AllocatedPointer =
          VirtualMemoryManager.AllocExecutionBlock(
          memorySize, ProcessHandle);
      Disposed = false;
  }

  public readonly IntPtr AllocatedPointer;
  readonly IntPtr ProcessHandle;
  readonly IntPtr MemorySize;
  bool Disposed;

  public static implicit operator IntPtr(
      VirtualMemoryPtr virtualMemoryPointer)
```

```
    {
        return virtualMemoryPointer.AllocatedPointer;
    }

    // SafeHandle abstract member
    public override bool IsInvalid
    {
        get
        {
            return Disposed;
        }
    }

    // SafeHandle abstract member
    protected override bool ReleaseHandle()
    {
        if (!Disposed)
        {
            Disposed = true;
            GC.SuppressFinalize(this);
            VirtualMemoryManager.VirtualFreeEx(ProcessHandle,
                AllocatedPointer, MemorySize);
        }
        return true;
    }
}
```

`System.Runtime.InteropServices.SafeHandle` includes the abstract members `IsInvalid` and `ReleaseHandle()`. You place your cleanup code in the latter; the former indicates whether this code has executed yet.

End 2.0

With `VirtualMemoryPtr`, you can allocate memory simply by instantiating the type and specifying the needed memory allocation.

Calling External Functions

Once you declare the P/Invoke functions, you invoke them just as you would any other class member. The key, however, is that the imported DLL must be in the path, including the executable directory, so that it can be successfully loaded. Listing 20.6 and Listing 20.7 provide demonstrations of this approach. However, they rely on some constants.

Since `flAllocationType` and `flProtect` are flags, it is a good practice to provide constants or enums for each. Instead of expecting the caller to define these constants or enums, encapsulation suggests you provide them as part of the API declaration, as shown in Listing 20.8.

LISTING 20.8: Encapsulating the APIs Together

```
class VirtualMemoryManager
{
  // ...

  /// <summary>
  /// The type of memory allocation. This parameter must
  /// contain one of the following values.
  /// </summary>
  [Flags]
  private enum AllocationType : uint
  {
      /// <summary>
      /// Allocates physical storage in memory or in the
      /// paging file on disk for the specified reserved
      /// memory pages. The function initializes the memory
      /// to zero.
      /// </summary>
      Commit = 0x1000,
      /// <summary>
      /// Reserves a range of the process's virtual address
      /// space without allocating any actual physical
      /// storage in memory or in the paging file on disk.
      /// </summary>
      Reserve = 0x2000,
      /// <summary>
      /// Indicates that data in the memory range specified by
      /// lpAddress and dwSize is no longer of interest. The
      /// pages should not be read from or written to the
      /// paging file. However, the memory block will be used
      /// again later, so it should not be decommitted. This
      /// value cannot be used with any other value.
      /// </summary>
      Reset = 0x80000,
      /// <summary>
      /// Allocates physical memory with read-write access.
      /// This value is solely for use with Address Windowing
      /// Extensions (AWE) memory.
      /// </summary>
      Physical = 0x400000,
      /// <summary>
      /// Allocates memory at the highest possible address.
      /// </summary>
      TopDown = 0x100000,
  }

  /// <summary>
  /// The memory protection for the region of pages to be
  /// allocated.
  /// </summary>
  [Flags]
  private enum ProtectionOptions : uint
```

```
    {
        /// <summary>
        /// Enables execute access to the committed region of
        /// pages. An attempt to read or write to the committed
        /// region results in an access violation.
        /// </summary>
        Execute = 0x10,
        /// <summary>
        /// Enables execute and read access to the committed
        /// region of pages. An attempt to write to the
        /// committed region results in an access violation.
        /// </summary>
        PageExecuteRead = 0x20,
        /// <summary>
        /// Enables execute, read, and write access to the
        /// committed region of pages.
        /// </summary>
        PageExecuteReadWrite = 0x40,
        // ...
    }

    /// <summary>
    /// The type of free operation
    /// </summary>
    [Flags]
    private enum MemoryFreeType : uint
    {
        /// <summary>
        /// Decommits the specified region of committed pages.
        /// After the operation, the pages are in the reserved
        /// state.
        /// </summary>
        Decommit = 0x4000,
        /// <summary>
        /// Releases the specified region of pages. After this
        /// operation, the pages are in the free state.
        /// </summary>
        Release = 0x8000
    }

    // ...
  }
```

The advantage of enums is that they group together the various values. Furthermore, they can limit the scope to nothing else besides these values.

Simplifying API Calls with Wrappers

Whether it is error handling, structs, or constant values, one goal of effective API developers is to provide a simplified managed API that wraps the underlying Win32 API. For example, Listing 20.9 overloads `VirtualFreeEx()` with public versions that simplify the call.

Listing 20.9: Wrapping the Underlying API

```
class VirtualMemoryManager
{
  // ...

  [DllImport("kernel32.dll", SetLastError = true)]
  static extern bool VirtualFreeEx(
      IntPtr hProcess, IntPtr lpAddress,
      IntPtr dwSize, IntPtr dwFreeType);
  public static bool VirtualFreeEx(
      IntPtr hProcess, IntPtr lpAddress,
      IntPtr dwSize)
  {
      bool result = VirtualFreeEx(
          hProcess, lpAddress, dwSize,
          (IntPtr)MemoryFreeType.Decommit);
      if (!result)
      {
          throw new System.ComponentModel.Win32Exception();
      }
      return result;
  }
  public static bool VirtualFreeEx(
      IntPtr lpAddress, IntPtr dwSize)
  {
      return VirtualFreeEx(
          GetCurrentProcessHandle(), lpAddress, dwSize);
  }

  [DllImport("kernel32", SetLastError = true)]
  static extern IntPtr VirtualAllocEx(
      IntPtr hProcess,
      IntPtr lpAddress,
      IntPtr dwSize,
      AllocationType flAllocationType,
      uint flProtect);

  // ...
}
```

Function Pointers Map to Delegates

One last key point related to P/Invoke is that function pointers in unmanaged code map to delegates in managed code. To set up a Microsoft Windows timer, for example, you would provide a function pointer that the timer could call back on, once it had expired. Specifically, you would pass a delegate instance that matches the signature of the callback.

Guidelines

Given the idiosyncrasies of P/Invoke, there are several guidelines to aid in the process of writing such code.

Guidelines

DO NOT unnecessarily replicate existing managed classes that already perform the function of the unmanaged API.

DO declare `extern` methods as private or internal.

DO provide public wrapper methods that use managed conventions such as structured exception handling, use of enums for special values, and so on.

DO simplify the wrapper methods by choosing default values for unnecessary parameters.

DO use the `SetLastErrorAttribute` to turn APIs that use `SetLastError` error codes into methods that throw `Win32Exception`.

DO extend `SafeHandle` or implement `IDisposable` and create a finalizer to ensure that unmanaged resources can be cleaned up effectively.

DO use delegate types that match the signature of the desired method when an unmanaged API requires a function pointer.

DO use `ref` parameters rather than pointer types when possible.

Pointers and Addresses

On occasion, developers may want to access and work with memory, and with pointers to memory locations, directly. This is necessary, for example, for certain operating system interactions as well as with certain types of time-critical algorithms. To support this capability, C# requires use of the unsafe code construct.

Unsafe Code

One of C#'s great features is the fact that it is strongly typed and supports type checking throughout the runtime execution. What makes this feature especially beneficial is that it is possible to circumvent this support and manipulate memory and addresses directly. You would do so when working with things such as memory-mapped devices, for example, or if you wanted to implement time-critical algorithms. The key is to designate a portion of the code as unsafe.

Unsafe code is an explicit code block and compilation option, as shown in Listing 20.10. The `unsafe` modifier has no effect on the generated CIL code itself, but rather is simply a directive to the compiler to permit pointer and address manipulation within the unsafe block. Furthermore, unsafe does not imply unmanaged.

LISTING 20.10: Designating a Method for Unsafe Code

```
class Program
{
  unsafe static int Main(string[] args)
  {
      // ...
  }
}
```

You can use `unsafe` as a modifier to the type or to specific members within the type.

In addition, C# allows `unsafe` as a statement that flags a code block to allow unsafe code (see Listing 20.11).

LISTING 20.11: Designating a Code Block for Unsafe Code

```
class Program
{
  static int Main(string[] args)
  {
      unsafe
      {
          // ...
      }
  }
}
```

Code within the `unsafe` block can include unsafe constructs such as pointers.

NOTE

It is necessary to explicitly indicate to the compiler that unsafe code is supported.

From the command line, notifying the compiler that unsafe code is supported requires using the `/unsafe` switch. For example, to compile the preceding code, you need to use the command shown in Output 20.1.

OUTPUT 20.1

```
csc.exe /unsafe Program.cs
```

With Visual Studio, you can activate this feature by checking the Allow Unsafe Code check box from the Build tab of the Project Properties window.

Using the `/unsafe` switch is necessary because unsafe code opens up the possibility of buffer overflows and similar outcomes that may potentially expose security holes. The `/unsafe` switch enables you to directly manipulate memory and execute instructions that are unmanaged. Requiring `/unsafe`, therefore, makes the choice of potential exposure explicit.

Pointer Declaration

Now that you have marked a code block as unsafe, it is time to look at how to write unsafe code. First, unsafe code allows the declaration of a pointer. Consider the following example:

```
byte* pData;
```

Assuming `pData` is not `null`, its value points to a location that contains one or more sequential `bytes`; the value of `pData` represents the memory address of the `bytes`. The type specified before the `*` is the **referent type,** or the type located where the value of the pointer refers. In this example, `pData` is the pointer and `byte` is the referent type, as shown in Figure 20.1.

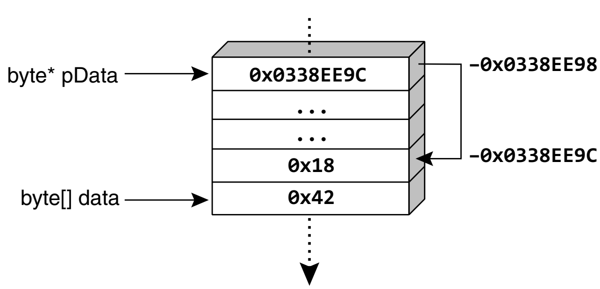


FIGURE 20.1: Pointers Contain the Address of the Data

Because pointers are simply integers that happen to refer to a memory address, they are not subject to garbage collection. C# does not allow referent types other than **unmanaged types,** which are types that are not reference types, are not generics, and do not contain reference types. Therefore, the following command is not valid:

```
string* pMessage;
```

Likewise, this command is not valid:

```
ServiceStatus* pStatus;
```

where `ServiceStatus` is defined as shown in Listing 20.12. The problem, once again, is that `ServiceStatus` includes a `string` field.

Language Contrast: C/C++—Pointer Declaration

In C/C++, multiple pointers within the same declaration are declared as follows:

```
int *p1, *p2;
```

Notice the `*` on `p2`; this makes `p2` an `int*` rather than an `int`. In contrast, C# always places the `*` with the data type:

```
int* p1, p2;
```

The result is two variables of type `int*`. The syntax matches that of declaring multiple arrays in a single statement:

```
int[] array1, array2;
```

Pointers are an entirely new category of type. Unlike structs, enums, and classes, pointers don't ultimately derive from `System.Object` and are not even convertible to `System.Object`. Instead, they are convertible (explicitly) to `System.IntPtr` (which can be converted to `System.Object`).

Listing 20.12: Invalid Referent Type Example

```
struct ServiceStatus
{
  int State;
  string Description;  // Description is a reference type
}
```

In addition to custom structs that contain only unmanaged types, valid referent types include enums, predefined value types (`sbyte`, `byte`, `short`, `ushort`, `int`, `uint`, `long`, `ulong`, `char`, `float`, `double`, `decimal`, and `bool`), and pointer types (such as `byte**`). Lastly, valid syntax includes `void*` pointers, which represent pointers to an unknown type.

Assigning a Pointer

Once code defines a pointer, it needs to assign a value before accessing it. Just like reference types, pointers can hold the value `null`; this is their default value. The value stored by the pointer is the address of a location. Therefore, to assign the pointer, you must first retrieve the address of the data.

You could explicitly cast an integer or a long into a pointer, but this rarely occurs without a means of determining the address of a particular data value at execution time. Instead, you need to use the address operator (`&`) to retrieve the address of the value type:

```
byte* pData = &bytes[0];  // Compile error
```

The problem is that in a managed environment, data can move, thereby invalidating the address. The error message is "You can only take the address of [an] unfixed expression inside a fixed statement initializer." In this case, the byte referenced appears within an array, and an array is a reference type (a movable type). Reference types appear on the heap and are subject to garbage collection or relocation. A similar problem occurs when referring to a value type field on a movable type:

```
int* a = &"message".Length;
```

Either way, to assign an address of some data requires the following.

- The data must be classified as a variable.
- The data must be an unmanaged type.
- The variable needs to be classified as fixed, not movable.

If the data is an unmanaged variable type but is not fixed, use the fixed statement to fix a movable variable.

Fixing Data

To retrieve the address of a movable data item, it is necessary to fix, or pin, the data, as demonstrated in Listing 20.13.

LISTING 20.13: Fixed Statement

```
byte[] bytes = new byte[24];
fixed (byte* pData = &bytes[0])  // pData = bytes also allowed
{
  // ...
}
```

Within the code block of a fixed statement, the assigned data will not move. In this example, `bytes` will remain at the same address, at least until the end of the fixed statement.

The fixed statement requires the declaration of the pointer variable within its scope. This avoids accessing the variable outside the fixed statement, when the data is no longer fixed. However, it is your responsibility as a programmer to ensure that you do not assign the pointer to another variable that survives beyond the scope of the fixed statement—possibly in an API call, for example. Unsafe code is called "unsafe" for a reason; you are required to ensure that you use the pointers safely rather than relying on the runtime to enforce safety on your behalf. Similarly, using `ref` or `out` parameters will be problematic for data that will not survive beyond the method call.

Since a string is an invalid referent type, it would appear invalid to define pointers to strings. However, as in C++, internally a string is a pointer to the first character of an array of characters, and it is possible to declare pointers to characters using `char*`. Therefore, C# allows for declaring a pointer of type `char*` and assigning it to a string within a fixed statement. The fixed statement prevents the movement of the string during the life of the pointer. Similarly, it allows any movable type that supports an implicit conversion to a pointer of another type, given a fixed statement.

You can replace the verbose assignment of `&bytes[0]` with the abbreviated `bytes`, as shown in Listing 20.14.

LISTING 20.14: Fixed Statement without Address or Array Indexer

```
byte[] bytes = new byte[24];
fixed (byte* pData = bytes)
{
  // ...
}
```

Depending on the frequency and time needed for their execution, fixed statements may have the potential to cause fragmentation in the heap because the garbage collector cannot compact fixed objects. To reduce this problem, the best practice is to pin blocks early in the execution and to pin fewer large blocks rather than many small blocks. Unfortunately, this preference has to be tempered with the practice of pinning as little as possible for as short a time as possible, so as to minimize the chance that a collection will happen during the time that the data is pinned. To some extent, .NET 2.0 reduces this problem, through its inclusion of some additional fragmentation-aware code.

It is possible that you might need to fix an object in place in one method body and have it remain fixed until another method is called; this is not possible with the `fixed` statement. If you are in this unfortunate situation, you can use methods on the `GCHandle` object to fix an object in place indefinitely. You should do so only if it is absolutely necessary, however; fixing an object for a long time makes it highly likely that the garbage collector will be unable to efficiently compact memory.

Allocating on the Stack

You should use the `fixed` statement on an array to prevent the garbage collector from moving the data. However, an alternative is to allocate the array on the call stack. Stack allocated data is not subject to garbage collection or to the finalizer patterns that accompany it. Like referent types, the requirement is that the `stackalloc` data is an array of unmanaged types. For example, instead of allocating an array of bytes on the heap, you can place it onto the call stack, as shown in Listing 20.15.

LISTING 20.15: Allocating Data on the Call Stack

```
byte* bytes = stackalloc byte[42];
```

Because the data type is an array of unmanaged types, the runtime can allocate a fixed buffer size for the array and then restore that buffer once the pointer goes out of scope. Specifically, it allocates `sizeof(T) * E`, where `E` is the array size and `T` is the referent type. Given the requirement of using `stackalloc` only on an array of unmanaged types, the runtime restores the buffer back to the system by simply unwinding the stack, thereby eliminating the complexities of iterating over the f-reachable queue (see, in Chapter 9, the section titled "Garbage Collection" and the discussion of finalization) and compacting reachable data. Therefore, there is no way to explicitly free `stackalloc` data.

The stack is a precious resource. Although it is small, running out of stack space will have a big effect—namely, the program will crash. For this reason, you should make every effort to avoid running out of stack space. If a program does run out of stack space, the best thing that can happen is for the program to shut down/crash immediately. Generally, programs have less than 1MB of stack space (possibly a lot less). Therefore, take great care to avoid allocating arbitrarily sized buffers on the stack.

Dereferencing a Pointer

Accessing the data stored in a variable of a type referred to by a pointer requires that you dereference the pointer, placing the indirection operator prior to the expression. `byte data = *pData;`, for example, dereferences the location of the `byte` referred to by `pData` and produces a variable of type `byte`. The variable provides read/write access to the single `byte` at that location.

Using this principle in unsafe code allows the unorthodox behavior of modifying the "immutable" string, as shown in Listing 20.16. In no way is this strategy recommended, even though it does expose the potential of low-level memory manipulation.

Listing 20.16: Modifying an Immutable String

```
string text = "S5280ft";
Console.Write("{0} = ", text);
unsafe  // Requires /unsafe switch.
{
  fixed (char* pText = text)
  {
      char* p = pText;
      *++p = 'm';
      *++p = 'i';
      *++p = 'l';
      *++p = 'e';
      *++p = ' ';
      *++p = ' ';
  }
}
Console.WriteLine(text);
```

The results of Listing 20.16 appear in Output 20.2.

Output 20.2

```
S5280ft = Smile
```

In this case, you take the original address and increment it by the size of the referent type (`sizeof(char)`), using the preincrement operator. Next, you dereference the address using the indirection operator and then assign the location with a different character. Similarly, using the + and – operators on a pointer changes the address by the `* sizeof(T)` operand, where `T` is the referent type.

Similarly, the comparison operators (`==`, `!=`, `<`, `>`, `<=`, and `>=`) work to compare pointers, translating effectively to the comparison of address location values.

One restriction on the dereferencing operator is the inability to dereference a `void*`. The `void*` data type represents a pointer to an unknown type. Since the data type is unknown, it can't be dereferenced to produce a variable. Instead, to access the data referenced by a `void*`, you must convert it to any other pointer type and then dereference the later type.

You can achieve the same behavior as implemented in Listing 20.16 by using the index operator rather than the indirection operator (see Listing 20.17).

Listing 20.17: Modifying an Immutable String with the Index Operator in Unsafe Code

```
string text;
text = "S5280ft";
Console.Write("{0} = ", text);

unsafe  // Requires /unsafe switch.
{
  fixed (char* pText = text)
  {
      pText[1] = 'm';
      pText[2] = 'i';
      pText[3] = 'l';
      pText[4] = 'e';
      pText[5] = ' ';
      pText[6] = ' ';
  }
}
Console.WriteLine(text);
```

The results of Listing 20.17 appear in Output 20.3.

Output 20.3

```
S5280ft = Smile
```

Modifications such as those in Listing 20.16 and Listing 20.17 can lead to unexpected behavior. For example, if you reassigned `text` to `"S5280ft"` following the `Console.WriteLine()` statement and then redisplayed `text`, the output would still be `Smile` because the address of two equal string literals is optimized to one string literal referenced by both variables. In spite of the apparent assignment

```
text = "S5280ft";
```

after the unsafe code in Listing 20.16, the internals of the string assignment are an address assignment of the modified `"S5280ft"` location, so `text` is never set to the intended value.

Accessing the Member of a Referent Type

Dereferencing a pointer produces a variable of the pointer's underlying type. You can then access the members of the underlying type using the member access "dot" operator in the usual way. However, the rules of operator precedence require that `*x.y` means `*(x.y)`, which is probably not what you intended. If `x` is a pointer, the correct code is `(*x).y`, which is an unpleasant syntax. To make it easier to access members of a dereferenced pointer, C# provides a special member access operator: `x->y` is a shorthand for `(*x).y`, as shown in Listing 20.18.

Listing 20.18: Directly Accessing a Referent Type's Members

```
unsafe
{
  Angle angle = new Angle(30, 18, 0);
  Angle* pAngle = &angle;
  System.Console.WriteLine("{0}° {1}' {2}\"",
      pAngle->Hours, pAngle->Minutes, pAngle->Seconds);
}
```

The results of Listing 20.18 appear in Output 20.4.

Output 20.4

```
30° 18' 0
```

Executing Unsafe Code via a Delegate

As promised at the beginning of this chapter, we finish up with a full working example of what is likely the most "unsafe" thing you can do in C#: obtain a pointer to a block of memory, fill it with the bytes of machine code, make a delegate that refers to the new code, and execute it. This particular bit of assembly code determines whether the machine that is executing the code is a virtual machine or a real machine. If the machine is virtual, it outputs "Inside Matrix!" Listing 20.19 shows how to do it.

BEGINNER TOPIC

What Is a Virtual Computer?

A **virtual computer** (or virtual machine), also called a **guest computer,** is virtualized or emulated through software running on the host operating system and interacting with the host computer's hardware. For example, virtual computer software (such as VMware Workstation and Microsoft Hyper-V) can be installed on a computer running a recent version of Windows. Once the software is installed, users can configure a guest computer within the software, boot it, and install an operating system as though it were a real computer, not just one virtualized with software.

Listing 20.19: Designating a Block for Unsafe Code

```
using System.Runtime.InteropServices;

class Program
{
  unsafe static int Main(string[] args)
  {
      // Assign redpill
      byte[] redpill = {
          0x0f, 0x01, 0x0d,       // asm SIDT instruction
          0x00, 0x00, 0x00, 0x00, // placeholder for an address
          0xc3};                  // asm return instruction

      unsafe
      {
          fixed (byte* matrix = new byte[6],
              redpillPtr = redpill)
          {
               // Move the address of matrix immediately
               // following the SIDT instruction of memory.
               *(uint*)&redpillPtr[3] = (uint)&matrix[0];
```

```
                using (VirtualMemoryPtr codeBytesPtr =
                    new VirtualMemoryPtr(redpill.Length))
                {
                    Marshal.Copy(
                        redpill, 0,
                        codeBytesPtr, redpill.Length);

                    MethodInvoker method =
                        (MethodInvoker)Marshal.GetDelegateForFunctionPointer(
                        codeBytesPtr, typeof(MethodInvoker));

                    method();
                }
                if (matrix[5] > 0xd0)
                {
                    Console.WriteLine("Inside Matrix!\n");
                    return 1;
                }
                else
                {
                    Console.WriteLine("Not in Matrix.\n");
                    return 0;
                }
            } // fixed
        } // unsafe
    }
}
```

The results of Listing 20.19 appear in Output 20.5.

Output 20.5

```
Inside Matrix!
```

Using the Windows Runtime Libraries from C#

Windows RT is the version of the Windows 8 operating system that supports only immersive "Metro-style" applications, not traditional "desktop" applications. The library of operating system APIs that support immersive applications is the **Windows Runtime,** or **WinRT** for short.

Although WinRT APIs are fundamentally unmanaged COM APIs, they are described using the same metadata format that the .NET runtime uses; thus WinRT supports development of immersive Windows applications written not only in unmanaged languages, but also in managed languages such as C#, without using the P/Invoke tricks described in the remainder of this chapter.

The WinRT APIs have been carefully designed to seem natural to C# users. However, there are a few small "impedance mismatches" that you should be aware of when writing C# programs that target WinRT.

WinRT Events with Custom Add and Remove Handlers

There are many different ways to implement the "observer" pattern. In C#, as we have already discussed, events are typically implemented as a field of multicast delegate type. That is, a field of delegate type is declared, and that delegate can refer to many different methods. When the event is fired, the delegate methods are invoked. To add an event handler to or remove an event handler from the event, you essentially create a new multicast delegate and replace the value of the field with the new delegate.

All of those mechanisms are implemented for you automatically when you use the `+=` and `-=` operators on an event. C# also allows you to run custom code when the user of your class adds or removes an event handler, via the `add` and `remove` event accessor methods.

From the consumer's perspective, WinRT events are no different. You can use `+=` and `-=` as usual in a C# program when adding or removing event handlers from a WinRT object; the C# compiler will take care of ensuring that the appropriate WinRT mechanisms are used when the code is generated. However, WinRT uses a slightly different mechanism than traditional C# programs for custom event accessors, which in turn affects how you write custom event accessors for WinRT types in C#.

In a regular C# event, when you remove a delegate from an event, the delegate is passed as the hidden `value` argument of the `remove` accessor. Neither the `add` nor the `remove` accessor returns a value. WinRT events with custom accessors use a slightly different mechanism: When you add a delegate to an event, the `add` accessor returns a "token." To remove that delegate from the event, you pass the token—not the delegate—to the `remove` accessor. Should you wish to write a custom accessor for a WinRT event, you must follow the WinRT event pattern.

Fortunately, the WinRT library provides a special helper class to keep track of the tokens and their corresponding delegates for you. The pattern looks like the code shown in Listing 20.20.

LISTING 20.20: The WinRT Event Pattern

```
using System;
class WinRTEvent
{
  EventRegistrationTokenTable<EventHandler> table = null;
  public event EventHandler MyEvent
  {
    add
    {
      return EventRegistrationTokenTable<EventHandler>
        .GetOrCreateEventRegistrationTokenTable(ref table)
        .AddEventHandler(value);
    }
    remove
    {
      return EventRegistrationTokenTable<EventHandler>
        .GetOrCreateEventRegistrationTokenTable(ref table)
        .RemoveEventHandler(value);
    }
  }
  void OnMyEvent()
  {
    EventHandler handler =
      EventRegistrationTokenTable<EventHandler>
        .GetOrCreateEventRegistrationTokenTable(ref table)
        .InvocationList;
      if (handler != null)
        handler(this, new EventArgs());
  }
}
```

As you can see, every time a handler is added to the event, removed from the event, or invoked, a table is created if one does not exist already. (There should be one table variable per event.) The table manages the relationship between the token returned from the adder and the multicast delegate in the table. Just replace the `EventHandler` type with the appropriate delegate type for your event, and add whatever code you want to the `add` and `remove` accessors.

Automatically Shimmed Interfaces

Another difference between WinRT invocation and regular .NET invocation code is that certain frequently used interfaces have slightly different names and members in WinRT. The C# compiler and .NET runtime know about these differences, and automatically generate code behind the scenes that "shims" one interface to another so as to minimize the impact on the developer. The two most notable examples are IEnumerable<T>, which is called IIterable<T> in WinRT, and IDisposable, which is called ICloseable in WinRT.

Because these interfaces are automatically shimmed, you can use a method that returns ICloseable in any context that requires an IDisposable, such as a using statement. Similarly, sequences and collections behave the same regardless of whether they use the C# standard interface or the WinRT version.

Task-Based Asynchrony

The WinRT APIs do not use Task<T> to represent asynchronous work. (See Chapter 18 for a detailed explanation of how to use Task<T> and the C# 5 await operator.) Rather, they use the IAsyncAction<T> interface. This type has many of the same features as Task<T>; for example, it supports a cancellation mechanism, a progress-reporting mechanism, and so on.

The C# 5 await operator works just as well with an operand of type IAsyncAction<T> as it does with Task<T>. However, a C# 5 method decorated with the async keyword that contains an await operator still must return Task or Task<T>, or be void-returning; it is not legal for an async method to return IAsyncAction<T>. To convert an IAsyncAction<T> to an equivalent Task<T>, just call the AsTask()method on it.

The vast majority of other issues related to WinRT are essentially API changes, and a detailed discussion of them is beyond the scope of this book. It is important to note, however, that in WinRT all high-latency synchronous methods previously available in .NET 4.5 and earlier have been dropped, leaving only the *Async asynchronous equivalents.

SUMMARY

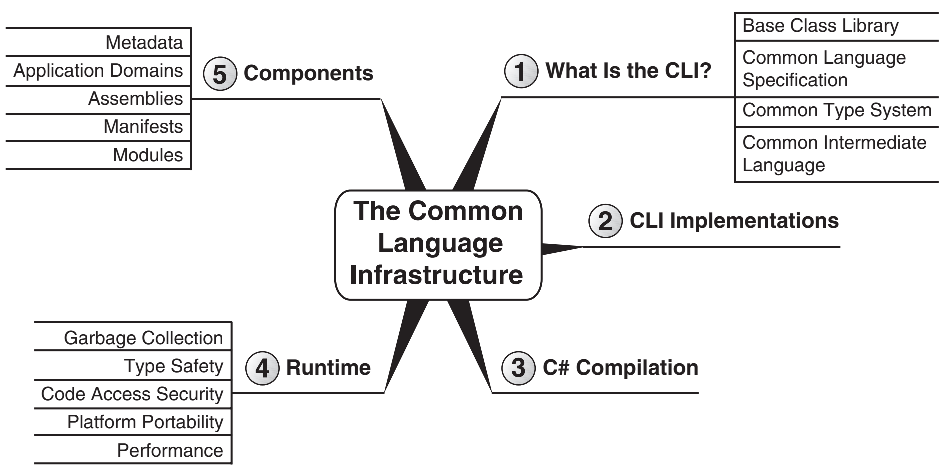
As demonstrated throughout this book, C# offers great power, flexibility, consistency, and a fantastic structure. This chapter highlighted the ability of C# programs to perform very low-level machine-code operations.

Before we end the book, Chapter 21 briefly describes the underlying execution platform and shifts the focus from the C# language to the broader platform in which C# programs execute.

21

The Common Language Infrastructure

ONE OF THE FIRST ITEMS that C# programmers encounter beyond the syntax is the context under which a C# program executes. This chapter discusses the underpinnings of how C# handles memory allocation and de-allocation, type checking, interoperability with other languages, cross-platform execution, and support for programming metadata. In other words, this chapter investigates the Common Language Infrastructure (CLI) on which C# relies both at compile time and during execution.



It covers the execution engine that governs a C# program at runtime and considers how C# fits into a broader set of languages that are governed by the same execution engine. Because of C#'s close ties with this infrastructure, most of the features that come with the infrastructure are made available to C#.

Defining the Common Language Infrastructure

Instead of generating instructions that a processor can interpret directly, the C# compiler generates instructions in an intermediate language, the **Common Intermediate Language (CIL).** A second compilation step occurs, generally at execution time, converting the CIL to **machine code** that the processor can understand. Conversion to machine code is still not sufficient for code execution, however. It is also necessary for a C# program to execute under the context of an agent. The agent responsible for managing the execution of a C# program is the **Virtual Execution System (VES),** generally more casually referred to as the **runtime.** (Note that the runtime in this context does not refer to a time, such as execution time; rather, the runtime—the Virtual Execution System—is an agent responsible for managing the execution of a C# program.) The runtime is responsible for loading and running programs and providing additional services (security, garbage collection, and so on) to the program as it executes.

The specifications for the CIL and the runtime are contained within an international standard known as the **Common Language Infrastructure (CLI).** The CLI is a key specification for understanding the context in which a C# program executes and how it can seamlessly interact with other programs and libraries, even when they are written in other languages. Note that the CLI does not prescribe the implementation for the standard, but rather identifies the requirements for how a CLI platform should behave once it conforms to the standard. This provides CLI implementers with the flexibility to innovate where necessary, while still providing enough structure that programs created by one platform can execute on a different CLI implementation, and even on a different operating system.

> **NOTE**
>
> Note the similarity between the CIL and CLI acronyms and the names they stand for. Distinguishing between them now will help you avoid confusion later.

Contained within the CLI standard are specifications for the following:

- The Virtual Execution System
- The Common Intermediate Language
- The Common Type System
- The Common Language Specification
- Metadata
- The framework

This chapter broadens your view of C# to include the CLI, which is critical to how C# programs operate and interact with programs and with the operating system.

CLI Implementations

There are several commonly used implementations of the CLI, and a number of implementations now of historical interest. Each implementation of the CLI includes a C# compiler and a set of framework class libraries; the version of C# supported by each, as well as the exact set of classes in the libraries, vary considerably. Table 21.1 on the next page describes these implementations.

C# Compilation to Machine Code

The `HelloWorld` program listing in Chapter 1 is obviously C# code, and you compiled it for execution using the C# compiler. However, the processor still cannot directly interpret compiled C# code. An additional compilation step is required to convert the result of C# compilation into machine code. Furthermore, the execution requires the involvement of an agent that adds more services to the C# program—services that it was not necessary to code for explicitly.

TABLE 21.1: Primary C# Compilers

Compiler	Description
Windows Desktop CLR	This version of the CLR is for creating Windows client applications.
CoreCLR	The .NET Core project, as the name implies, contains the core functionality common to all upcoming flavors of .NET from Microsoft. It is intended to be a cross-platform, open source implementation designed for high-performance server applications. The CoreCLR is the implementation of the CLR for this project. At the time of this book's writing, Microsoft had announced that it was in preview release for Windows, OS X, and Linux. See https://github.com/dotnet/coreclr for more details.
Microsoft Silverlight	This cross-platform implementation of the CLI was for creating browser-based web client applications. Microsoft stopped developing Silverlight in 2013.
.NET Compact Framework	This is a trimmed-down implementation of the .NET Framework designed to run on PDAs, phones, and the Xbox 360. The XNA library and tools for developing Xbox 360 applications are based on the Compact Framework 2.0 release; Microsoft stopped development of XNA in 2013.
.NET Micro Framework	The Micro Framework is Microsoft's open source implementation of the CLI for devices so resource constrained that they cannot run the compact framework. See http://www.netmf.com/ for details.
Mono	Mono is an open source, cross-platform implementation of the CLI for many UNIX-based operating systems, mobile operating systems such as Android, and game consoles such as PlayStation and Xbox. It is under active development by Xamarin, which has partnered with Microsoft to provide extensions integrating it into Visual Studio 2015.
DotGNU Portable.NET	This effort to create a cross-platform implementation of the CLI was "decommissioned" in 2012.
Shared Source CLI (Rotor)	Between 2001 and 2006, Microsoft released "shared source" reference implementations of the CLI licensed for noncommercial use.

All computer languages define syntax and semantics for programming. Since languages such as C and C++ compile to machine code, the platform for these languages is the underlying operating system and machine instruction set, be it Microsoft Windows, Linux, UNIX, or something else. In contrast, with languages such as C#, the underlying platform is the runtime (or VES).

CIL is what the C# compiler produces after compiling. It is termed a "common intermediate language" because an additional step is required to transform the CIL into something that processors can understand. Figure 21.1 on the next page shows the process.

In other words, C# compilation requires two steps:

1. Conversion from C# to CIL by the C# compiler
2. Conversion from CIL to instructions that the processor can execute

The runtime is able to understand CIL statements and compile them to machine code. Generally, a **component** within the runtime performs this compilation from CIL to machine code. This component is the **just-in-time (JIT) compiler,** and **jitting** can occur when the program is installed or executed. Most CLI implementations favor execution-time compilation of the CIL, but the CLI does not specify when the compilation needs to occur. In fact, the CLI even allows the CIL to be interpreted rather than compiled, similar to the way many scripting languages work. In addition, .NET includes a tool called `NGEN` that enables compilation to machine code prior to actually running the program. This preexecution-time compilation needs to take place on the computer on which the program will be executing because it will evaluate the machine characteristics (processor, memory, and so on) as part of its effort to generate more efficient code. The advantage of using `NGEN` at installation (or at any time prior to execution) is that you can reduce the need for the jitter to run at startup, thereby decreasing startup time.

As of Visual Studio 2015, the C# compiler also supports ".NET native" compilation, whereby the C# code is compiled into native machine code when creating a deployed version of the application, much like using the `NGEN` tool. Windows Universal applications make use of this feature.

C# Code

```
class  HelloWorld
{
   static void  Main()
   {
      System.Console.WriteLine(
         "Hello. My name is Inigo Montoya");
   }
}
```

C# Compiler

CIL Code

```
.method private hidebysig static void Main() cil
managed
{
   .entrypoint
   //Code size       11 (0xb)
   .maxstack 8
   IL_0000: ldstr      "Hello. My name is Inigo Montoya"
   IL_0005: call       void
[mscorlib]System.Console::WriteLine(string)
   IL_000a: ret
} // end of method HelloWorld::Main
```

Runtime

Machine Code

```
00000000  push           ebp
00000001  mov            ebp,esp
00000003  sub            esp,28h
00000006  mov            dword ptr [ebp-4],0
0000000d  mov            dword ptr [ebp-0Ch],0
00000014  cmp            dword ptr ds:[001833E0h],0
0000001b  je             00000022
0000001d  call           75F9C9E0
00000022  mov            ecx,dword ptr ds:[01C31418h]
00000028  call           dword ptr ds: [03C8E854h]
0000002e  nop
0000002f  mov            esp,ebp
00000031  pop            ebp
00000032  ret
```

FIGURE 21.1: Compiling C# to Machine Code

Runtime

Even after the runtime converts the CIL code to machine code and starts to execute it, it continues to maintain control of the execution. The code that executes under the context of an agent such as the runtime is **managed code,** and the process of executing under control of the runtime is **managed execution.** The control over execution transfers to the data; this makes it **managed data** because memory for the data is automatically allocated and de-allocated by the runtime.

Somewhat inconsistently, the term *Common Language Runtime* is not technically a generic term that is part of the CLI. Rather, CLR is the Microsoft-specific implementation of the runtime for the .NET platform. Regardless, CLR is casually used as a generic term for *runtime,* and the technically accurate term, *Virtual Execution System,* is seldom used outside the context of the CLI specification.

Because an agent controls program execution, it is possible to inject additional services into a program, even though programmers did not explicitly code for them. Managed code, therefore, provides information to allow these services to be attached. Among other items, managed code enables the location of metadata about a type member, exception handling, access to security information, and the capability to walk the stack. The remainder of this section includes a description of some additional services made available via the runtime and managed execution. The CLI does not explicitly require all of them, but the established CLI platforms have an implementation of each.

Garbage Collection

Garbage collection is the process of automatically de-allocating memory based on the program's needs. It represents a significant programming problem for languages that don't have an automated system for performing this cleanup. Without the garbage collector, programmers must remember to always free any memory allocations they make. Forgetting to do so, or doing so repeatedly for the same memory allocation, introduces memory leaks or corruption into the program—something exacerbated by long-running programs such as web servers. Because of the runtime's built-in support for garbage collection, programmers targeting runtime execution can focus on adding program features rather than "plumbing" related to memory management.

Language Contrast: C++—Deterministic Destruction

The exact mechanics for how the garbage collector works are not part of the CLI specification; therefore, each implementation can take a slightly different approach. (In fact, garbage collection is one item not explicitly required by the CLI.) One key concept with which C++ programmers may need to become familiar is the notion that garbage-collected objects are not necessarily collected **deterministically** (at well-defined, compile-time–known locations). In fact, objects can be garbage-collected anytime between when they are last accessed and when the program shuts down. This includes collection prior to falling out of scope, or waiting until well after an object instance is accessible by the code.

The garbage collector takes responsibility only for handling memory management; that is, it does not provide an automated system for managing resources unrelated to memory. Therefore, if an explicit action to free a resource (other than memory) is required, programmers using that resource should utilize special CLI-compatible programming patterns that will aid in the cleanup of those resources (see Chapter 9).

Garbage Collection on .NET

Most implementations of the CLI use a generational, compacting, mark-and-sweep–based algorithm to reclaim memory. It is "generational" because objects that have lived for only a short period will be cleaned up sooner than objects that have already survived garbage collection sweeps because they were still in use. This conforms to the general pattern of memory allocation that objects that have been around longer will continue to outlive objects that have only recently been instantiated.

Additionally, the .NET garbage collector uses a mark-and-sweep algorithm. During each garbage collection execution, it marks objects that are to be de-allocated and compacts together the objects that remain so that there is no "dirty" space between them. The use of compression to fill in the space left by de-allocated objects often results in faster instantiation of new objects (than is possible with unmanaged code), because it is not necessary to search through memory to locate space for a new allocation. This also decreases the chance of paging because more objects are located in the same page, which improves performance as well.

The garbage collector takes into consideration the resources on the machine and the demand on those resources at execution time. For example, if memory on the computer is still largely untapped, the garbage collector is less likely to run and take time to clean up those resources. This is an optimization rarely taken by platforms and languages that are not based on garbage collection.

Type Safety

One of the key advantages the runtime offers is checking conversions between types, known as **type checking.** Via type checking, the runtime prevents programmers from unintentionally introducing invalid casts that can lead to buffer overrun vulnerabilities. Such vulnerabilities are one of the most common means of breaking into a computer system, and having the runtime automatically prevent these holes from opening up is a significant gain.[1] Type checking provided by the runtime ensures the following:

- Both the variables and the data that the variables refer to are typed, and the type of the variable is compatible with the type of the data to which it refers.
- It is possible to locally analyze a type (without analyzing all of the code in which the type is used) to determine which permissions will be required to execute that type's members.
- Each type has a compile-time–defined set of methods and the data they contain. The runtime enforces rules about which classes can access those methods and data. Methods marked as "private," for example, are accessible only by the containing type.

ADVANCED TOPIC

Circumventing Encapsulation and Access Modifiers

Given appropriate permissions, it is possible to circumvent encapsulation and access modifiers via a mechanism known as **reflection.** Reflection provides late binding by enabling support for browsing through a type's members, looking up the names of particular constructs within an object's metadata, and invoking the type's members.

1. Assuming you are not the unscrupulous type who is looking for such vulnerabilities.

Code Access Security

The runtime can make security checks as the program executes, allowing and disallowing the specific types of operations depending on permissions. Permission to execute a specific function is not restricted to authentication of the user running the program. The runtime also controls execution based on who created the program and whether she is a trusted provider. Similarly, you might want to note that code access security (CAS) also applies the security policy based on the location of the code—by default, code installed on the local machine is more trusted than code from the LAN, which is much more trusted than code on the Internet. Permissions can be tuned such that partially trusted providers can read and write files from controlled locations on the disk, but are prevented from accessing other locations (such as email addresses from an email program) for which the provider has not been granted permission. Identification of a provider is handled by certificates that are embedded into the program when the provider compiles the code.

Platform Portability

One theoretical feature of the runtime is the opportunity it provides for C# code and the resultant programs to be **platform-portable**—that is, capable of running on multiple operating systems and executing on different CLI implementations. Portability in this context is not limited to the source code such that recompiling is necessary. Rather, a single CLI module compiled for one platform should run on any CLI-compatible platform without needing to be recompiled. This portability occurs because the work of porting the code lies in the hands of the runtime implementation rather than the application developer.

The restriction is, of course, that no platform-specific APIs are used. Because of this restriction, many developers forgo CLI platform-neutral code in favor of accessing the underlying platform functionality, rather than writing it all from scratch.

Historically, it has been quite difficult to write a library of C# code that can be used on multiple platforms because the framework class libraries on each platform have all had different classes available (or different methods in those classes). If you wish to write your core application logic once and ensure that it can be used in any modern implementation of .NET, the easiest way to do so is to create a Portable Class Library project (available as a project type in Visual Studio since 2012). Visual Studio will ensure that any code in the library can reference only classes and methods common to your choice of Windows Desktop, Silverlight, Windows Phone, iOS, Android, and other platform class libraries. Alternatively, cross platform support is available in .NET Core—the long term strategic direction for on which ASP.NET 5 is built.

To create a full graphical application that can run on Windows Desktop, mobile, and console platforms, select one of the "Universal Application" project types in Visual Studio 2015.

Performance

Many programmers accustomed to writing unmanaged code will correctly point out that managed environments impose overhead on applications, no matter how simple they are. The trade-off is one of increased development productivity and reduced bugs in managed code versus runtime performance. The same dichotomy emerged as programming went from assembler to higher-level languages such as C, and from structured programming to object-oriented development. In the vast majority of scenarios, development productivity wins out, especially as the speed and reduced price of hardware surpass the demands of applications. Time spent on architectural design is much more likely to yield big performance gains than the complexities of a low-level development platform. In the climate of security holes caused by buffer overruns, managed execution is even more compelling.

Undoubtedly, certain development scenarios (device drivers, for example) may not yet fit with managed execution. However, as managed execution increases in capability and sophistication, many of these performance considerations will likely vanish. Unmanaged execution will then be reserved for development where precise control or circumvention of the runtime is deemed necessary.[2]

Furthermore, the runtime introduces several factors that can contribute to improved performance over native compilation. For example, because translation to machine code takes place on the destination machine, the resultant compiled code matches the processor and memory layout of that machine, resulting in performance gains generally not leveraged by nonjitted languages. Also, the runtime is able to respond to execution conditions

2. Indeed, Microsoft has indicated that managed development will be the predominant means of writing applications for its Windows platform in the future, even for those applications that are integrated with the operating system.

that direct compilation to machine code rarely takes into account. If, for example, the box has more memory than is required, unmanaged languages will still de-allocate their memory at deterministic, compile-time–defined execution points in the code. Alternatively, jit-compiled languages will need to de-allocate memory only when it is running low or when the program is shutting down. Even though jitting can add a compile step to the execution process, code efficiencies that a jitter can insert may lead to improved performance rivaling that of programs compiled directly to machine code. Ultimately, CLI programs are not necessarily faster than non-CLI programs, but their performance is competitive.

Application Domains

By introducing a layer between the program and the operating system, it is possible to implement virtual processes or applications known as **application domains (app domains).** An application domain behaves like an operating system process in that it offers a level of isolation between other application domains. For example, an app domain has its own virtual memory allocation, and communication between app domains requires distributed communication paradigms, just as it would between two operating system processes. Similarly, static data is not shared between application domains, so static constructors run for each app domain; assuming a single thread per app domain, there is no need to synchronize the static data because each application has its own instance of the data. Furthermore, each application domain has its own threads, and just like with an operating system process, threads cannot cross app domain boundaries.

The point of an application domain is that processes are considered relatively expensive. With application domains, you can avoid this additional expense by running multiple app domains within a single process. For example, you can use a single process to host a series of websites, but then isolate the websites from one another by placing them in their own application domains. In summary, application domains represent a virtual process on a layer between an operating system process and the threads.

Assemblies, Manifests, and Modules

Included in the CLI is the specification of the CIL output from a source language compiler, usually an assembly. In addition to the CIL instructions themselves, an assembly includes a **manifest** that is made up of the following components:

- The types that an assembly defines and imports
- Version information about the assembly itself
- Additional files the assembly depends on
- Security permissions for the assembly

The manifest is essentially a header to the assembly, providing all the information about what an assembly is composed of, along with the information that uniquely identifies it.

Assemblies can be class libraries or the executables themselves, and one assembly can reference other assemblies (which, in turn, can reference more assemblies), thereby establishing an application composed of many components rather than existing as one large, monolithic program. This is an important feature that modern programming platforms take for granted, because it significantly improves maintainability and allows a single component to be shared across multiple programs.

In addition to the manifest, an assembly contains the CIL code within one or more modules. Generally, the assembly and the manifest are combined into a single file, as was the case with `HelloWorld.exe` in Chapter 1. However, it is possible to place modules into their own separate files and then use an assembly linker (`al.exe`) to create an assembly file that includes a manifest that references each module.[3] This approach not only provides another means of breaking a program into components, but also enables the development of one assembly using multiple source languages.

Casually, the terms *module* and *assembly* are somewhat interchangeable. However, the term *assembly* is predominant for those talking about CLI-compatible programs or libraries. Figure 21.2 depicts the various component terms.

Note that both assemblies and modules can also reference files such as resource files that have been localized to a particular language. Although it is rare, two different assemblies can reference the same module or file.

---

3. This is partly because one of the primary CLI IDEs, Visual Studio .NET, lacks functionality for working with assemblies composed of multiple modules. Current implementations of Visual Studio .NET do not have integrated tools for building multimodule assemblies, and when they use such assemblies, IntelliSense does not fully function.

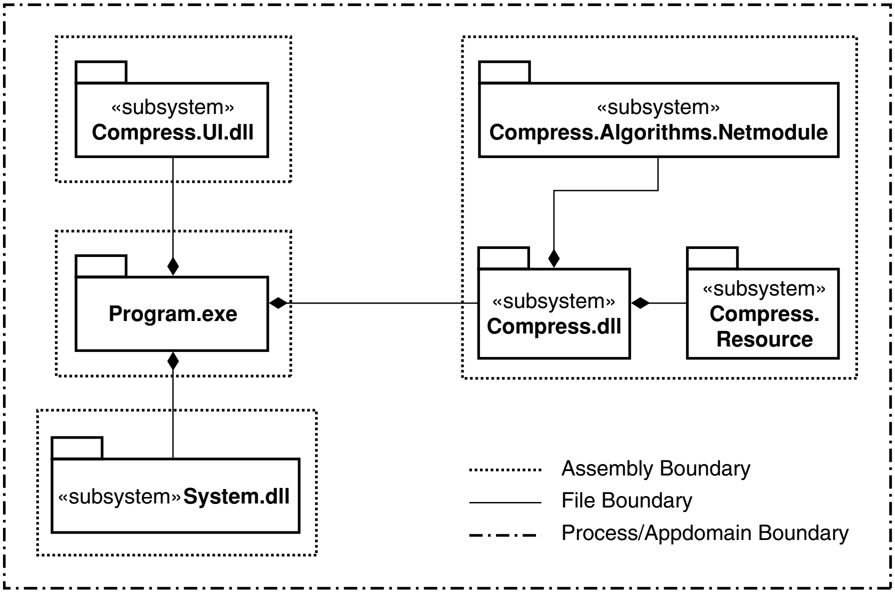


FIGURE 21.2: Assemblies with the Modules and Files They Reference

Even though an assembly can include multiple modules and files, the entire group of files has only one version number, which is placed in the assembly manifest. Therefore, the smallest versionable component within an application is the assembly, even if that assembly is composed of multiple files. If you change any of the referenced files—even to release a patch—without updating the assembly manifest, you will violate the integrity of the manifest and the entire assembly itself. As a result, assemblies form the logical construct of a component or unit of deployment.

NOTE

Assemblies—not the individual modules that compose them—form the smallest unit that can be versioned and installed.

Even though an assembly (the logical construct) could consist of multiple modules, most assemblies contain only one. Furthermore, Microsoft provides an `ILMerge.exe` utility for combining multiple modules and their manifests into a single file assembly.

Because the manifest includes a reference to all the files an assembly depends on, it is possible to use the manifest to determine an assembly's dependencies. Furthermore, at execution time, the runtime needs to examine only the manifest to determine which files it requires. Only tool vendors distributing libraries shared by multiple applications (Microsoft, for example) need to register those files at deployment time. This makes deployment significantly easier. Often, deployment of a CLI-based application is referred to as **xcopy deployment,** after the Windows `xcopy` command that simply copies files to a selected destination.

Language Contrast: COM DLL Registration

Unlike Microsoft's COM files of the past, CLI assemblies rarely require any type of registration. Instead, it is possible to deploy applications by copying all the files that compose a program into a particular directory, and then executing the program.

Common Intermediate Language

In keeping with the Common Language Infrastructure name, another important feature of the CIL and the CLI is to support the interaction of multiple languages within the same application (instead of portability of source code across multiple operating systems). As a result, the CIL is the intermediate language not only for C#, but also for many other languages, including Visual Basic .NET, the Java-like language of J#, some incantations of Smalltalk, C++, and a host of others (more than 20 at the time of this writing, including versions of COBOL and FORTRAN). Languages that compile to the CIL are termed **source languages,** and each has a custom compiler that converts the source language to the CIL. Once compiled to the CIL, the source language is insignificant. This powerful feature enables the development of libraries by different development groups across multiple organizations, without concern for the language choice of a particular group. Thus, the CIL enables programming language interoperability as well as platform portability.

> **NOTE**
>
> A powerful feature of the CLI is its support for multiple languages. This enables the creation of programs using multiple languages and the accessibility of libraries written in one language from code written in a different language.

Common Type System

Regardless of the programming language, the resultant program operates internally on data types; therefore, the CLI includes the **Common Type System (CTS).** The CTS defines how types are structured and laid out in memory, as well as the concepts and behaviors that surround types. It includes type manipulation directives alongside the information about the data stored within the type. The CTS standard applies to how types appear and behave at the external boundary of a language because the purpose of the CTS is to achieve interoperability between languages. It is the responsibility of the runtime at execution time to enforce the contracts established by the CTS.

Within the CTS, types are classified into two categories.

- **Values** are bit patterns used to represent basic types, such as integers and characters, as well as more complex data in the form of structures. Each value type corresponds to a separate type designation not stored within the bits themselves. The separate type designation refers to the type definition that provides the meaning of each bit within the value and the operations that the value supports.
- **Objects** contain within them the object's type designation. (This helps in enabling type checking.) Objects have identity that makes each instance unique. Furthermore, objects have slots that can store other types (either values or object references). Unlike with values, changing the contents of a slot does not change the identity of the object.

These two categories of types translate directly to C# syntax that provides a means of declaring each type.

Common Language Specification

Since the language integration advantages provided by the CTS generally outweigh the costs of implementing it, the majority of source languages support the CTS. However, there is also a subset of CTS language conformance called the **Common Language Specification (CLS),** whose focus is on library implementations. The CLS is intended for library developers, and provides them with standards for writing libraries that are accessible from the majority of source languages, regardless of whether the source languages using the library are CTS-compliant. It is called the Common Language Specification because it is intended to also encourage CLI languages to provide a means of creating interoperable libraries, or libraries that are accessible from other languages.

For example, although it is perfectly reasonable for a language to provide support for an unsigned integer, such a type is not included as part of the CLS. Therefore, developers implementing a class library should not externally expose unsigned integers because doing so would cause the library to be less accessible from CLS-compliant source languages that do not support unsigned integers. Ideally, then, any libraries that are to be accessible from multiple languages should conform to the CLS. Note that the CLS is not concerned with types that are not exposed externally to the assembly.

Also note that it is possible to have the compiler issue a warning when you create an API that is not CLS-compliant. To accomplish this, you use the assembly attribute `System.CLSCompliant` and specify a value of `true` for the parameter.

Base Class Library

In addition to providing a platform in which CIL code can execute, the CLI defines a core set of class libraries that programs may employ, called the **Base Class Library (BCL).** These libraries provide foundational types and APIs, allowing programs to interact with the runtime and underlying operating system in a consistent manner. The BCL includes support for collections, simple file access, some security, fundamental data types (`string`, among others), streams, and the like.

Similarly, a Microsoft-specific library called the **Framework Class Library (FCL)** includes support for rich client user interfaces, web user interfaces, database access, distributed communication, and more.

Metadata

In addition to execution instructions, CIL code includes **metadata** about the types and files included in a program. The metadata includes the following items:

- A description of each type within a program or class library
- The manifest information containing data about the program itself, along with the libraries it depends on
- Custom attributes embedded in the code, providing additional information about the constructs the attributes decorate

The metadata is not a cursory, nonessential add-on to the CIL. Rather, it represents a core component of the CLI implementation. It provides the representation and the behavior information about a type and includes location information about which assembly contains a particular type definition. It serves a key role in saving data from the compiler and making it accessible at execution time to debuggers and the runtime. This data not only is available in the CIL code, but also is accessible during machine code execution so that the runtime can continue to make any necessary type checks.

Metadata provides a mechanism for the runtime to handle a mixture of native and managed code execution. Also, it increases code and execution robustness because it smooths the migration from one library version to the next, replacing compile-time–defined binding with a load-time implementation.

All header information about a library and its dependencies is found in a portion of the metadata known as the manifest. As a result, the manifest portion of the metadata enables developers to determine a module's dependencies, including information about particular versions of the dependencies and signatures indicating who created the module. At execution time, the runtime uses the manifest to determine which dependent libraries to load, whether the libraries or the main program has been tampered with, and whether assemblies are missing.

The metadata also contains **custom attributes** that may decorate the code. Attributes provide additional metadata about CIL instructions that are accessible via the program at execution time.

Metadata is available at execution time by a mechanism known as **reflection.** With reflection, it is possible to look up a type or its member at execution time and then invoke that member or determine whether a construct is decorated with a particular attribute. This provides **late binding,** in which the system determines which code to execute at execution time rather than at compile time. Reflection can even be used for generating documentation by iterating through metadata and copying it into a help document of some kind (see Chapter 17).

SUMMARY

This chapter described many new terms and acronyms that are important for understanding the context under which C# programs run. The preponderance of three-letter acronyms can be confusing. Table 21.2 provides a summary list of the terms and acronyms that are part of the CLI.

TABLE 21.2: Common C#-Related Acronyms

Acronym	Definition	Description
.NET	None	Microsoft's implementation of the entire CLI stack. Includes the CLR, CIL, and various languages, all of which are CLS-compliant.
BCL	Base Class Library	The portion of the CLI specification that defines the collection, threading, console, and other base classes necessary to build virtually all programs.
C#	None	A programming language. Separate from the CLI standard is a C# Language Specification, also ratified by the ECMA and ISO standards bodies.
CIL (IL)	Common Intermediate Language	The language of the CLI specification that defines the instructions for the code executable on implementations of the CLI. It is sometimes also referred to as IL or Microsoft IL (MSIL) to distinguish it from other intermediate languages. (To indicate that it is a standard broader than Microsoft, CIL is preferred over MSIL and even IL.)
CLI	Common Language Infrastructure	The specification that defines the intermediate language, base classes, and behavioral characteristics which enable implementers to create Virtual Execution Systems and compilers in which source languages are interoperable on top of a common execution environment.

continues

TABLE 21.2: Common C#-Related Acronyms (*continued*)

Acronym	Definition	Description
CLR	Common Language Runtime	Microsoft's implementation of the runtime, as defined in the CLI specification.
CLS	Common Language Specification	The portion of the CLI specification that defines the core subset of features that source languages *must* support to be executable on runtimes implemented according to the CLI specification.
CTS	Common Type System	A standard generally implemented by CLI-compliant languages that defines the representation and behavior of types that the language exposes visibly outside a module. It includes concepts for how types can be combined to form new types.
FCL	.NET Framework Class Library	The class library that makes up Microsoft's .NET Framework. It includes Microsoft's implementation of the BCL as well as a large library of classes for such things as web development, distributed communication, database access, and rich client user interface development, among others.
WinRT	Windows Runtime	The Windows 8–based platform under which Metro-style applications execute. WinRT includes the WinAPI, a new and improved Windows 8 operating system API that includes .NET-styled metadata, making it seamlessly accessible from C#.
VES (runtime)	Virtual Execution System	An agent that manages the execution of a program that is compiled for the CLI.

A

Downloading and Installing the C# Compiler and CLI Platform

TO COMPILE AND RUN C# programs, it is necessary to install a version of the compiler and the CLI platform.

Microsoft .NET for Windows

The predominant CLI platform is Microsoft .NET, which is the platform of choice for development on Microsoft Windows.

- For a rich IDE that includes IntelliSense and support for project files, install a version of the Visual Studio IDE. The "Community Edition" of Visual Studio 2015 is free and contains everything you need to make server applications, rich client applications, and cross-platform mobile applications. This edition, along with other editions of Visual Studio, is available at http://visualstudio.com.
- Microsoft provides free, redistributable packages that include the .NET Framework and compiler binaries for all versions of .NET going back to version 2.0. These are available in the downloads section at http://www.microsoft.com/net. At the time of this book's writing, the latest released version is .NET 4.6.

Visual Studio Compilation

In 2015, Microsoft made Visual Studio 2015 Community[1] available for free. This is a full version of the company's IDE that provides a premium platform for .NET software development. One of the primary advantages of developing with Visual Studio is the ability to create and open entire projects of files and even combine such projects together into solutions.

The associated source code[2] includes a solution file, `EssentialCSharp.sln`, that can be opened up with Visual Studio 2015, compiled (built), and run. After opening the solution file, use the **Build->Build Solution** menu to compile the code.

Before you can execute the source code, you need to select which project to execute by selecting the associated chapter's project as the startup project. For example, to execute the samples in Chapter 1, you would right-click on the **Chapter01** project and choose **Set As Startup Project**. Failure to choose the correct chapter will result in an exception with the message ("Error, could not run the Listing….") when you specify the listing number at execution time.

Once you have selected the correct project, you can run the project from the **Debug->Start Without Debugging** menu. Alternatively, if you wish to debug the project, you can use **Debug->Start Debugging**. Once running, the program will prompt for the listing (for example, 18.33) that you wish to execute. As mentioned earlier, you can enter only listings from the project that was set to start up.

Many of the listings have corresponding unit tests. To execute a particular test, open the test project and navigate to the test corresponding to the listing you wish to execute. From there, right-click on the test method and choose either **Run Tests (Ctrl+R, T)** or **Debug Tests (Ctrl+R, Ctrl+T)**.

Setting up the Compiler Path for Command-Line Compilation

For command-line compilation, regardless of whether you are working with Visual Studio or just the runtime, you must set the `PATH` environment variable to include the C# compiler, `CSC.EXE`. If Visual Studio is installed on your computer, open the command prompt from the **Start** menu by

---

1. Visual Studio Express was available or free prior to 2015 and is also sufficient for compiling all samples in this book save those depending on C# 6.0 features.
2. The source code available for this book (along with some chapters related to earlier versions of C#) is available for download at IntelliTect.com/EssentialCSharp. You can also download the code from http://itl.tc/EssentialCSharpSCC.

selecting the **Developer Command Prompt** shortcut from the Visual Studio section of the Windows Start menu. This command prompt places `CSC.EXE` in the path to be available for execution from any directory.

Without Visual Studio installed, no special compiler command prompt item appears in the **Start** menu. Instead, you need to reference the full compiler pathname explicitly or add it to the path. The compiler is located at `%Windir%\Microsoft.NET\Framework\<version>`, where `<version>` is the version of the .NET Framework (typically v4.0.30319, which contains the compiler tools for all versions of .NET since .NET 4.0) and `%Windir%` is the environment variable that points to the location of the Windows directory. To add this location to the path, use `Set PATH=%PATH%;%Windir%\Microsoft.NET\Framework\<version>`, again substituting the value of `<version>` appropriately. Output A.1 provides an example.

OUTPUT A.1

```
Set PATH=%PATH%;%Windir%\Microsoft.NET\Framework\v4.0.30319
```

Once the path includes the framework, you can then use the .NET C# compiler, `CSC.EXE`, without providing the full path to its location.

.NET on OS X and Linux

Since its initial release, there has always been cross platforms versions of the CLI that allow execution of .NET and CIL code on operating systems in addition to Windows. As of this writing, the key platforms are the .NET Core project (CoreCLR) and Mono. Both of these are open source implementations that allow development on OS X and Linux (in addition to Windows).

.NET Core

Microsoft provides an open-source version of the ".NET Core" version of the .NET Framework for OS X and Linux (in addition to Windows); at the time of this book's writing, it was in preview release with development driven primarily by ASP.NET 5. Sources and binary downloads are available at https://github.com/dotnet/coreclr.

Unlike the full .NET Framework on Windows, the .NET Core project does not require installing the .NET Framework as part of the operating system. Rather, all the files you need are copied to a single directory. To prepare the environment requires downloading some general-purpose packages so that .NET can be installed. Next, it is necessary to install the .NET Version Manager followed by the .NET Core Execution Environment (DNX). This environment provides the engine for executing CIL under the CoreCLR implementation. Finally, once everything is set up, the environment is ready to compile and run your C# code.

Execution of managed executables created with the .NET Framework is built into the Windows operating system, but not into OS X or Linux (or even on Windows with .NET Core). To execute the generated binary, you use a utility that launches the executable in the CLR; it is activated by executing `dnx.exe`.

For complete and up-to-date instructions for installation and execution using .NET Core, see http://itl.tc/GettingStartedWithDNX.

Note that the Core .NET project on OS X and Linux is intended for writing high-performance server-side code, not for writing graphical user interface applications; there is no GUI library package included with Core .NET. To make applications with user interfaces on non-Windows platforms, use Mono.

Mono

For CLI development on platforms other than Microsoft Windows, consider Mono, which is a platform you can download at http://www.mono-project.com. As with the .NET platform, Mono requires the full path to the C# compiler if it is not already in the search path. The default installation path on Linux is `/usr/lib/mono/<version>`, and the compiler is `gmcs.exe` or `mcs.exe`, depending on the version. (If Mono is installed on Microsoft Windows, the default path is `%ProgramFiles%\Mono-<version>\lib\mono\<version>\`.)

One option for a Linux version that includes an installation of Mono is Monoppix. This version builds on the CD-bootable Linux distribution known as Knoppix and is available for download at http://www.monoppix.com.

Instead of `CSC.EXE`, the Mono platform's compiler is `MCS.EXE` or `GMCS.EXE`, depending on the compiler version. Therefore, the command for compiling `HelloWorld.cs` is as shown in Output A.2.

OUTPUT A.2

```
C:\SAMPLES>msc.exe HelloWorld.cs
```

Unfortunately, the Linux environment cannot run the resultant binaries directly. Instead, it requires explicit execution of the runtime using `mono.exe`, as shown in Output A.3.

OUTPUT A.3

```
C:\SAMPLES>mono.exe HelloWorld.exe
Hello. My name is Inigo Montoya.
```

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B

Tic-Tac-Toe Source Code Listing

Listing B.1: Tic-Tac-Toe

```
#define CSHARP2

using System;

#pragma warning disable 1030 // Disable user-defined warnings

// The TicTacToe class enables two players to
// play tic-tac-toe.
class TicTacToeGame      // Declares the TicTacToeGame class.
{
  static void Main()  // Declares the entry point to the program.
  {
      // Stores locations each player has moved.
      int[] playerPositions = { 0, 0 };

      // Initially set the currentPlayer to Player 1.
      int currentPlayer = 1;

      // Winning player.
      int winner = 0;

      string input = null;


      // Display the board and prompt the current player
      // for his next move.
      for (int turn = 1; turn <= 10; ++turn)
      {
          DisplayBoard(playerPositions);
```

```
            #region Check for End Game
            if (EndGame(winner, turn, input))
            {
                break;
            }
            #endregion Check for End Game

            input = NextMove(playerPositions, currentPlayer);

            winner = DetermineWinner(playerPositions);

            // Switch players.
            currentPlayer = (currentPlayer == 2) ? 1 : 2;
        }
    }

    private static string NextMove(int[] playerPositions,
                   int currentPlayer)
    {
        string input;

        // Repeatedly prompt the player for a move
        // until a valid move is entered.
        bool validMove;
        do
        {
            // Request a move from the current player.
            System.Console.Write($"\nPlayer {currentPlayer} - Enter move:");
            input = System.Console.ReadLine();
            validMove = ValidateAndMove(playerPositions,
                          currentPlayer, input);
        } while (!validMove);

        return input;
    }

    static bool EndGame(int winner, int turn, string input)
    {
        bool endGame = false;
        if (winner > 0)
        {
            System.Console.WriteLine($"\nPlayer {winner} has won!!!!");
            endGame = true;
        }
        else if (turn == 10)
        {
            // After completing the 10th display of the
            // board, exit rather than prompting the
            // user again.
            System.Console.WriteLine("\nThe game was a tie!");
            endGame = true;
        }
        else if (input == "" || input == "quit")
```

```
        {
            // Check if user quit by hitting Enter without
            // any characters or by typing "quit".
            System.Console.WriteLine("The last player quit");
            endGame = true;
        }
        return endGame;
    }

    static int DetermineWinner(int[] playerPositions)
    {
        int winner = 0;

        // Determine if there is a winner.
        int[] winningMasks = {
            7, 56, 448, 73, 146, 292, 84, 273};

        foreach (int mask in winningMasks)
        {
            if ((mask & playerPositions[0]) == mask)
            {
                winner = 1;
                break;
            }
            else if ((mask & playerPositions[1]) == mask)
            {
                winner = 2;
                break;
            }
        }
        return winner;
    }

    static bool ValidateAndMove(
      int[] playerPositions, int currentPlayer, string input)
    {
        bool valid = false;

        // Check the current player's input.
        switch (input)
        {
            case "1":
            case "2":
            case "3":
            case "4":
            case "5":
            case "6":
            case "7":
            case "8":
            case "9":
  #warning  "Same move allowed multiple times."
                int shifter;  // The number of places to shift
                // over to set a bit.
```

```
                int position;  // The bit which is to be set.

                // int.Parse() converts "input" to an integer.
                // "int.Parse(input) - 1" because arrays
                // are zero-based.
                shifter = int.Parse(input) - 1;

                // Shift mask of 00000000000000000000000000000001
                // over by cellLocations.
                position = 1 << shifter;

                // Take the current player cells and OR them
                // to set the new position as well.
                // Since currentPlayer is either 1 or 2, you
                // subtract 1 to use currentPlayer as an
                // index in a zero-based array.
                playerPositions[currentPlayer - 1] |= position;

                valid = true;
                break;

            case "":
            case "quit":
                valid = true;
                break;

            default:
                // If none of the other case statements
                // is encountered, then the text is invalid.
                System.Console.WriteLine(
                    "\nERROR:  Enter a value from 1-9. "
                    + "Push ENTER to quit");
                break;
        }

        return valid;
    }

    static void DisplayBoard(int[] playerPositions)
    {
        // This represents the borders between each cell
        // for one row.
        string[] borders = {
    "|", "|", "\n---+---+---\n", "|", "|",
    "\n---+---+---\n", "|", "|", ""
    };

        // Display the current board;
        int border = 0;  // set the first border (border[0] = "|").

  #if CSHARP2
        System.Console.Clear();
  #endif
```

```
        for (int position = 1;
             position <= 256;
             position <<= 1, border++)
        {
            char token = CalculateToken(
                playerPositions, position);

            // Write out a cell value and the border that
            // comes after it.
            System.Console.Write($" {token} {borders[border]}");
        }
    }

    static char CalculateToken(
        int[] playerPositions, int position)
    {
        // Initialize the players to 'X' and 'O'
        char[] players = {'X', 'O'};

        char token;
        // If player has the position set,
        // then set the token to that player.
        if ((position & playerPositions[0]) == position)
        {
            // Player 1 has that position marked.
            token = players[0];
        }
        else if ((position & playerPositions[1]) == position)
        {
            // Player 2 has that position marked.
            token = players[1];
        }
        else
        {
            // The position is empty.
            token = ' ';
        }
        return token;
    }

    #line 113 "TicTacToe.cs"
    // Generated code goes here.
    #line default
  }
```

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C

Interfacing with Multithreading Patterns prior to the TPL and C# 6.0

From Chapter 18, readers will recall that multithreading patterns are used to address the multithreading complexities of monitoring an asynchronous operation, thread pooling, avoiding deadlocks, and implementing atomicity and synchronization across operations and data access. In the ten years prior to the introduction of .NET 4.5 and C# 5.0, there were six versions of the .NET Framework and four versions of the C# language, and a similar number of corresponding multithreading patterns emerged. During that time, however, there were numerous improvements in multithreading and—as is frequently the case with frameworks and even languages—some patterns from those earlier versions were suboptimal. Suboptimal or not, as a C# developer you are likely to encounter these patterns either because you are developing for a .NET/C# version prior to .NET 4.5/C# 5.0 or because you are using an API from another framework that exposes one of the earlier patterns. The purpose of this additional "chapter" is to discuss these patterns. If you are lucky enough to be working solely with C# 5.0 or better, consider this an Advanced Topic, reading it simply to gain familiarity with the details of multithreading in the past. Alternatively, if you are still programming without the Task Programming Library (TPL) and the Task-based Asynchronous Pattern (TAP) and its `async`/`await` keywords, treat the remaining topics as an important part of the multithreading API available to you. Perhaps most importantly, this content describes how to effectively interact with the earlier patterns using the TPL and C# 5.0 and above.

Throughout these examples, exception handling has been eliminated for the purposes of elucidation.

Asynchronous Programming Model

One particularly prominent pattern established prior to the TPL is the Asynchronous Programming Model (APM) pattern. Given a long-running synchronous method `X()`, the APM pattern uses a `BeginX()` method to start `X()` equivalent work asynchronously and an `EndX()` method to conclude it. (Henceforth we will name these methods `X`, `BeginX`, and `EndX`.)

Using the APM Pattern

Listing C.1 demonstrates the pattern by using the `System.Net.WebRequest` class to download a web page. The functionality is the same as that found in the section titled "The Task-Based Asynchronous Pattern" in Chapter 18; however, this time we assume that the TPL and TAP are not available, and instead use the APM pattern. To maintain backward compatibility prior to TPL-related asynchronous methods being added, `WebRequest` also supports the APM pattern with the methods `BeginGetResponse()` (`BeginX`) and `EndGetResponse()` (`EndX`)—that is, asynchronous versions of the synchronous `GetResponse()` (`X`) method.

Listing C.1: Using the APM Pattern with `WebRequest`

```
using System;
using System.IO;
using System.Net;
using System.Linq;

public class Program
{
  public static void Main(string[] args)
  {
      string url = "http://www.IntelliTect.com";
      if (args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);
```

```
        WebRequest webRequest =
            WebRequest.Create(url);

        IAsyncResult asyncResult =
            webRequest.BeginGetResponse(null, null);

        // Indicate busy using dots; ideally (at least in a non-Console
        // implementation) should use a callback rather than a wait.
        while (
            !asyncResult.AsyncWaitHandle.WaitOne(100))
        {
            Console.Write('.');
        }

        // Retrieve the results when finished downloading.
        WebResponse response =
            webRequest.EndGetResponse(asyncResult);
        using (StreamReader reader =
            new StreamReader(response.GetResponseStream()))
        {
            // Note: ReadToEnd() is blocking. A production implementation
            //should offload this to another thread.
            int length = reader.ReadToEnd().Length;
            Console.WriteLine(FormatBytes(length));
        }
    }

    static public string FormatBytes(long bytes)
    {
        string[] magnitudes =
            new string[] { "GB", "MB", "KB", "Bytes" };
        long max =
            (long)Math.Pow(1024, magnitudes.Length);

        return string.Format("{1:##.##} {0}",
            magnitudes.FirstOrDefault(
                magnitude =>
                    bytes > (max /= 1024) )?? "0 Bytes",
                (decimal)bytes / (decimal)max).Trim();
    }
}
```

The results of Listing C.1 appear in Output C.1.

Output C.1

```
http://www.IntelliTect.com..........29.36 KB
```

As mentioned, the key aspect of the APM pattern is the pair of `BeginX` and `EndX` methods with well-established signatures. The `BeginX` method returns a `System.IAsyncResult` object providing access to the state of the asynchronous call so it knows whether to wait or poll for completion. The `EndX` method then takes this return as an input parameter. This pairs up the two methods so that it is clear which `BeginX` method call pairs with which `EndX` method call. The APM pattern requires that for all `BeginX` invocations, there must be exactly one `EndX` invocation; thus multiple calls to `EndX` for the same `IAsyncResult` instance should not occur.

In Listing C.1, we also use the `IAsyncResult`'s `WaitHandle` to determine when the asynchronous method completes. As we iteratively poll the `WaitHandle`, we print out periods to the console indicating that the download is running. Following that, we call `EndGetResponse()`.

The `EndX` method serves four purposes. First, calling `EndX` will block further execution until the work requested completes successfully (or an error occurs and throws an exception). Second, if method `X` returns data, this data is accessible from the `EndX` method call. Third, if an exception occurs while performing the requested work, the exception will be rethrown on the call to `EndX`, ensuring that the exception is visible to the calling code as though it had occurred on a synchronous invocation. Finally, if any resource needs cleanup due to `X`'s invocation, `EndX` will be responsible for cleaning up these resources.

APM Signatures

Together, the combination of the `BeginX` and `EndX` APM methods should match the synchronous version of the signature. Therefore, the return parameter on `EndX` should match the return parameters on the `X` method (`GetResponse()` in this case). Furthermore, the input parameters on the `BeginX` method also need to match. In the case of `WebRequest.GetResponse()` there are no parameters, but let's consider a fictitious synchronous method, `bool TryDoSomething(string url, ref string data, out string[] links)`. The parameters map from the synchronous method to the APM methods, as shown in Figure C.1.

```
System.IAsyncResult BeginTryDoSomething(
    String url, ref string data, out string[] links,
    System.AsyncCallback callback, object state)

bool TryDosomething(
    string url, ref string data, out string[] links)

bool EndTryDoSomething (ref string data, out string[] links,
    System.IAyncResult result);
```

FIGURE C.1: APM Parameter Distribution

All input parameters map to the BeginX method. Similarly, the return parameter maps to the EndX return parameter. Also, notice that since the ref and out parameters return results, they are included in the EndX method signature. In contrast, url is just an input parameter, so it is not included in the EndX method.

Continuation Passing Style with AsyncCallback

There are two additional parameters on the BeginX method that were not included in the synchronous method: the callback parameter (a System.AsyncCallback delegate to be called when the method completes) and a state parameter of type object. Listing C.2 demonstrates how they are used. (The output is the same as Output C.1.)

Listing C.2: Invoking an APM Method with Callback and State

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading;

public class Program
{
  public static void Main(string[] args)
  {
      string url = "http://www.intelliTechture.com";
      if (args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);
      WebRequest webRequest = WebRequest.Create(url);
      WebRequestState state =
          new WebRequestState(webRequest);
      IAsyncResult asyncResult =
          webRequest.BeginGetResponse(
              GetResponseAsyncCompleted, state);

      // Indicate busy using dots.
      while (
          !asyncResult.AsyncWaitHandle.WaitOne(100))
      {
          Console.Write('.');
      }
      state.ResetEvent.Wait();
  }
```

```
    // Retrieve the results when finished downloading.
    private static void GetResponseAsyncCompleted(
        IAsyncResult asyncResult)
    {
        WebRequestState completedState =
            (WebRequestState)asyncResult.AsyncState;
        HttpWebResponse response =
            (HttpWebResponse)completedState.WebRequest
                .EndGetResponse(asyncResult);
        Stream stream = response.GetResponseStream();
        StreamReader reader = new StreamReader(stream);
        // Note: ReadToEnd() is blocking. A production implementation
        //should offload this to another thread.
        int length = reader.ReadToEnd().Length;

        Console.WriteLine(FormatBytes(length));
        completedState.ResetEvent.Set();
        completedState.Dispose();
    }
    // ...
  }
```

```
  class WebRequestState : IDisposable
  {
    public WebRequestState(WebRequest webRequest)
    {
        WebRequest = webRequest;
    }
    public WebRequest WebRequest { get; private set; }
    private ManualResetEventSlim _ResetEvent =
        new ManualResetEventSlim();
    public ManualResetEventSlim ResetEvent
        { get { return _ResetEvent; } }

    public void Dispose()
    {
        ResetEvent.Dispose();
        GC.SuppressFinalize(this);
    }
  }
```

In Listing C.2, we pass data for both of the parameters on `BeginGetResponse()`. The first parameter is a delegate of type `System.AsyncCallback` that takes a single parameter of type `System.AsyncResult`. The `AsyncCallback` identifies the code that will execute once the asynchronous call completes. Registering a callback enables a fire-and-forget calling pattern called **continuation passing style (CPS),** rather than placing the `EndGetResponse()` and `Console.WriteLine()` code sequentially below

`BeginGetResponse()`. With CPS, we can "register" the code that will execute upon completion of the asynchronous method. Note that it is still necessary to call `EndGetResponse()`, but by placing it in the callback we ensure that it doesn't block the main thread while the asynchronous call completes.

Passing State between APM Methods

The `state` parameter is used to pass additional data to the callback when it executes. Listing C.2 includes a `WebRequestState` class for passing additional data into the callback, and it includes the `WebRequest` itself in this case so that we can use it to call `EndGetResponse()`. One alternative to the `WebRequestState` class itself would be to use an anonymous method (including a lambda expression) with closures for the additional data, as shown in Listing C.3.

Listing C.3: Passing State Using Closure on an Anonymous Method

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading;

public class Program
{
  public static void Main(string[] args)
  {
      string url = "http://www.intelliTechture.com";
      if (args.Length > 0)
      {
          url = args[0];
      }

      Console.Write(url);
      WebRequest webRequest = WebRequest.Create(url);
      ManualResetEventSlim resetEvent =
          new ManualResetEventSlim();
      IAsyncResult asyncResult =
          webRequest.BeginGetResponse(
              (completedAsyncResult) =>
              {
                  HttpWebResponse response =
                  (HttpWebResponse)webRequest.EndGetResponse(
                      completedAsyncResult);
              Stream stream =
                  response.GetResponseStream();
              StreamReader reader =
                  new StreamReader(stream);
              int length = reader.ReadToEnd().Length;
```

```
                  Console.WriteLine(FormatBytes(length));
                  resetEvent.Set();
                  resetEvent.Dispose();
              },
              null);

          // Indicate busy using dots.
          while (
              !asyncResult.AsyncWaitHandle.WaitOne(100))
          {
              Console.Write('.');
          }
          resetEvent.Wait();
      }

      // ...
  }
```

Regardless of whether we pass the state via closures, notice that we are using a `ManualResetEvent` to signal when the `AsyncCallback` has completed. This is somewhat peculiar because `IAsyncResult` already includes a `WaitHandle`. The difference, however, is that `IAsyncResult`'s `WaitHandle` is set when the asynchronous method completes but before `AsyncCallback` executes. If we blocked on only `IAsyncResult`'s `WaitHandle`, we would be likely to exit the program before `AsyncCallback` has executed. For this reason, we use a separate `ManualResetEvent`.

Resource Cleanup

Another important APM rule is that no resource leaks should occur, even if the `EndX` method is mistakenly not called. Since `WebRequestState` owns the `ManualResetEvent`, it specifically owns a resource that requires such cleanup. To handle this task, the state object uses the standard `IDisposable` pattern with the `IDispose()` method.

Begin 4.0

Calling APM Methods Using the TPL

Even though the TPL greatly simplifies making an asynchronous call on a long-running method, it is generally better to use the API-provided APM methods than to code the TPL against the synchronous version. The reason for this is that the API developer best understands what is the most efficient threading code to write, which data to synchronize, and which type of synchronization to use. Fortunately, there are special methods on the TPL's `TaskFactory` that are designed specifically for invoking the APM methods. As a result, if you have access to the TPL but are using APM-related APIs, you can still use the TPL to invoke them.

APM with the TPL and CPS

The TPL includes a set of overloads on `FromAsync` for invoking APM methods. Listing C.4 provides an example. The same listing expands on the other APM examples to support downloading of multiple URLs; see Output C.2.

Listing C.4: Using the TPL to Call the APM

```
using System;
using System.IO;
using System.Net;
using System.Linq;
using System.Threading.Tasks;

public class Program
{
  static private object ConsoleSyncObject =
      new object();

  public static void Main(string[] args)
  {
      string[] urls = args;
      if (args.Length == 0)
      {
          urls = new string[]
              {
                  "http://www.habitat-spokane.org",
                  "http://www.partnersintl.org",
                  "http://www.iassist.org",
                  "http://www.fh.org",
                  "http://www.worldvision.org"
              };
      }

      Task[] tasks = new Task[urls.Length];
      for (int line = 0; line < urls.Length; line++)
      {
          tasks[line] = DisplayPageSizeAsync(
              urls[line], line);
      }

      while (!Task.WaitAll(tasks, 50))
      {
          DisplayProgress(tasks);
      }
      Console.SetCursorPosition(0, urls.Length);
  }
```

4.0

```
private static Task<WebResponse>
    DisplayPageSizeAsync(string url, int line)
{
    WebRequest webRequest = WebRequest.Create(url);
    WebRequestState state =
        new WebRequestState(webRequest, line);
    Write(state, url + " ");
    return Task<WebResponse>.Factory.FromAsync(
            webRequest.BeginGetResponse,
            GetResponseAsyncCompleted, state);
}

private static WebResponse GetResponseAsyncCompleted(
    IAsyncResult asyncResult)
{
    WebRequestState completedState =
            (WebRequestState)asyncResult.AsyncState;
    HttpWebResponse response =
        (HttpWebResponse)completedState.WebRequest
            .EndGetResponse(asyncResult);
    Stream stream =
        response.GetResponseStream();
    using (StreamReader reader =
        new StreamReader(stream))
    {
        int length = reader.ReadToEnd().Length;
        Write(
            completedState, FormatBytes(length));
    }
    return response;
}

private static void Write(
    WebRequestState completedState, string text)
{
    lock (ConsoleSyncObject)
    {
        Console.SetCursorPosition(
            completedState.ConsoleColumn,
            completedState.ConsoleLine);
        Console.Write(text);
        completedState.ConsoleColumn +=
            text.Length;
    }
}

private static void DisplayProgress(
    Task[] tasks)
{
    for (int i = 0; i < tasks.Length; i++)
    {
        if (!tasks[i].IsCompleted)
        {
```

4.0

```
                DisplayProgress(
                    (WebRequestState)tasks[i]
                    .AsyncState);
            }
        }
    }

private static void DisplayProgress(
        WebRequestState state)
    {
        lock (ConsoleSyncObject)
        {
            int left = state.ConsoleColumn;
            int top = state.ConsoleLine;
            if (left >= Console.BufferWidth -
                int.MaxValue.ToString().Length)
            {
                left = state.Url.Length;

                Console.SetCursorPosition(left, top);
                Console.Write("".PadRight(
                    Console.BufferWidth -
                        state.Url.Length));

                state.ConsoleColumn = left;
            }

            Write(state, ".");
        }
    }

    static public string FormatBytes(long bytes)
    {
        string[] magnitudes =
            new string[] { "GB", "MB", "KB", "Bytes" };
        long max =
            (long)Math.Pow(1024, magnitudes.Length);

        return string.Format("{1:##.##} {0}",
            magnitudes.FirstOrDefault(
                magnitude =>
                    bytes > (max /= 1024) )?? "0 Bytes",
                (decimal)bytes / (decimal)max).Trim();
    }
}

class WebRequestState
{
    public WebRequestState(
        WebRequest webRequest, int line)
    {
        WebRequest = webRequest;
```

4.0

```
            ConsoleLine = line;
            ConsoleColumn = 0;
        }
        public WebRequestState(WebRequest webRequest)
        {
            WebRequest = webRequest;
        }
        public WebRequest WebRequest { get; private set; }
        public string Url
        {
            get
            {
                return WebRequest.RequestUri.ToString();
            }
        }
        public int ConsoleLine { get; set; }
        public int ConsoleColumn { get; set; }
    }
```

Output C.2

4.0

```
http://www.habitat-spokane.org ..9.18 KB
http://www.partnersintl.org .........14.74 KB
http://www.iassist.org ...17.12 KB
http://www.fh.org ...................35.09 KB
http://www.worldvision.org ............54.56 KB
```

Connecting a `Task` with the APM method pair is relatively easy. The overload used in Listing C.4 takes three parameters. First, there is the `BeginX` method delegate (`webRequest.BeginGetResponse`). Next is a delegate that matches the `EndX` method. Although the `EndX` method (`webRequest.EndGetResponse`) could be used directly, passing a delegate (`GetResponseAsyncCompleted`) and using the CPS allows additional completion activity to execute. The last parameter is the `state` parameter, similar to what the `BeginX` method accepts.

One of the advantages of invoking a pair of APM methods using the TPL is that we don't have to worry about signaling the conclusion of the `AsyncCallback` method. Instead, we monitor the `Task` for completion. As a result, `WebRequestState` no longer needs to contain a `ManualResetEventSlim`.

Using the TPL and `ContinueWith()` to Call an APM Method

Another option when calling `TaskFactory.FromAsync()` is to pass the `EndX` method directly and then to use `ContinueWith()` for any follow-up code. The result is that you have a single object to represent any kind of asynchronous operation and, therefore, you can start composing task-based operations together, even if the underlying implementation is APM-based. In addition, you can query the continue-with-`Task` parameter (see `continueWithTask` in Listing C.5) for the result (`continueWithTask.Result`) rather than storing a means to access the `EndX` method via an `async`-state object or using closure and an anonymous delegate (we store `WebRequest` in Listing C.4).

Listing C.5: Using the TPL to Call an APM Method Using `ContinueWith()`

```
// ...

  private static Task
      DisplayPageSizeAsync(string url, int line)
  {
      WebRequest webRequest = WebRequest.Create(url);
      WebRequestState state =
          new WebRequestState(webRequest, line);
      Write(state, url + " ");
      return Task<WebResponse>.Factory.FromAsync(
              webRequest.BeginGetResponse,
              webRequest.EndGetResponse, state)
          .ContinueWith(
              (antecedent, antecedentState) =>
          {
              Stream stream =
                  antecedent.Result.
                      GetResponseStream();
              using (StreamReader reader =
                  new StreamReader(stream))
              {
                  int length =
                      reader.ReadToEnd().Length;
                  Write(state,
                      FormatBytes(length).ToString());
              }
          }, state);
  }

// ...
```

Notice that for the state to be passed into the `Task` returned from `ContinueWith()`, the `ContinueWith()` call explicitly includes `antecedentState` in the delegate in addition to having it as a parameter.

End 4.

Begin 5.0

Using TAP to Call an APM Method

Given that TAP is essentially designed for handling the continuation tasks, an obvious enhancement (albeit one depending on C# 5.0) is to use `async`/`await` rather than `ContinueWith()`, as shown in Listing C.6.

Listing C.6: Using TAP to Call the APM

```
// ...

  private async static Task
      DisplayPageSizeAsync(string url, int line)
  {
      WebRequestState state =
          new WebRequestState(url, line);
      Write(state, url + " ");
      WebRequest webRequest = WebRequest.Create(url);
      WebResponse webResponse =
          await Task<WebResponse>.Factory.FromAsync(
              webRequest.BeginGetResponse,
              webRequest.EndGetResponse, state);
      Stream stream =
          webResponse.GetResponseStream();
      using (StreamReader reader =
          new StreamReader(stream))
      {
          int length = reader.ReadToEnd().Length;
          Write(state,
              FormatBytes(length).ToString());
      }
  }

// ...
```

End 5.0

BEGINNER TOPIC

Synchronizing Console Using lock

In Listing C.4, we repeatedly change the location of the console's cursor and then proceed to write text to the console. Since multiple threads are executing that are also writing to the console, possibly changing the cursor location as well, we need to synchronize changes to the cursor location with write operations so that together they are atomic.

Listing C.4 includes a `ConsoleSyncObject` of type `object` as the synchronization lock identifier. Using it within a lock construct whenever we are moving the cursor or writing to the console prevents an interim update between the move and write operations to the console. Notice that even one-line `Console.WriteLine()` statements are surrounded with `lock`. Although they will be atomic, we don't want them to interrupt a different block that is not atomic. To ensure this outcome, all console changes require the synchronization as long as there are multiple threads of execution.

Asynchronous Delegate Invocation

One specific implementation of the APM pattern is "asynchronous delegate invocation," which leverages special C# compiler-generated code on all delegate data types. Given a delegate instance of `Func<string, int>`, for example, there is an APM pair of methods available on the instance:

```
System.IAsyncResult BeginInvoke(
    string arg, AsyncCallback callback, object @object)
int EndInvoke(IAsyncResult result)
```

The result is that you can call any delegate (and therefore any method) synchronously just by using the C# compiler-generated methods.

Unfortunately, the underlying technology used by the asynchronous delegate invocation pattern is an end-of-further-development technology for distributed programming known as **remoting.** Although Microsoft still supports the use of asynchronous delegate invocation and for the foreseeable future it will continue to function as it does today, the performance characteristics are suboptimal given other approaches—namely, `Thread`, `ThreadPool`, and the TPL. Given this reality, developers should favor one of these alternatives rather than implementing new development using the asynchronous delegate invocation API. Further discussion of this pattern is included in the Advanced Topic text that follows so that developers who encounter it will understand how it works.

ADVANCED TOPIC

Asynchronous Delegate Invocation in Detail

With asynchronous delegate invocation, you do not code using an explicit reference to `Task` or `Thread`. Instead, you use delegate instances and the compiler-generated `BeginInvoke()` and `EndInvoke()` methods—whose implementation requests threads from the `ThreadPool`. Consider the code in Listing C.7.

Listing C.7: Asynchronous Delegate Invocation

```
using System;

public class Program
{
  public static void Main(string[] args)
  {
      Console.WriteLine("Application started....");

      Console.WriteLine("Starting thread....");
      Func<int,string> workerMethod =
          PiCalculator.Calculate;
      IAsyncResult asyncResult =
          workerMethod.BeginInvoke(500, null, null);

      // Display periods as progress bar.
      while(!asyncResult.AsyncWaitHandle.WaitOne(
          100, false))
      {
          Console.Write('.');
      }
      Console.WriteLine();

      Console.WriteLine("Thread ending....");
      Console.WriteLine(
          workerMethod.EndInvoke(asyncResult));

      Console.WriteLine(
          "Application shutting down....");
  }
}
```

The results of Listing C.7 appear in Output C.3.

Output C.3

```
Application started....
Starting thread....
..........................
Thread ending....
3.14159265358979323846264338327950288419716939937510582097494459230781
6406286208998628034825342117067982148086513282306647093844609550582231
7253594081284811174502841027019385211055596446229489549303819644288109
7566593344612847564823378678316527120190914564856692346034861045432664
8213393607260249141273724587006606315588174881520920962829254091715364
3678925903600113305305488204665213841469519415116094330572703657595919
5309218611738193261179310511854807446237996274956735188575272489122793
818301194912
Application shutting down....
```

`Main()` begins by assigning a delegate of type `Func<int, string>` that is pointing to `PiCalculator.Calculate(int digits)`.

Next, the code calls `BeginInvoke()`. This method starts the `PiCalculator.Calculate()` method on a thread from the thread pool and then returns immediately. This allows other code to run in parallel with the pi calculation. In this example, we print periods while waiting for the `PiCalculator.Calculate()` method to complete.

We poll the status of the delegate using `IAsyncResult.AsyncWaitHandle.WaitOne()` on `asyncResult`—the same mechanism available on APM. As a result, the code prints periods to the screen each second during which the `PiCalculator.Calculate()` method is executing.

Once the wait handle signals, the code calls `EndInvoke()`. As with all APM implementations, it is important to pass to `EndInvoke()` the same `IAsyncResult` reference returned when calling `BeginInvoke()`. In this example, `EndInvoke()` doesn't block because we poll the thread's state in the `while` loop and call `EndInvoke()` only after the thread has completed.

The example in Listing C.5 passed an integer and received a string—the signature of `Func<int, string>`. The key feature of asynchronous delegate invocation, however, is that passing data in and out of the target invocation is trivial; it just lines up with the synchronous method signature as it did in the APM pattern. Consider a delegate type that includes `out` and `ref` parameters, as shown in Figure C.2. (Although commonly encountered, this example intentionally doesn't use `Func` or `Action` because generics don't allow `ref` and `out` modifiers on type parameters.)

```
System.IAsyncResult UpdateHandler.BeginInvoke(
    Object[] data, ref object value, out string text
        AsyncCallback callback, object @object);

delegate bool UpdateHandlerFunc
    object[] data, ref object value, out string text);

bool UpdateHandler.EndInvoke(
    ref object value, out text);
```

FIGURE C.2: Delegate Parameter Distribution to `BeginInvoke()` and `EndInvoke()`

The `BeginInvoke()` method matches the delegate signature except for the additional `AsyncCallback` and `object` parameters. Like the `IAsyncResult` return, the additional parameters correspond to the standard APM parameters specifying a callback and passing state object. Similarly, the `EndInvoke()` method matches the original signature except that only outgoing parameters appear. Since `object[] data` is only incoming, it doesn't appear in the `EndInvoke()` method. Also, since the `EndInvoke()` method concludes the asynchronous call, its return matches the original delegate's return.

Because all delegates include the C# compiler-generated `BeginInvoke()` and `EndInvoke()` methods used by the asynchronous delegate invocation pattern, invoking any method synchronously—especially given `Func` and `Action` delegates—becomes relatively easy. Furthermore, it is a simple matter for the caller to invoke a method asynchronously regardless of whether the API programmer explicitly implemented it.

Before the TPL became available, the asynchronous delegate invocation pattern was significantly easier to use than the alternatives—a factor that encouraged programmers to use it when an API didn't provide explicit asynchronous calling patterns. However, apart from support for .NET 3.5 and earlier frameworks, the advent of the TPL diminished the need to use the asynchronous delegate invocation approach, if it is necessary at all.

The Event-Based Asynchronous Pattern[1]

Thus far we've made the assumption that an asynchronous method will return a task; the caller is notified that the asynchronous work is completed when the status and result of the task become set. Doing so may, in turn, cause completions of the task to execute asynchronously as well. Although this pattern is common and powerful, it is not the only option for dealing with asynchrony. Notably, the **Event-based Asynchronous Pattern (EAP)** is often used for long-running asynchronous work.

A method that uses the EAP typically has a name that ends in `Async`, returns `void`, and has no `out` parameters. EAP methods also typically take an `object` or generic parameter that contains caller-determined state that is associated with the asynchronous work, and sometimes they take a cancellation token if the asynchronous work is cancellable. For example, if we had

1. See *Concurrent Programming on Windows* by Joe Duffy (Addison-Wesley, 2009), pp. 421–426, for more information.

an EAP method that computes a given number of digits of pi and returns them in a string, the signature of the method might be

```
void CalculateAsync(int digits)
```

or

```
void CalculateAsync(
      int digits, object state, CancellationToken ct)
```

What is clearly missing from these signatures is the result. The asynchronous methods we've seen so far would return a `Task<string>` that could be used to fetch the asynchronously computed value after the computation has finished. In contrast, the EAP methods have no return value.

We have not yet seen the "event" part of the Event-based Asynchronous Pattern. The method is associated with an event; the caller of the EAP method registers an event handler on the associated event and then calls the method. The method starts the asynchronous work and returns; when the asynchronous work completes, the event is fired and the handler executes. The event arguments passed to the handler contain the computed string and any other information that the asynchronous method assumes would be useful to the listener, such as the caller-provided state, information about any exceptions or cancellations that occurred during the asynchronous operation, and so on. (Unsurprisingly, the exact information that would be available on a task object is instead made available in the event handler arguments.)

In Listing C.8, we show one way to use task-based asynchrony as an implementation detail of an EAP method. The EAP method `CalculateAsync<TState>()` has associated with it the `CalculateCompleted` event. The asynchronous method creates a task (which, by default, will run on a thread obtained from the thread pool) to do the calculation. The continuation of that task triggers the event when the task completes.

Listing C.8: Event-Based Asynchronous Pattern

```
using System;
using System.ComponentModel;
using System.Threading;
using System.Threading.Tasks;
using AddisonWesley.Michaelis.EssentialCSharp.Shared;

partial class PiCalculation
{
```

```
    public void CalculateAsync<TState>(
        int digits,
        CancellationToken cancelToken
          = default(CancellationToken),
        TState userState
          = default(TState))
    {
        SynchronizationContext.
            SetSynchronizationContext(
               AsyncOperationManager.
                   SynchronizationContext);
        // Ensure the continuation runs on the current thread, so that
        // the event will be raised on the same thread that
        // called this method in the first place.
        TaskScheduler scheduler =
            TaskScheduler.
                FromCurrentSynchronizationContext();
        Task.Run(
            () =>
            {
                return PiCalculator.Calculate(digits);
            }, cancelToken)
            .ContinueWith(
                continueTask =>
                {
                    Exception exception =
                        continueTask.Exception == null ?
                        continueTask.Exception :
                        continueTask.Exception.
                             InnerException;
                    CalculateCompleted(
                        typeof(PiCalculator),
                        new CalculateCompletedEventArgs(
                            continueTask.Result,
                            exception,
                            cancelToken.IsCancellationRequested,
                            userState));
                }, scheduler);
    }

    public event
        EventHandler<CalculateCompletedEventArgs>
            CalculateCompleted = delegate { };
```

```
    public class CalculateCompletedEventArgs
        : AsyncCompletedEventArgs
    {
        public CalculateCompletedEventArgs(
            string value,
            Exception error,
```

```
            bool cancelled,
            object userState) : base(
              error, cancelled, userState)
        {
            Result = value;
        }
        public string Result { get; private set; }
    }
  }
```

In Listing C.8, as with the async/await approach, we wish to ensure that the continuation that fires the event is always run on the same thread on which the original asynchronous method was run. To achieve this goal, we request the synchronization context from the TaskScheduler class. As this is a console application, the current thread has no synchronization (causing it to depend on the thread pool by default), so Listing C.8 shows creation of the default context first.

As mentioned earlier, EAP methods are often used for long-running asynchronous operations. Long-running operations frequently provide not only notification when the task completes, fails, or is canceled, but also occasional progress updates. This sort of information is particularly useful when the user interface displays the progress of the long-running asynchronous operation with some sort of progress bar or other indicator. The standard way to do so in an EAP method is to associate the method with a second event named ProgressChanged of type ProgressChangedEventHandler.

The EAP method and its associated event (or events, if the method produces progress updates) are typically instance members, not static members. This makes it easier to support multiple concurrent operations because each separate operation can be associated with a different instance.

Background Worker Pattern

Begin 2.0

Another pattern that provides operation status and the possibility of cancellation is the **background worker pattern,** a specific implementation of EAP. The .NET Framework 2.0 (or later) includes a BackgroundWorker class for programming this type of pattern.

Listing C.9 is an example of this pattern—again calculating pi to the number of digits specified.

LISTING C.9: Using the Background Worker API

```
using System;
using System.Threading;
using System.ComponentModel;
using System.Text;

public class PiCalculator
{
  public static BackgroundWorker calculationWorker =
      new BackgroundWorker();
  public static AutoResetEvent resetEvent =
      new AutoResetEvent(false);

  public static void Main()
  {
      int digitCount;

      Console.Write(
          "Enter the number of digits to calculate:");
      if (int.TryParse(
          Console.ReadLine(), out digitCount))
      {
          Console.WriteLine("ENTER to cancel");
          // C# 2.0 syntax for registering delegates.
          calculationWorker.DoWork += CalculatePi;
          // Register the ProgressChanged callback.
          calculationWorker.ProgressChanged +=
              UpdateDisplayWithMoreDigits;
          calculationWorker.WorkerReportsProgress =
              true;
          // Register a callback for when the calculation completes.
          calculationWorker.RunWorkerCompleted +=
              new RunWorkerCompletedEventHandler(
                  Complete);
          calculationWorker.
              WorkerSupportsCancellation = true;

          // Begin calculating pi for up to digitCount digits.
          calculationWorker.RunWorkerAsync(
              digitCount);

          Console.ReadLine();
          // If cancel is called after the calculation
          // has completed, it doesn't matter.
          calculationWorker.CancelAsync();
          // Wait for Complete() to run.
          resetEvent.WaitOne();
      }
      else
      {
          Console.WriteLine(
              "The value entered is an invalid integer.");
```

2.0

```
    }
}


private static void CalculatePi(
    object sender, DoWorkEventArgs eventArgs)
{
    int digits = (int)eventArgs.Argument;

    StringBuilder pi =
        new StringBuilder("3.", digits + 2);
    calculationWorker.ReportProgress(
        0, pi.ToString());

    // Calculate rest of pi, if required.
    if (digits > 0)
    {
        for (int i = 0; i < digits; i += 9)
        {
            // Calculate next i decimal places.
            int nextDigit =
                PiDigitCalculator.StartingAt(
                    i + 1);
            int digitCount =
                Math.Min(digits - i, 9);
            string ds =
                string.Format("{0:D9}", nextDigit);
            pi.Append(ds.Substring(0, digitCount));

            // Show current progress.
            calculationWorker.ReportProgress(
                0, ds.Substring(0, digitCount));

            // Check for cancellation.
            if (
              calculationWorker.CancellationPending)
            {
                // Need to set Cancel if you want to
                // distinguish how a worker thread completed--
                // i.e., by checking
               //RunWorkerCompletedEventArgs.Cancelled.
                eventArgs.Cancel = true;
                break;
            }
        }
    }

    eventArgs.Result = pi.ToString();
}

private static void UpdateDisplayWithMoreDigits(
    object sender,
    ProgressChangedEventArgs eventArgs)
```

```
    {
        string digits = (string)eventArgs.UserState;

        Console.Write(digits);
    }


    static void Complete(
        object sender,
        RunWorkerCompletedEventArgs eventArgs)
    {
        // ...
    }
}
```

```
public class PiDigitCalculator
{
  // ...
}
```

Establishing the Pattern

The process of hooking up the background worker pattern is as follows:

1. Register the long-running method with the `BackgroundWorker.DoWork` event. In this example, the long-running task is the call to `CalculatePi()`.
2. To receive progress or status notifications, hook up a listener to `BackgroundWorker.ProgressChanged` and set `BackgroundWorker.WorkerReportsProgress` to `true`. In Listing C.9, the `UpdateDisplayWithMoreDigits()` method takes care of updating the display as more digits become available.
3. Register a method (`Complete()`) with the `BackgroundWorker.RunWorkerCompleted` event.
4. Assign the `WorkerSupportsCancellation` property to support cancellation. Once this property is assigned the value `true`, a call to `BackgroundWorker.CancelAsync` will set the `DoWorkEventArgs.CancellationPending` flag.

2.0

5. Within the `DoWork`-provided method (`CalculatePi()`), check the `DoWorkEventArgs.CancellationPending` property and exit the method when it is `true`.

6. Once everything is set up, start the work by calling `BackgroundWorker.RunWorkerAsync()` and providing a state parameter that is passed to the specified `DoWork()` method.

When you break it into steps, the background worker pattern is relatively easy to follow and, true to EAP, it provides explicit support for progress notification. The drawback is that you cannot use it arbitrarily on any method. Instead, the `DoWork()` method must conform to a `System.ComponentModel.DoWorkEventHandler` delegate, which takes arguments of type `object` and `DoWorkEventArgs`. If this isn't the case, a wrapper function is required—something fairly trivial using anonymous methods. The cancellation- and progress-related methods also require specific signatures, but these are in control of the programmer setting up the background worker pattern.

Exception Handling

If an unhandled exception occurs while the background worker thread is executing, the `RunWorkerCompletedEventArgs` parameter of the `RunWorkerCompleted` delegate (`Completed`'s `eventArgs`) will have an `Error` property set with the exception. As a result, checking the `Error` property within the `RunWorkerCompleted` callback in Listing C.10 provides a means of handling the exception.

Listing C.10: Handling Unhandled Exceptions from the Worker Thread

```
// ...
static void Complete(
    object sender, RunWorkerCompletedEventArgs eventArgs)
{
    Console.WriteLine();
    if (eventArgs.Cancelled)
    {
        Console.WriteLine("Cancelled");
    }
    else if (eventArgs.Error != null)
    {
        // IMPORTANT: check error to retrieve any exceptions.
        Console.WriteLine(
            "ERROR: {0}", eventArgs.Error.Message);
    }
    else
    {
        Console.WriteLine("Finished");
```

2.0

```
        }
        resetEvent.Set();
    }
    // ...
```

End 2.0

It is important that the code check `eventArgs.Error` inside the `RunWorkerCompleted` callback. Otherwise, the exception will go undetected—it won't even be reported to `AppDomain`.

Dispatching to the Windows UI

One other important threading concept relates to user interface development using the `System.Windows.Forms` and `System.Windows` namespaces. As already discussed in the UI-related content of Chapter 18, the Microsoft Windows suite of operating systems uses a single-threaded, message-processing–based user interface. As a consequence, only one thread at a time should access the user interface, and code should marshal any alternative thread interaction via the Windows message pump. Fortunately, thanks to the fact that TAP uses the synchronization context when executing the continuation task, calls following an `await` expression call can freely invoke the UI API without concern for dispatching invocations to the UI thread. Unfortunately, in prior versions of C#, this was not the case. Instead, invoking a UI method on the UI thread required special invocation logic both for Windows Forms and for the Windows Presentation Framework API, as we discuss in the following sections.

Windows Forms

When programming against Windows Forms, the process of checking whether UI invocation is allowable from a thread involves calling a component's `InvokeRequired` property to determine whether marshalling is necessary. If `InvokeRequired` returns `true`, marshalling is necessary and can be implemented via a call to `Invoke()`. Internally, `Invoke()` will check `InvokeRequired` anyway, but it can be more efficient to do so beforehand explicitly. Listing C.11 demonstrates this pattern.

Listing C.11: Accessing the User Interface via `Invoke()`

```
using System;
using System.Drawing;
```

```
using System.Threading;
using System.Windows.Forms;

class Program : Form
{
    private System.Windows.Forms.ProgressBar _ProgressBar;

  [STAThread]
  static void Main()
  {
      Application.Run(new Program());
  }

  public Program()
  {
      InitializeComponent();
      // Use Task.Factory.StartNew for .NET 4.0.
      Task task = Task.Run((Action)Increment);
  }

  void UpdateProgressBar()
  {
      if (_ProgressBar.InvokeRequired)
      {
          MethodInvoker updateProgressBar =
              UpdateProgressBar;
          _ProgressBar.BeginInvoke(updateProgressBar);
      }
      else
      {
          _ProgressBar.Increment(1);
      }
  }

  private void Increment()
  {
      for (int i = 0; i < 100; i++)
      {
          UpdateProgressBar();
          Thread.Sleep(100);
      }

      if (InvokeRequired)
      {
          // Close cannot be called directly from a non-UI thread.
          Invoke(new MethodInvoker(Close));
      }
      else
      {
          Close();
      }
  }
```

```
    private void InitializeComponent()
    {
        _ProgressBar = new ProgressBar();
        SuspendLayout();

        _ProgressBar.Location = new Point(13, 17);
        _ProgressBar.Size = new Size(267, 19);

        ClientSize = new Size(292, 53);
        Controls.Add(this._ProgressBar);
        Text = "Multithreading in Windows Forms";
        ResumeLayout(false);
    }
}
```

This program displays a window containing a progress bar that automatically starts incrementing. Once the progress bar reaches 100 percent, the dialog box closes.

In Listing C.11, notice that you have to check `InvokeRequired` twice, and then the marshal calls across to the user interface thread if it returns `true`. In both cases, the marshalling involves instantiating a `MethodInvoker` delegate that is then passed to `Invoke()`. Since marshalling across to another thread could be relatively slow, an asynchronous invocation of the call is also available via `BeginInvoke()` and `EndInvoke()`.

`Invoke()`, `BeginInvoke()`, `EndInvoke()`, and `InvokeRequired` constitute the members of the `System.ComponentModel.ISynchronizeInvoke` interface that is implemented by `System.Windows.Forms.Control`, from which Windows Forms controls derive.

Windows Presentation Foundation

Achieving the same marshalling check on the **Windows Presentation Foundation (WPF)** platform involves a slightly different approach. WPF includes a static member property called `Current` of type `DispatcherObject` on the `System.Windows.Application` class. Calling `CheckAccess()` on the dispatcher serves the same function as `InvokeRequired` on controls in Windows Forms.

Listing C.12 demonstrates this approach with a static `UIAction` object. Whenever a developer wants to call a method that might interact with the user interface, she simply calls `UIAction.Invoke()` and passes a delegate for the UI code she wishes to call. This, in turn, checks the dispatcher to see if marshalling is necessary and responds accordingly.

LISTING C.12: Safely Invoking User Interface Objects

```
using System;
using System.Windows;
using System.Windows.Threading;

public static class UIAction
{
  public static void Invoke<T>(
      Action<T> action, T parameter)
  {
      Invoke(() => action(parameter));
  }
  public static void Invoke(Action action)
  {
      DispatcherObject dispatcher =
          Application.Current;
      if (dispatcher == null
          || dispatcher.CheckAccess()
          || dispatcher.Dispatcher == null
          )
      {
          action();
      }
      else
      {
          SafeInvoke(action);
      }
  }

  // We want to catch all exceptions here so we can rethrow them.
  private static void SafeInvoke(Action action)
  {
      Exception exceptionThrown = null;
      Action target = () =>
      {
          try
          {
              action();
          }
          catch (Exception exception)
          {
              exceptionThrown = exception;
          }
      };
      Application.Current.Dispatcher.Invoke(target);
      if (exceptionThrown != null)
      {
          // Use ExceptionDispatchInfo.Throw() for .NET 4.5+.
          throw exceptionThrown;
      }
  }
}
```

One additional feature in the `UIAction` of Listing C.12 is the marshalling of any exceptions on the UI thread that may have occurred. `SafeInvoke()` wraps all requested delegate calls in a try/catch block; if an exception is thrown, it saves the exception and then rethrows it once the context returns to the calling thread. In this way, `UIAction` avoids throwing unhandled exceptions on the UI thread.

D

Timers Prior to the Async/Await Pattern of C# 5.0

CHAPTER 19 INTRODUCED THE USE of `Task.Delay()` when a timer was required. For scenarios prior to .NET 4.5, several timer classes are available, including `System.Windows.Forms.Timer`, `System.Timers.Timer`, and `System.Threading.Timer`.

The development team designed `System.Windows.Forms.Timer` specifically for use within a rich client user interface. Programmers can drag it onto a form as a nonvisual control and regulate the behavior from within the Properties window. Most importantly, it will always safely fire an event from a thread that can interact with the user interface.

The other two timers are very similar. `System.Timers.Timer` is a wrapper for `System.Threading.Timer`, abstracting and layering on functionality. Specifically, `System.Threading.Timer` does not derive from `System.ComponentModel.Component`, and therefore, you cannot use it as a component within a component container, something that implements `System.ComponentModel.IContainer`. Another difference is that `System.Threading.Timer` enables the passing of state, an object parameter, from the call to start the timer and then into the call that fires the timer notification. The remaining differences simply concern API usability, with `System.Timers.Timer` supporting a synchronization object and having calls that are slightly more intuitive. Both `System.Timers.Timer` and `System.Threading.Timer` are designed for use in server-type processes, but `System.Timers.Timer` includes a synchronization object to allow it to interact with the UI. Furthermore, both timers use the system thread pool. Table D.1 provides an overall comparison of the various timers.

TABLE D.1: Overview of the Various Timer Characteristics

Feature Description	`System.Timers.Timer`	`System.Threading.Timer`	`System.Windows.Forms.Timer`
Supports adding and removing listeners after the timer is instantiated	Yes	No	Yes
Supports callbacks on the user interface thread	Yes	No	Yes
Calls back from threads obtained from the thread pool	Yes	Yes	No
Supports drag-and-drop in the Windows Forms Designer	Yes	No	Yes
Suitable for running in a multithreaded server environment	Yes	Yes	No
Includes support for passing arbitrary state from the timer initialization to the callback	No	Yes	No
Implements `IDisposable`	Yes	Yes	Yes
Supports on-off callbacks as well as periodic repeating callbacks	Yes	Yes	Yes
Accessible across application domain boundaries	Yes	Yes	Yes
Supports `IComponent`; hostable in an `IContainer`	Yes	No	Yes

Using `System.Windows.Forms.Timer` is a relatively obvious choice for user interface programming with Windows Forms. The only caution is that a long-running operation on the user interface thread may delay the arrival of a timer's expiration.[1] Choosing between the other two options is less obvious, and generally, the difference between the two is insignificant. If hosting within an `IContainer` is necessary, `System.Timers.Timer` is the right choice. However, if no specific `System.Timers.Timer` feature is required, choose `System.Threading.Timer` by default, simply because it is a slightly lighter-weight implementation.

Listing D.1 and Listing D.2 provide sample code for using `System.Timers.Timer` and `System.Threading.Timer`, respectively. Their code is very similar, including the fact that both support instantiation within a `using` statement because both support `IDispose`. The output for both listings is identical, and it appears in Output D.1. The purpose of each is to display a timestamp in association with a counting value indicating the number of times the timer fired. Once complete, the output verifies that the timer thread is not the same as the Main thread along with the final value of the count.

Listing D.1: Using `System.Timers.Timer`

```
using System;
using System.Timers;
using System.Threading;
// Because Timer exists in both the System.Timers and
// System.Threading namespaces, you disambiguate "Timer"
// using an alias directive.
using Timer = System.Timers.Timer;

class UsingSystemTimersTimer
{
    private static int _Count=0;
    private static readonly ManualResetEvent _ResetEvent =
       new ManualResetEvent(false);
    private static int _AlarmThreadId;

    public static void Main()
    {
        using( Timer timer = new Timer() )
        {
            // Initialize Timer
            timer.AutoReset = true;
            timer.Interval = 1000;
            timer.Elapsed +=
                new ElapsedEventHandler(Alarm);

            timer.Start();
```

1. In theory, a similar delay is possible with timers that depend on a thread pool as well because the thread pool may already be busy.

```
            // Wait for Alarm to fire for the 10th time.
                _ResetEvent.WaitOne();
      }

            // Verify that the thread executing the alarm
            // Is different from the thread executing Main
            if(_AlarmThreadId ==
                Thread.CurrentThread.ManagedThreadId)
            {
                throw new ApplicationException(
                    "Thread Ids are the same.");
            }
            if(_Count < 9)
            {
                throw new ApplicationException(
                    " _Count < 9");
            };

            Console.WriteLine(
                "(Alarm Thread Id) {0} != {1} (Main Thread Id)",
                _AlarmThreadId,
                Thread.CurrentThread.ManagedThreadId);
            Console.WriteLine(
                "Final Count = {0}", _Count);
        }

        static void Alarm(
            object sender, ElapsedEventArgs eventArgs)
        {
            _Count++;

            Console.WriteLine("{0}:- {1}",
                eventArgs.SignalTime.ToString("T"),
                _Count);

            if (_Count >= 9)
            {
                _AlarmThreadId =
                    Thread.CurrentThread.ManagedThreadId;
                _ResetEvent.Set();
            }
        }
    }
```

In Listing D.1, you have using directives for both System.Threading and System.Timers. This makes the Timer type ambiguous. Therefore, use an alias to explicitly associate Timer with System.Timers.Timer.

One noteworthy characteristic of `System.Threading.Timer` is that it takes the callback delegate and interval within the constructor.

Listing D.2: Using `System.Threading.Timer`

```
using System;
using System.Threading;

class UsingSystemThreadingTimer
{
    private static int _Count=0;
    private static readonly AutoResetEvent _ResetEvent =
        new AutoResetEvent(false);
    private static int _AlarmThreadId;

    public static void Main()
    {
        // Timer(callback, state, dueTime, period)
        using( Timer timer =
            new Timer(Alarm, null, 0, 1000) )
  {
     // Wait for Alarm to fire for the 10th time.
        _ResetEvent.WaitOne();
        }

     // Verify that the thread executing the alarm
     // Is different from the thread executing Main
        if(_AlarmThreadId ==
            Thread.CurrentThread.ManagedThreadId)
        {
            throw new ApplicationException(
                "Thread Ids are the same.");
        }
        if(_Count < 9)
        {
            throw new ApplicationException(
                " _Count < 9");
        };

        Console.WriteLine(
            "(Alarm Thread Id) {0} != {1} (Main Thread Id)",
            _AlarmThreadId,
            Thread.CurrentThread.ManagedThreadId);
        Console.WriteLine(
            "Final Count = {0}", _Count);
    }

    static void Alarm(object state)
    {
        _Count++;
```

```
            Console.WriteLine("{0}:- {1}",
                DateTime.Now.ToString("T"),
                _Count);

            if (_Count >= 9)
            {
                _AlarmThreadId =
                    Thread.CurrentThread.ManagedThreadId;
                _ResetEvent.Set();
            }
        }
    }
```

OUTPUT D.1

```
12:19:36 AM:- 1
12:19:37 AM:- 2
12:19:38 AM:- 3
12:19:39 AM:- 4
12:19:40 AM:- 5
12:19:41 AM:- 6
12:19:42 AM:- 7
12:19:43 AM:- 8
12:19:44 AM:- 9
(Alarm Thread Id) 4 != 1 (Main Thread Id)
Final Count = 9
```

You can change the interval or time due after instantiation on `System.Threading.Timer` via the `Change()` method. However, you cannot change the callback listeners after instantiation. Instead, you must create a new instance.

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