PROGRAMMING LANGUAGE PRAGMATICS

IV

FOURTH EDITION

Michael L. Scott

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MORGAN KAUFMANN

Programming Language Pragmatics

FOURTH EDITION

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Contents

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Foreword

Programming languages are universally accepted as one of the core subjects that every computer scientist must master. The reason is clear: these languages are the main notation we use for developing products and for communicating new ideas. They have influenced the field by enabling the development of those multimillion-line programs that shaped the information age. Their success is owed to the long-standing effort of the computer science community in the creation of new languages and in the development of strategies for their implementation. The large number of computer scientists mentioned in the footnotes and bibliographic notes in this book by Michael Scott is a clear manifestation of the magnitude of this effort as is the sheer number and diversity of topics it contains.

Over 75 programming languages are discussed. They represent the best and most influential contributions in language design across time, paradigms, and application domains. They are the outcome of decades of work that led initially to Fortran and Lisp in the 1950s, to numerous languages in the years that followed, and, in our times, to the popular dynamic languages used to program the Web. The 75 plus languages span numerous paradigms including imperative, functional, logic, static, dynamic, sequential, shared-memory parallel, distributed-memory parallel, dataflow, high-level, and intermediate languages. They include languages for scientific computing, for symbolic manipulations, and for accessing databases. This rich diversity of languages is crucial for programmer productivity and is one of the great assets of the discipline of computing.

Cutting across languages, this book presents a detailed discussion of control flow, types, and abstraction mechanisms. These are the representations needed to develop programs that are well organized, modular, easy to understand, and easy to maintain. Knowledge of these core features and of their incarnation in today's languages is a basic foundation to be an effective programmer and to better understand computer science today.

Strategies to implement programming languages must be studied together with the design paradigms. A reason is that success of a language depends on the quality of its implementation. Also, the capabilities of these strategies sometimes constraint the design of languages. The implementation of a language starts with parsing and lexical scanning needed to compute the syntactic structure of programs. Today's parsing techniques, described in Part I, are among the most beautiful algorithms ever developed and are a great example of the use of mathematical objects to create practical instruments. They are worthwhile studying just as an intellectual achievement. They are of course of great practical value, and a good way to appreciate the greatness of these strategies is to go back to the first Fortran compiler and study the ad hoc, albeit highly ingenious, strategy used to implement precedence of operators by the pioneers that built that compiler.

The other usual component of implementation are the compiler components that carry out the translation from the high-level language representation to a lower level form suitable for execution by real or virtual machines. The translation can be done ahead of time, during execution (just in time), or both. The book discusses these approaches and implementation strategies including the elegant mechanisms of translation driven by parsing. To produce highly efficient code, translation routines apply strategies to avoid redundant computations, make efficient use of the memory hierarchy, and take advantage of intra-processor parallelism. These, sometimes conflicting goals, are undertaken by the optimization components of compilers. Although this topic is typically outside the scope of a first course on compilers, the book gives the reader access to a good overview of program optimization in Part IV.

An important recent development in computing is the popularization of parallelism and the expectation that, in the foreseeable future, performance gains will mainly be the result of effectively exploiting this parallelism. The book responds to this development by presenting the reader with a range of topics in concurrent programming including mechanisms for synchronization, communication, and coordination across threads. This information will become increasingly important as parallelism consolidates as the norm in computing.

Programming languages are the bridge between programmers and machines. It is in them that algorithms must be represented for execution. The study of programming languages design and implementation offers great educational value by requiring an understanding of the strategies used to connect the different aspects of computing. By presenting such an extensive treatment of the subject, Michael Scott's *Programming Language Pragmatics*, is a great contribution to the literature and a valuable source of information for computer scientists.

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Preface

A course in computer programming provides the typical student's first exposure to the field of computer science. Most students in such a course will have used computers all their lives, for social networking, email, games, web browsing, word processing, and a host of other tasks, but it is not until they write their first programs that they begin to appreciate how applications *work*. After gaining a certain level of facility as programmers (presumably with the help of a good course in data structures and algorithms), the natural next step is to wonder how *programming languages* work. This book provides an explanation. It aims, quite simply, to be the most comprehensive and accurate languages text available, in a style that is engaging and accessible to the typical undergraduate. This aim reflects my conviction that students will understand more, and enjoy the material more, if we explain what is really going on.

In the conventional "systems" curriculum, the material beyond data structures (and possibly computer organization) tends to be compartmentalized into a host of separate subjects, including programming languages, compiler construction, computer architecture, operating systems, networks, parallel and distributed computing, database management systems, and possibly software engineering, object-oriented design, graphics, or user interface systems. One problem with this compartmentalization is that the list of subjects keeps growing, but the number of semesters in a Bachelor's program does not. More important, perhaps, many of the most interesting discoveries in computer science occur at the boundaries *between* subjects. Computer architecture and compiler construction, for example, have inspired each other for over 50 years, through generations of supercomputers, pipelined microprocessors, multicore chips, and modern GPUs. Over the past decade, advances in virtualization have blurred boundaries among the hardware, operating system, compiler, and language run-time system, and have spurred the explosion in cloud computing. Programming language technology is now routinely embedded in everything from dynamic web content, to gaming and entertainment, to security and finance.

Increasingly, both educators and practitioners have come to emphasize these sorts of interactions. Within higher education in particular, there is a growing trend toward integration in the core curriculum. Rather than give the typical student an in-depth look at two or three narrow subjects, leaving holes in all the others, many schools have revised the programming languages and computer organization courses to cover a wider range of topics, with follow-on electives in various specializations. This trend is very much in keeping with the ACM/IEEE-CS *Computer Science Curricula 2013* guidelines [SR13], which emphasize the need to manage the size of the curriculum and to cultivate both a "system-level perspective" and an appreciation of the interplay between theory and practice. In particular, the authors write,

> Graduates of a computer science program need to think at multiple levels of detail and abstraction. This understanding should transcend the implementation details of the various components to encompass an appreciation for the structure of computer systems and the processes involved in their construction and analysis [p. 24].

On the specific subject of this text, they write

> Programming languages are the medium through which programmers precisely describe concepts, formulate algorithms, and reason about solutions. In the course of a career, a computer scientist will work with many different languages, separately or together. Software developers must understand the programming models underlying different languages and make informed design choices in languages supporting multiple complementary approaches. Computer scientists will often need to learn new languages and programming constructs, and must understand the principles underlying how programming language features are defined, composed, and implemented. The effective use of programming languages, and appreciation of their limitations, also requires a basic knowledge of programming language translation and static program analysis, as well as run-time components such as memory management [p. 155].

The first three editions of *Programming Language Pragmatics* (PLP) had the good fortune of riding the trend toward integrated understanding. This fourth edition continues and strengthens the "systems perspective" while preserving the central focus on programming language design.

At its core, PLP is a book about *how programming languages work*. Rather than enumerate the details of many different languages, it focuses on concepts that underlie all the languages the student is likely to encounter, illustrating those concepts with a variety of concrete examples, and exploring the tradeoffs that explain *why* different languages were designed in different ways. Similarly, rather than explain how to build a compiler or interpreter (a task few programmers will undertake in its entirety), PLP focuses on what a compiler does to an input program, and why. Language design and implementation are thus explored together, with an emphasis on the ways in which they interact.

Changes in the Fourth Edition

In comparison to the third edition, PLP-4e includes

1. New chapters devoted to type systems and composite types, in place of the older single chapter on types

2. Updated treatment of functional programming, with extensive coverage of OCaml
3. Numerous other reflections of changes in the field
4. Improvements inspired by instructor feedback or a fresh consideration of familiar topics

Item 1 in this list is perhaps the most visible change. Chapter 7 was the longest in previous editions, and there is a natural split in the subject material. Reorganization of this material for PLP-4e afforded an opportunity to devote more explicit attention to the subject of type inference, and of its role in ML-family languages in particular. It also facilitated an update and reorganization of the material on parametric polymorphism, which was previously scattered across several different chapters and sections.

Item 2 reflects the increasing adoption of functional techniques into mainstream imperative languages, as well as the increasing prominence of SML, OCaml, and Haskell in both education and industry. Throughout the text, OCaml is now co-equal with Scheme as a source of functional programming examples. As noted in the previous paragraph, there is an expanded section (7.2.4) on the ML type system, and Section 11.4 includes an OCaml overview, with coverage of equality and ordering, bindings and lambda expressions, type constructors, pattern matching, and control flow and side effects. The choice of OCaml, rather than Haskell, as the ML-family exemplar reflects its prominence in industry, together with classroom experience suggesting that—at least for many students—the initial exposure to functional thinking is easier in the context of eager evaluation. To colleagues who wish I'd chosen Haskell, my apologies!

Other new material (Item 3) appears throughout the text. Wherever appropriate, reference has been made to features of the latest languages and standards, including C & C++11, Java 8, C# 5, Scala, Go, Swift, Python 3, and HTML 5. Section 3.6.4 pulls together previously scattered coverage of lambda expressions, and shows how these have been added to various imperative languages. Complementary coverage of object closures, including C++11's `std::function` and `std::bind`, appears in Section 10.4.4. Section c-5.4.5 introduces the x86-64 and ARM architectures in place of the x86-32 and MIPS used in previous editions. Examples using these same two architectures subsequently appear in the sections on calling sequences (9.2) and linking (15.6). Coverage of the x86 calling sequence continues to rely on `gcc`; the ARM case study uses LLVM. Section 8.5.3 introduces smart pointers. R-value references appear in Section 9.3.1. JavaFX replaces Swing in the graphics examples of Section 9.6.2. Appendix A has new entries for Go, Lua, Rust, Scala, and Swift.

Finally, Item 4 encompasses improvements to almost every section of the text. Among the more heavily updated topics are FOLLOW and PREDICT sets (Section 2.3.3); Wirth's error recovery algorithm for recursive descent (Section c-2.3.5); overloading (Section 3.5.2); modules (Section 3.3.4); duck typing (Section 7.3); records and variants (Section 8.1); intrusive lists (removed from the running example of Chapter 10); static fields and methods (Section 10.2.2);

mix-in inheritance (moved from the companion site back into the main text, and updated to cover Scala traits and Java 8 default methods); multicore processors (pervasive changes to Chapter 13); phasers (Section 13.3.1); memory models (Section 13.3.3); semaphores (Section 13.3.5); futures (Section 13.4.5); GIMPLE and RTL (Section c-15.2.1); QEMU (Section 16.2.2); DWARF (Section 16.3.2); and language genealogy (Figure A.1).

To accommodate new material, coverage of some topics has been condensed or even removed. Examples include modules (Chapters 3 and 10), variant records and `with` statements (Chapter 8), and metacircular interpretation (Chapter 11). Additional material—the Common Language Infrastructure (CLI) in particular—has moved to the companion site. Throughout the text, examples drawn from languages no longer in widespread use have been replaced with more recent equivalents wherever appropriate. Almost all remaining references to Pascal and Modula are merely historical. Most coverage of Occam and Tcl has also been dropped.

Overall, the printed text has grown by roughly 40 pages. There are 5 more “Design & Implementation” sidebars, 35 more numbered examples, and about 25 new end-of-chapter exercises and explorations. Considerable effort has been invested in creating a consistent and comprehensive index. As in earlier editions, Morgan Kaufmann has maintained its commitment to providing definitive texts at reasonable cost: PLP-4e is far less expensive than competing alternatives, but larger and more comprehensive.

The Companion Site

To minimize the physical size of the text, make way for new material, and allow students to focus on the fundamentals when browsing, over 350 pages of more advanced or peripheral material can be found on a companion web site: *booksite.elsevier.com/web/9780124104099*. Each companion-site (CS) section is represented in the main text by a brief introduction to the subject and an “In More Depth” paragraph that summarizes the elided material.

Note that placement of material on the companion site does *not* constitute a judgment about its technical importance. It simply reflects the fact that there is more material worth covering than will fit in a single volume or a single-semester course. Since preferences and syllabi vary, most instructors will probably want to assign reading from the CS, and most will refrain from assigning certain sections of the printed text. My intent has been to retain in print the material that is likely to be covered in the largest number of courses.

Also included on the CS are pointers to on-line resources and compilable copies of all significant code fragments found in the text (in more than two dozen languages).

Design & Implementation Sidebars

Like its predecessors, PLP-4e places heavy emphasis on the ways in which language design constrains implementation options, and the ways in which anticipated implementations have influenced language design. Many of these connections and interactions are highlighted in some 140 "Design & Implementation" sidebars. A more detailed introduction appears in Sidebar 1.1. A numbered list appears in Appendix B.

Numbered and Titled Examples

Examples in PLP-4e are intimately woven into the flow of the presentation. To make it easier to find specific examples, to remember their content, and to refer to them in other contexts, a number and a title for each is displayed in a marginal note. There are over 1000 such examples across the main text and the CS. A detailed list appears in Appendix C.

Exercise Plan

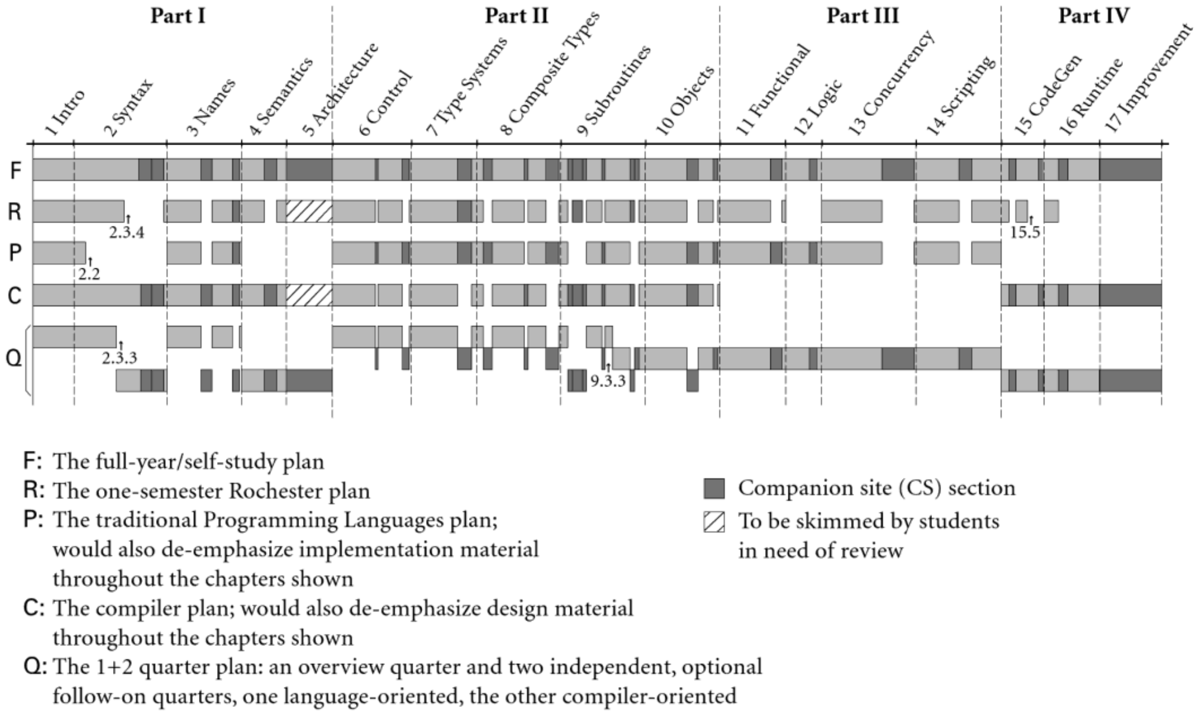
Review questions appear throughout the text at roughly 10-page intervals, at the ends of major sections. These are based directly on the preceding material, and have short, straightforward answers.

More detailed questions appear at the end of each chapter. These are divided into *Exercises* and *Explorations*. The former are generally more challenging than the per-section review questions, and should be suitable for homework or brief projects. The latter are more open-ended, requiring web or library research, substantial time commitment, or the development of subjective opinion. Solutions to many of the exercises (but not the explorations) are available to registered instructors from a password-protected web site: visit *textbooks.elsevier.com/web/9780124104099*.

How to Use the Book

Programming Language Pragmatics covers almost all of the material in the PL "knowledge units" of the *Computing Curricula 2013* report [SR13]. The languages course at the University of Rochester, for which this book was designed, is in fact one of the featured "course exemplars" in the report (pp. 369–371). Figure 1 illustrates several possible paths through the text.

For self-study, or for a full-year course (track `F` in Figure 1), I recommend working through the book from start to finish, turning to the companion site as each "In More Depth" section is encountered. The one-semester course at Rochester (track `R`) also covers most of the book, but leaves out most of the CS



F: The full-year/self-study plan

R: The one-semester Rochester plan

P: The traditional Programming Languages plan; would also de-emphasize implementation material throughout the chapters shown

C: The compiler plan; would also de-emphasize design material throughout the chapters shown

Q: The 1+2 quarter plan: an overview quarter and two independent, optional follow-on quarters, one language-oriented, the other compiler-oriented

■ Companion site (CS) section

▨ To be skimmed by students in need of review

Figure 1 **Paths through the text.** Darker shaded regions indicate supplemental "In More Depth" sections on the companion site. Section numbers are shown for breaks that do not correspond to supplemental material.

sections, as well as bottom-up parsing (2.3.4), logic languages (Chapter 12), and the second halves of Chapters 15 (Building a Runnable Program) and 16 (Run-time Program Management). Note that the material on functional programming (Chapter 11 in particular) can be taught in either OCaml or Scheme.

Some chapters (2, 4, 5, 15, 16, 17) have a heavier emphasis than others on implementation issues. These can be reordered to a certain extent with respect to the more design-oriented chapters. Many students will already be familiar with much of the material in Chapter 5, most likely from a course on computer organization; hence the placement of the chapter on the companion site. Some students may also be familiar with some of the material in Chapter 2, perhaps from a course on automata theory. Much of this chapter can then be read quickly as well, pausing perhaps to dwell on such practical issues as recovery from syntax errors, or the ways in which a scanner differs from a classical finite automaton.

A traditional programming languages course (track P in Figure 1) might leave out all of scanning and parsing, plus all of Chapter 4. It would also de-emphasize the more implementation-oriented material throughout. In place of these, it could add such design-oriented CS sections as multiple inheritance (10.6), Smalltalk (10.7.1), lambda calculus (11.7), and predicate calculus (12.3).

PLP has also been used at some schools for an introductory compiler course (track C in Figure 1). The typical syllabus leaves out most of Part III (Chapters 11 through 14), and de-emphasizes the more design-oriented material throughout. In place of these, it includes all of scanning and parsing, Chapters 15 through 17, and a slightly different mix of other CS sections.

For a school on the quarter system, an appealing option is to offer an introductory one-quarter course and two optional follow-on courses (track Q in Figure 1). The introductory quarter might cover the main (non-CS) sections of Chapters 1, 3, 6, 7, and 8, plus the first halves of Chapters 2 and 9. A language-oriented follow-on quarter might cover the rest of Chapter 9, all of Part III, CS sections from Chapters 6 through 9, and possibly supplemental material on formal semantics, type theory, or other related topics. A compiler-oriented follow-on quarter might cover the rest of Chapter 2; Chapters 4–5 and 15–17, CS sections from Chapters 3 and 9–10, and possibly supplemental material on automatic code generation, aggressive code improvement, programming tools, and so on.

Whatever the path through the text, I assume that the typical reader has already acquired significant experience with at least one imperative language. Exactly which language it is shouldn't matter. Examples are drawn from a wide variety of languages, but always with enough comments and other discussion that readers without prior experience should be able to understand easily. Single-paragraph introductions to more than 60 different languages appear in Appendix A. Algorithms, when needed, are presented in an informal pseudocode that should be self-explanatory. Real programming language code is set in `"typewriter" font`. Pseudocode is set in a sans-serif font.

Supplemental Materials

In addition to supplemental sections, the companion site contains complete source code for all nontrivial examples, and a list of all known errors in the book. Additional resources are available on-line at *textbooks.elsevier.com/web/9780124104099*. For instructors who have adopted the text, a password-protected page provides access to

- Editable PDF source for all the figures in the book
- Editable PowerPoint slides
- Solutions to most of the exercises
- Suggestions for larger projects

Acknowledgments for the Fourth Edition

In preparing the fourth edition, I have been blessed with the generous assistance of a very large number of people. Many provided errata or other feedback on the third edition, among them Yacine Belkadi, Björn Brandenburg, Bob Cochran, Daniel Crisman, Marcelino Debajo, Chen Ding, Peter Drake, Michael Edgar, Michael Glass, Sérgio Gomes, Allan Gottlieb, Hossein Hadavi, Chris Hart, Thomas Helmuth, Wayne Heym, Scott Hoge, Kelly Jones, Ahmed Khademzadeh, Eleazar Enrique Leal, Kyle Liddell, Annie Liu, Hao Luo, Dirk Müller, Holger Peine, Andreas Priesnitz, Mikhail Prokharau, Harsh Raju, and Jingguo Yao. I also remain indebted to the many individuals acknowledged in previous editions, and to the reviewers, adopters, and readers who made those editions a success.

Anonymous reviewers for the fourth edition provided a wealth of useful suggestions; my thanks to all of you! Special thanks to Adam Chlipala of MIT for his detailed and insightful suggestions on the coverage of functional programming. My thanks as well to Nelson Beebe (University of Utah) for pointing out that compilers cannot safely use integer comparisons for floating-point numbers that may be NaNs; to Dan Scarafoni for prompting me to distinguish between FIRST/EPS of symbols and FIRST/EPS of strings in the algorithm to generate PREDICT sets; to Dave Musicant for suggested improvements to the description of deep binding; to Allan Gottlieb (NYU) for several key clarifications regarding Ada semantics; and to Benjamin Kowarsch for similar clarifications regarding Objective-C. Problems that remain in all these areas are entirely my own.

In preparing the fourth edition, I have drawn on 25 years of experience teaching this material to upper-level undergraduates at the University of Rochester. I am grateful to all my students for their enthusiasm and feedback. My thanks as well to my colleagues and graduate students, and to the department's administrative, secretarial, and technical staff for providing such a supportive and productive work environment. Finally, my thanks to David Padua, whose work I have admired since I was in graduate school; I am deeply honored to have him as the author of the Foreword.

As they were on previous editions, the staff at Morgan Kaufmann has been a genuine pleasure to work with, on both a professional and a personal level. My thanks in particular to Nate McFadden, Senior Development Editor, who shepherded both this and the previous two editions with unfailing patience, good humor, and a fine eye for detail; to Mohana Natarajan, who managed the book's production; and to Todd Green, Publisher, who upholds the personal touch of the Morgan Kauffman imprint within the larger Elsevier universe.

Most important, I am indebted to my wife, Kelly, for her patience and support through endless months of writing and revising. Computing is a fine profession, but family is what really matters.

Michael L. Scott
Rochester, NY
August 2015

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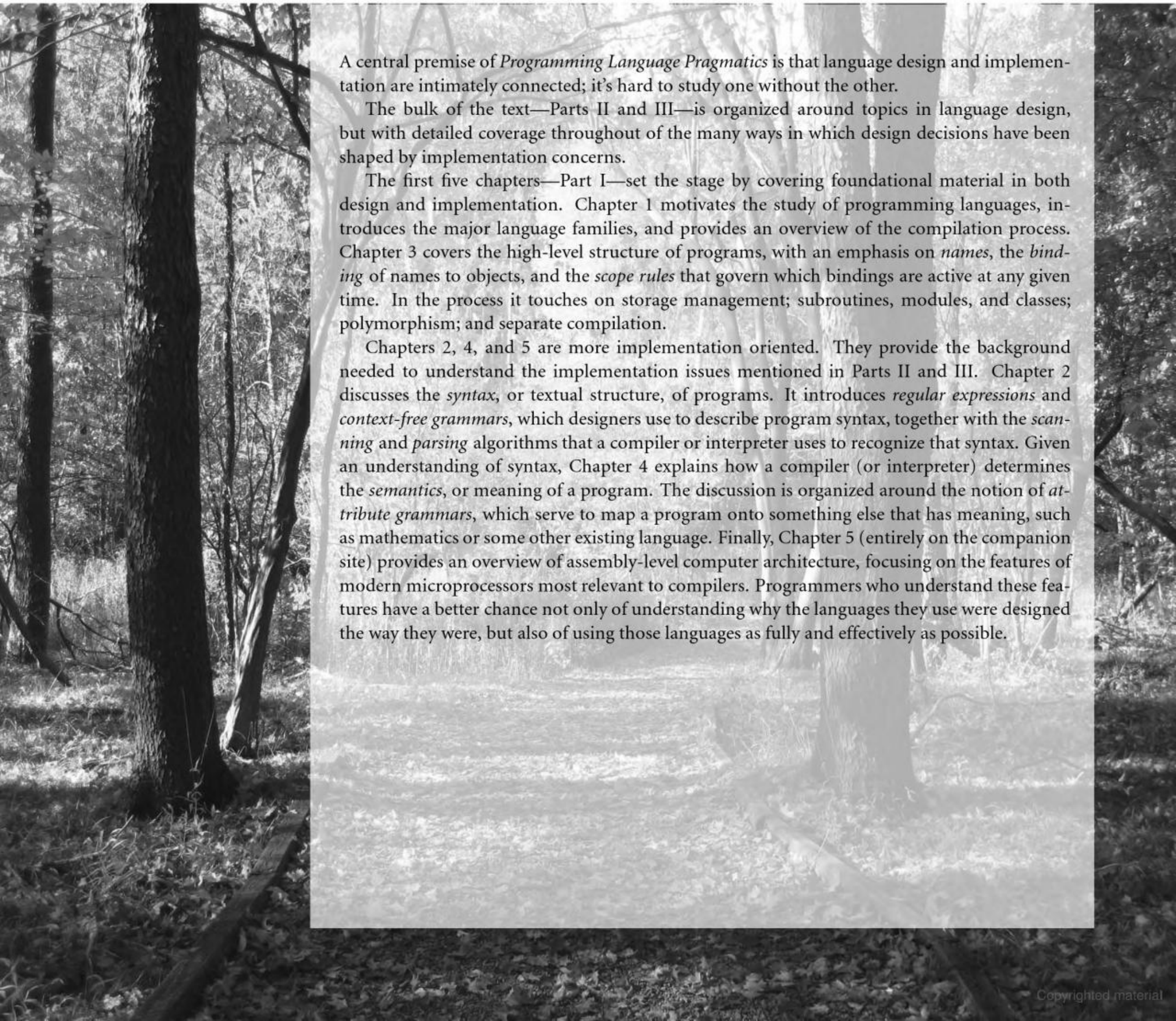
I Foundations



A central premise of *Programming Language Pragmatics* is that language design and implementation are intimately connected; it's hard to study one without the other.

The bulk of the text—Parts II and III—is organized around topics in language design, but with detailed coverage throughout of the many ways in which design decisions have been shaped by implementation concerns.

The first five chapters—Part I—set the stage by covering foundational material in both design and implementation. Chapter 1 motivates the study of programming languages, introduces the major language families, and provides an overview of the compilation process. Chapter 3 covers the high-level structure of programs, with an emphasis on *names*, the *binding* of names to objects, and the *scope rules* that govern which bindings are active at any given time. In the process it touches on storage management; subroutines, modules, and classes; polymorphism; and separate compilation.

Chapters 2, 4, and 5 are more implementation oriented. They provide the background needed to understand the implementation issues mentioned in Parts II and III. Chapter 2 discusses the *syntax*, or textual structure, of programs. It introduces *regular expressions* and *context-free grammars*, which designers use to describe program syntax, together with the *scanning* and *parsing* algorithms that a compiler or interpreter uses to recognize that syntax. Given an understanding of syntax, Chapter 4 explains how a compiler (or interpreter) determines the *semantics*, or meaning of a program. The discussion is organized around the notion of *attribute grammars*, which serve to map a program onto something else that has meaning, such as mathematics or some other existing language. Finally, Chapter 5 (entirely on the companion site) provides an overview of assembly-level computer architecture, focusing on the features of modern microprocessors most relevant to compilers. Programmers who understand these features have a better chance not only of understanding why the languages they use were designed the way they were, but also of using those languages as fully and effectively as possible.

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1 Introduction

The first electronic computers were monstrous contraptions, filling several rooms, consuming as much electricity as a good-size factory, and costing millions of 1940s dollars (but with much less computing power than even the simplest modern cell phone). The programmers who used these machines believed that the computer's time was more valuable than theirs. They programmed in machine language. Machine language is the sequence of bits that directly controls a processor, causing it to add, compare, move data from one place to another, and so forth at appropriate times. Specifying programs at this level of detail is an enormously tedious task. The following program calculates the greatest common divisor (GCD) of two integers, using Euclid's algorithm. It is written in machine language, expressed here as hexadecimal (base 16) numbers, for the x86 instruction set.

EXAMPLE 1.1

GCD program in x86 machine language

```
55 89 e5 53  83 ec 04 83  e4 f0 e8 31  00 00 00 89  c3 e8 2a 00
00 00 39 c3  74 10 8d b6  00 00 00 00  39 c3 7e 13  29 c3 39 c3
75 f6 89 1c  24 e8 6e 00  00 00 8b 5d  fc c9 c3 29  d8 eb eb 90
```

EXAMPLE 1.2

GCD program in x86 assembler

As people began to write larger programs, it quickly became apparent that a less error-prone notation was required. Assembly languages were invented to allow operations to be expressed with mnemonic abbreviations. Our GCD program looks like this in x86 assembly language:

```
    pushl   %ebp                      jle     D
    movl    %esp, %ebp                subl    %eax, %ebx
    pushl   %ebx                  B:  cmpl    %eax, %ebx
    subl    $4, %esp                  jne     A
    andl    $-16, %esp            C:  movl    %ebx, (%esp)
    call    getint                    call    putint
    movl    %eax, %ebx                movl    -4(%ebp), %ebx
    call    getint                    leave
    cmpl    %eax, %ebx                ret
    je      C                     D:  subl    %ebx, %eax
A:  cmpl    %eax, %ebx                jmp     B
```

Assembly languages were originally designed with a one-to-one correspondence between mnemonics and machine language instructions, as shown in this example.[1] Translating from mnemonics to machine language became the job of a systems program known as an *assembler*. Assemblers were eventually augmented with elaborate "macro expansion" facilities to permit programmers to define parameterized abbreviations for common sequences of instructions. The correspondence between assembly language and machine language remained obvious and explicit, however. Programming continued to be a machine-centered enterprise: each different kind of computer had to be programmed in its own assembly language, and programmers thought in terms of the instructions that the machine would actually execute.

As computers evolved, and as competing designs developed, it became increasingly frustrating to have to rewrite programs for every new machine. It also became increasingly difficult for human beings to keep track of the wealth of detail in large assembly language programs. People began to wish for a machine-independent language, particularly one in which numerical computations (the most common type of program in those days) could be expressed in something more closely resembling mathematical formulae. These wishes led in the mid-1950s to the development of the original dialect of Fortran, the first arguably high-level programming language. Other high-level languages soon followed, notably Lisp and Algol.

Translating from a high-level language to assembly or machine language is the job of a systems program known as a *compiler*.[2] Compilers are substantially more complicated than assemblers because the one-to-one correspondence between source and target operations no longer exists when the source is a high-level language. Fortran was slow to catch on at first, because human programmers, with some effort, could almost always write assembly language programs that would run faster than what a compiler could produce. Over time, however, the performance gap has narrowed, and eventually reversed. Increases in hardware complexity (due to pipelining, multiple functional units, etc.) and continuing improvements in compiler technology have led to a situation in which a state-of-the-art compiler will usually generate better code than a human being will. Even in cases in which human beings can do better, increases in computer speed and program size have made it increasingly important to economize on programmer effort, not only in the original construction of programs, but in subsequent

[1] The 22 lines of assembly code in the example are encoded in varying numbers of bytes in machine language. The three `cmp` (compare) instructions, for example, all happen to have the same register operands, and are encoded in the two-byte sequence (`39 c3`). The four `mov` (move) instructions have different operands and lengths, and begin with `89` or `8b`. The chosen syntax is that of the GNU `gcc` compiler suite, in which results overwrite the last operand, not the first.

[2] High-level languages may also be *interpreted* directly, without the translation step. We will return to this option in Section 1.4. It is the principal way in which scripting languages like Python and JavaScript are implemented.

program *maintenance*—enhancement and correction. Labor costs now heavily outweigh the cost of computing hardware.

1.1 The Art of Language Design

Today there are thousands of high-level programming languages, and new ones continue to emerge. Why are there so many? There are several possible answers:

Evolution. Computer science is a young discipline; we're constantly finding better ways to do things. The late 1960s and early 1970s saw a revolution in "structured programming," in which the `goto`-based control flow of languages like Fortran, Cobol, and Basic[3] gave way to `while` loops, `case` (`switch`) statements, and similar higher-level constructs. In the late 1980s the nested block structure of languages like Algol, Pascal, and Ada began to give way to the object-oriented structure of languages like Smalltalk, C++, Eiffel, and—a decade later—Java and C#. More recently, scripting languages like Python and Ruby have begun to displace more traditional compiled languages, at least for rapid development.

Special Purposes. Some languages were designed for a specific problem domain. The various Lisp dialects are good for manipulating symbolic data and complex data structures. Icon and Awk are good for manipulating character strings. C is good for low-level systems programming. Prolog is good for reasoning about logical relationships among data. Each of these languages can be used successfully for a wider range of tasks, but the emphasis is clearly on the specialty.

Personal Preference. Different people like different things. Much of the parochialism of programming is simply a matter of taste. Some people love the terseness of C; some hate it. Some people find it natural to think recursively; others prefer iteration. Some people like to work with pointers; others prefer the implicit dereferencing of Lisp, Java, and ML. The strength and variety of personal preference make it unlikely that anyone will ever develop a universally acceptable programming language.

Of course, some languages are more successful than others. Of the many that have been designed, only a few dozen are widely used. What makes a language successful? Again there are several answers:

Expressive Power. One commonly hears arguments that one language is more "powerful" than another, though in a formal mathematical sense they are all

[3] The names of these languages are sometimes written entirely in uppercase letters and sometimes in mixed case. For consistency's sake, I adopt the convention in this book of using mixed case for languages whose names are pronounced as words (e.g., Fortran, Cobol, Basic), and uppercase for those pronounced as a series of letters (e.g., APL, PL/I, ML).

Turing complete—each can be used, if awkwardly, to implement arbitrary algorithms. Still, language features clearly have a huge impact on the programmer's ability to write clear, concise, and maintainable code, especially for very large systems. There is no comparison, for example, between early versions of Basic on the one hand, and C++ on the other. The factors that contribute to expressive power—abstraction facilities in particular—are a major focus of this book.

Ease of Use for the Novice. While it is easy to pick on Basic, one cannot deny its success. Part of that success was due to its very low "learning curve." Pascal was taught for many years in introductory programming language courses because, at least in comparison to other "serious" languages, it was compact and easy to learn. Shortly after the turn of the century, Java came to play a similar role; though substantially more complex than Pascal, it is simpler than, say, C++. In a renewed quest for simplicity, some introductory courses in recent years have turned to scripting languages like Python.

Ease of Implementation. In addition to its low learning curve, Basic was successful because it could be implemented easily on tiny machines, with limited resources. Forth had a small but dedicated following for similar reasons. Arguably the single most important factor in the success of Pascal was that its designer, Niklaus Wirth, developed a simple, portable implementation of the language, and shipped it free to universities all over the world (see Example 1.15).[4] The Java and Python designers took similar steps to make their language available for free to almost anyone who wants it.

Standardization. Almost every widely used language has an official international standard or (in the case of several scripting languages) a single canonical implementation; and in the latter case the canonical implementation is almost invariably written in a language that has a standard. Standardization—of both the language and a broad set of libraries—is the only truly effective way to ensure the portability of code across platforms. The relatively impoverished standard for Pascal, which was missing several features considered essential by many programmers (separate compilation, strings, static initialization, random-access I/O), was at least partially responsible for the language's drop from favor in the 1980s. Many of these features were implemented in different ways by different vendors.

Open Source. Most programming languages today have at least one open-source compiler or interpreter, but some languages—C in particular—are much more closely associated than others with freely distributed, peer-reviewed, community-supported computing. C was originally developed in the early

[4] Niklaus Wirth (1934–), Professor Emeritus of Informatics at ETH in Zürich, Switzerland, is responsible for a long line of influential languages, including Euler, Algol W, Pascal, Modula, Modula-2, and Oberon. Among other things, his languages introduced the notions of enumeration, subrange, and set types, and unified the concepts of records (structs) and variants (unions). He received the annual ACM Turing Award, computing's highest honor, in 1984.

1970s by Dennis Ritchie and Ken Thompson at Bell Labs,[5] in conjunction with the design of the original Unix operating system. Over the years Unix evolved into the world's most portable operating system—the OS of choice for academic computer science—and C was closely associated with it. With the standardization of C, the language became available on an enormous variety of additional platforms. Linux, the leading open-source operating system, is written in C. As of June 2015, C and its descendants account for well over half of a variety of language-related on-line content, including web page references, book sales, employment listings, and open-source repository updates.

Excellent Compilers. Fortran owes much of its success to extremely good compilers. In part this is a matter of historical accident. Fortran has been around longer than anything else, and companies have invested huge amounts of time and money in making compilers that generate very fast code. It is also a matter of language design, however: Fortran dialects prior to Fortran 90 lacked recursion and pointers, features that greatly complicate the task of generating fast code (at least for programs that can be written in a reasonable fashion without them!). In a similar vein, some languages (e.g., Common Lisp) have been successful in part because they have compilers and supporting tools that do an unusually good job of helping the programmer manage very large projects.

Economics, Patronage, and Inertia. Finally, there are factors other than technical merit that greatly influence success. The backing of a powerful sponsor is one. PL/I, at least to first approximation, owed its life to IBM. Cobol and Ada owe their life to the U. S. Department of Defense. C# owes its life to Microsoft. In recent years, Objective-C has enjoyed an enormous surge in popularity as the official language for iPhone and iPad apps. At the other end of the life cycle, some languages remain widely used long after "better" alternatives are available, because of a huge base of installed software and programmer expertise, which would cost too much to replace. Much of the world's financial infrastructure, for example, still functions primarily in Cobol.

Clearly no single factor determines whether a language is "good." As we study programming languages, we shall need to consider issues from several points of view. In particular, we shall need to consider the viewpoints of both the programmer and the language implementor. Sometimes these points of view will be in harmony, as in the desire for execution speed. Often, however, there will be conflicts and tradeoffs, as the conceptual appeal of a feature is balanced against the cost of its implementation. The tradeoff becomes particularly thorny when the implementation imposes costs not only on programs that use the feature, but also on programs that do not.

[5] Ken Thompson (1943–) led the team that developed Unix. He also designed the B programming language, a child of BCPL and the parent of C. Dennis Ritchie (1941–2011) was the principal force behind the development of C itself. Thompson and Ritchie together formed the core of an incredibly productive and influential group. They shared the ACM Turing Award in 1983.

In the early days of computing the implementor's viewpoint was predominant. Programming languages evolved as a means of telling a computer what to do. For programmers, however, a language is more aptly defined as a means of expressing algorithms. Just as natural languages constrain exposition and discourse, so programming languages constrain what can and cannot easily be expressed, and have both profound and subtle influence over what the programmer can *think*. Donald Knuth has suggested that programming be regarded as the art of telling another human being what one wants the computer to do [Knu84].[6] This definition perhaps strikes the best sort of compromise. It acknowledges that both conceptual clarity and implementation efficiency are fundamental concerns. This book attempts to capture this spirit of compromise, by simultaneously considering the conceptual and implementation aspects of each of the topics it covers.

DESIGN & IMPLEMENTATION

1.1 Introduction

Throughout the book, sidebars like this one will highlight the interplay of language design and language implementation. Among other things, we will consider

- Cases (such as those mentioned in this section) in which ease or difficulty of implementation significantly affected the success of a language
- Language features that many designers now believe were mistakes, at least in part because of implementation difficulties
- Potentially useful features omitted from some languages because of concern that they might be too difficult or slow to implement
- Language features introduced at least in part to facilitate efficient or elegant implementations
- Cases in which a machine architecture makes reasonable features unreasonably expensive
- Various other tradeoffs in which implementation plays a significant role

A complete list of sidebars appears in Appendix B.

[6] Donald E. Knuth (1938–), Professor Emeritus at Stanford University and one of the foremost figures in the design and analysis of algorithms, is also widely known as the inventor of the TEX typesetting system (with which this book was produced) and of the *literate programming* methodology with which TEX was constructed. His multivolume *The Art of Computer Programming* has an honored place on the shelf of most professional computer scientists. He received the ACM Turing Award in 1974.

declarative	
functional	Lisp/Scheme, ML, Haskell
dataflow	Id, Val
logic, constraint-based	Prolog, spreadsheets, SQL
imperative	
von Neumann	C, Ada, Fortran, …
object-oriented	Smalltalk, Eiffel, Java, …
scripting	Perl, Python, PHP, …

Figure 1.1 **Classification of programming languages.** Note that the categories are fuzzy, and open to debate. In particular, it is possible for a functional language to be object-oriented, and many authors do not consider functional programming to be declarative.

1.2 The Programming Language Spectrum

EXAMPLE 1.3
Classification of programming languages

The many existing languages can be classified into families based on their model of computation. Figure 1.1 shows a common set of families. The top-level division distinguishes between the *declarative* languages, in which the focus is on *what* the computer is to do, and the *imperative* languages, in which the focus is on *how* the computer should do it.

Declarative languages are in some sense "higher level"; they are more in tune with the programmer's point of view, and less with the implementor's point of view. Imperative languages predominate, however, mainly for performance reasons. There is a tension in the design of declarative languages between the desire to get away from "irrelevant" implementation details and the need to remain close enough to the details to at least control the outline of an algorithm. The design of efficient algorithms, after all, is what much of computer science is about. It is not yet clear to what extent, and in what problem domains, we can expect compilers to discover good algorithms for problems stated at a very high level of abstraction. In any domain in which the compiler cannot find a good algorithm, the programmer needs to be able to specify one explicitly.

Within the declarative and imperative families, there are several important subfamilies:

- *Functional* languages employ a computational model based on the recursive definition of functions. They take their inspiration from the *lambda calculus*, a formal computational model developed by Alonzo Church in the 1930s. In essence, a program is considered a function from inputs to outputs, defined in terms of simpler functions through a process of refinement. Languages in this category include Lisp, ML, and Haskell.
- *Dataflow* languages model computation as the flow of information (*tokens*) among primitive functional *nodes*. They provide an inherently parallel model: nodes are triggered by the arrival of input tokens, and can operate concurrently. Id and Val are examples of dataflow languages. Sisal, a descendant of Val, is more often described as a functional language.

- *Logic* or *constraint-based* languages take their inspiration from predicate logic. They model computation as an attempt to find values that satisfy certain specified relationships, using goal-directed search through a list of logical rules. Prolog is the best-known logic language. The term is also sometimes applied to the SQL database language, the XSLT scripting language, and programmable aspects of spreadsheets such as Excel and its predecessors.
- The *von Neumann* languages are probably the most familiar and widely used. They include Fortran, Ada, C, and all of the others in which the basic means of computation is the modification of variables.[7] Whereas functional languages are based on expressions that have values, von Neumann languages are based on statements (assignments in particular) that influence subsequent computation via the *side effect* of changing the value of memory.
- *Object-oriented* languages trace their roots to Simula 67. Most are closely related to the von Neumann languages, but have a much more structured and distributed model of both memory and computation. Rather than picture computation as the operation of a monolithic processor on a monolithic memory, object-oriented languages picture it as interactions among semi-independent *objects*, each of which has both its own internal state and subroutines to manage that state. Smalltalk is the purest of the object-oriented languages; C++ and Java are probably the most widely used. It is also possible to devise object-oriented functional languages (the best known of these are CLOS [Kee89] and OCaml), but they tend to have a strong imperative flavor.
- *Scripting* languages are distinguished by their emphasis on coordinating or "gluing together" components drawn from some surrounding context. Several scripting languages were originally developed for specific purposes: `csh` and `bash` are the input languages of job control (shell) programs; PHP and JavaScript are primarily intended for the generation of dynamic web content; Lua is widely used to control computer games. Other languages, including Perl, Python, and Ruby, are more deliberately general purpose. Most place an emphasis on rapid prototyping, with a bias toward ease of expression over speed of execution.

One might suspect that concurrent (parallel) languages would form a separate family (and indeed this book devotes a chapter to such languages), but the distinction between concurrent and sequential execution is mostly independent of the classifications above. Most concurrent programs are currently written using special library packages or compilers in conjunction with a sequential language such as Fortran or C. A few widely used languages, including Java, C#, and Ada, have explicitly concurrent features. Researchers are investigating concurrency in each of the language families mentioned here.

[7] John von Neumann (1903–1957) was a mathematician and computer pioneer who helped to develop the concept of *stored program* computing, which underlies most computer hardware. In a stored program computer, both programs and data are represented as bits in memory, which the processor repeatedly fetches, interprets, and updates.

As a simple example of the contrast among language families, consider the greatest common divisor (GCD) problem introduced at the beginning of this chapter. The choice among, say, von Neumann, functional, or logic programming for this problem influences not only the appearance of the code, but how the programmer thinks. The von Neumann algorithm version of the algorithm is very imperative:

EXAMPLE 1.4
GCD function in C

> To compute the `gcd` of `a` and `b`, check to see if `a` and `b` are equal. If so, print one of them and stop. Otherwise, replace the larger one by their difference and repeat.

C code for this algorithm appears at the top of Figure 1.2.

EXAMPLE 1.5
GCD function in OCaml

In a functional language, the emphasis is on the mathematical relationship of outputs to inputs:

> The `gcd` of `a` and `b` is defined to be (1) `a` when `a` and `b` are equal, (2) the `gcd` of `b` and `a - b` when `a > b`, and (3) the `gcd` of `a` and `b - a` when `b > a`. To compute the `gcd` of a given pair of numbers, expand and simplify this definition until it terminates.

An OCaml version of this algorithm appears in the middle of Figure 1.2. The keyword `let` introduces a definition; `rec` indicates that it is permitted to be recursive (self-referential); arguments for a function come between the name (in this case, `gcd`) and the equals sign.

EXAMPLE 1.6
GCD rules in Prolog

In a logic language, the programmer specifies a set of axioms and proof rules that allows the system to find desired values:

> The proposition `gcd(a, b, g)` is true if (1) `a`, `b`, and `g` are all equal; (2) `a` is greater than `b` and there exists a number `c` such that `c` is `a - b` and `gcd(c, b, g)` is true; or (3) `a` is less than `b` and there exists a number `c` such that `c` is `b - a` and `gcd(c, a, g)` is true. To compute the `gcd` of a given pair of numbers, search for a number `g` (and various numbers `c`) for which these rules allow one to prove that `gcd(a, b, g)` is true.

A Prolog version of this algorithm appears at the bottom of Figure 1.2. It may be easier to understand if one reads "if" for `:-` and "and" for commas.

It should be emphasized that the distinctions among language families are not clear-cut. The division between the von Neumann and object-oriented languages, for example, is often very fuzzy, and many scripting languages are also object-oriented. Most of the functional and logic languages include some imperative features, and several recent imperative languages have added functional features. The descriptions above are meant to capture the general flavor of the families, without providing formal definitions.

Imperative languages—von Neumann and object-oriented—receive the bulk of the attention in this book. Many issues cut across family lines, however, and the interested reader will discover much that is applicable to alternative computational models in most chapters of the book. Chapters 11 through 14 contain additional material on functional, logic, concurrent, and scripting languages.

```
int gcd(int a, int b) {                         // C
    while (a != b) {
        if (a > b) a = a - b;
        else b = b - a;
    }
    return a;
}

let rec gcd a b =                               (* OCaml *)
    if a = b then a
    else if a > b then gcd b (a - b)
         else gcd a (b - a)

gcd(A,B,G) :- A = B, G = A.                     % Prolog
gcd(A,B,G) :- A > B, C is A-B, gcd(C,B,G).
gcd(A,B,G) :- B > A, C is B-A, gcd(C,A,G).
```

Figure 1.2 **The GCD algorithm in C (top), OCaml (middle), and Prolog (bottom).** All three versions assume (without checking) that their inputs are positive integers.

1.3 Why Study Programming Languages?

Programming languages are central to computer science, and to the typical computer science curriculum. Like most car owners, students who have become familiar with one or more high-level languages are generally curious to learn about other languages, and to know what is going on "under the hood." Learning about languages is interesting. It's also practical.

For one thing, a good understanding of language design and implementation can help one choose the most appropriate language for any given task. Most languages are better for some things than for others. Few programmers are likely to choose Fortran for symbolic computing or string processing, but other choices are not nearly so clear-cut. Should one choose C, C++, or C# for systems programming? Fortran or C for scientific computations? PHP or Ruby for a web-based application? Ada or C for embedded systems? Visual Basic or Java for a graphical user interface? This book should help equip you to make such decisions.

Similarly, this book should make it easier to learn new languages. Many languages are closely related. Java and C# are easier to learn if you already know C++; Common Lisp if you already know Scheme; Haskell if you already know ML. More importantly, there are basic concepts that underlie all programming languages. Most of these concepts are the subject of chapters in this book: types, control (iteration, selection, recursion, nondeterminacy, concurrency), abstraction, and naming. Thinking in terms of these concepts makes it easier to assimilate the syntax (form) and semantics (meaning) of new languages, compared to picking them up in a vacuum. The situation is analogous to what happens in natural languages: a good knowledge of grammatical forms makes it easier to learn a foreign language.

Whatever language you learn, understanding the decisions that went into its design and implementation will help you use it better. This book should help you:

Understand obscure features. The typical C++ programmer rarely uses unions, multiple inheritance, variable numbers of arguments, or the `.*` operator. (If you don't know what these are, don't worry!) Just as it simplifies the assimilation of new languages, an understanding of basic concepts makes it easier to understand these features when you look up the details in the manual.

Choose among alternative ways to express things, based on a knowledge of implementation costs. In C++, for example, programmers may need to avoid unnecessary temporary variables, and use copy constructors whenever possible, to minimize the cost of initialization. In Java they may wish to use `Executor` objects rather than explicit thread creation. With certain (poor) compilers, they may need to adopt special programming idioms to get the fastest code: pointers for array traversal; `x*x` instead of `x**2`. In any language, they need to be able to evaluate the tradeoffs among alternative implementations of abstractions—for example between computation and table lookup for functions like bit set cardinality, which can be implemented either way.

Make good use of debuggers, assemblers, linkers, and related tools. In general, the high-level language programmer should not need to bother with implementation details. There are times, however, when an understanding of those details is virtually essential. The tenacious bug or unusual system-building problem may be dramatically easier to handle if one is willing to peek at the bits.

Simulate useful features in languages that lack them. Certain very useful features are missing in older languages, but can be emulated by following a deliberate (if unenforced) programming style. In older dialects of Fortran, for example, programmers familiar with modern control constructs can use comments and self-discipline to write well-structured code. Similarly, in languages with poor abstraction facilities, comments and naming conventions can help imitate modular structure, and the extremely useful *iterators* of Clu, C#, Python, and Ruby (which we will study in Section 6.5.3) can be imitated with subroutines and static variables.

Make better use of language technology wherever it appears. Most programmers will never design or implement a conventional programming language, but most will need language technology for other programming tasks. The typical personal computer contains files in dozens of structured formats, encompassing word processing, spreadsheets, presentations, raster and vector graphics, music, video, databases, and a wide variety of other application domains. Web content is increasingly represented in XML, a text-based format designed for easy manipulation in the XSLT scripting language (discussed in Section C-14.3.5). Code to parse, analyze, generate, optimize, and otherwise manipulate structured data can thus be found in almost any sophisticated program, and all of this code is based on language technology. Programmers with a strong grasp of this technology will be in a better position to write well-structured, maintainable tools.

In a similar vein, most tools themselves can be customized, via start-up configuration files, command-line arguments, input commands, or built-in *extension languages* (considered in more detail in Chapter 14). My home directory holds more than 250 separate configuration ("preference") files. My personal configuration files for the `emacs` text editor comprise more than 1200 lines of Lisp code. The user of almost any sophisticated program today will need to make good use of configuration or extension languages. The designers of such a program will need either to adopt (and adapt) some existing extension language, or to invent new notation of their own. Programmers with a strong grasp of language theory will be in a better position to design elegant, well-structured notation that meets the needs of current users and facilitates future development.

Finally, this book should help prepare you for further study in language design or implementation, should you be so inclined. It will also equip you to understand the interactions of languages with operating systems and architectures, should those areas draw your interest.

✓ CHECK YOUR UNDERSTANDING

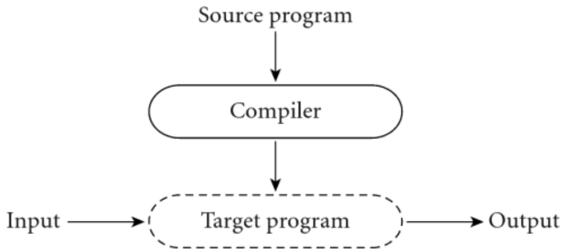
1. What is the difference between machine language and assembly language?
2. In what way(s) are high-level languages an improvement on assembly language? Are there circumstances in which it still make sense to program in assembler?
3. Why are there so many programming languages?
4. What makes a programming language successful?
5. Name three languages in each of the following categories: von Neumann, functional, object-oriented. Name two logic languages. Name two widely used concurrent languages.
6. What distinguishes declarative languages from imperative languages?
7. What organization spearheaded the development of Ada?
8. What is generally considered the first high-level programming language?
9. What was the first functional language?
10. Why aren't concurrent languages listed as a separate family in Figure 1.1?

1.4 Compilation and Interpretation

EXAMPLE 1.7

Pure compilation

At the highest level of abstraction, the compilation and execution of a program in a high-level language look something like this:

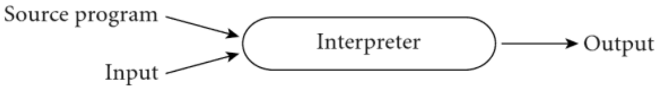


The compiler *translates* the high-level source program into an equivalent target program (typically in machine language), and then goes away. At some arbitrary later time, the user tells the operating system to run the target program. The compiler is the locus of control during compilation; the target program is the locus of control during its own execution. The compiler is itself a machine language program, presumably created by compiling some other high-level program. When written to a file in a format understood by the operating system, machine language is commonly known as *object code*. ■

EXAMPLE 1.8

Pure interpretation

An alternative style of implementation for high-level languages is known as *interpretation*:



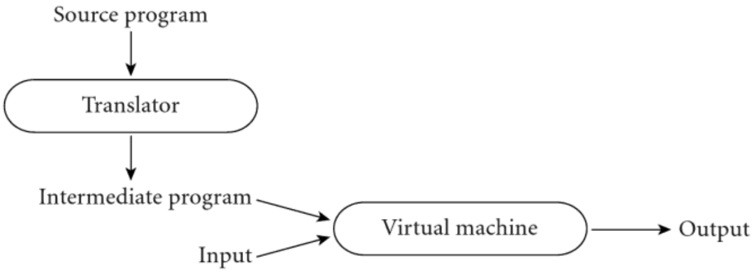
Unlike a compiler, an interpreter stays around for the execution of the application. In fact, the interpreter is the locus of control during that execution. In effect, the interpreter implements a virtual machine whose "machine language" is the high-level programming language. The interpreter reads statements in that language more or less one at a time, executing them as it goes along. ■

In general, interpretation leads to greater flexibility and better diagnostics (error messages) than does compilation. Because the source code is being executed directly, the interpreter can include an excellent source-level debugger. It can also cope with languages in which fundamental characteristics of the program, such as the sizes and types of variables, or even which names refer to which variables, can depend on the input data. Some language features are almost impossible to implement without interpretation: in Lisp and Prolog, for example, a program can write new pieces of itself and execute them on the fly. (Several scripting languages also provide this capability.) Delaying decisions about program implementation until run time is known as *late binding*; we will discuss it at greater length in Section 3.1.

Compilation, by contrast, generally leads to better performance. In general, a decision made at compile time is a decision that does not need to be made at run time. For example, if the compiler can guarantee that variable x will always lie at location 49378, it can generate machine language instructions that access this location whenever the source program refers to x. By contrast, an interpreter may need to look x up in a table every time it is accessed, in order to find its location. Since the (final version of a) program is compiled only once, but generally executed many times, the savings can be substantial, particularly if the interpreter is doing unnecessary work in every iteration of a loop.

EXAMPLE 1.9
Mixing compilation and interpretation

While the conceptual difference between compilation and interpretation is clear, most language implementations include a mixture of both. They typically look like this:



We generally say that a language is "interpreted" when the initial translator is simple. If the translator is complicated, we say that the language is "compiled." The distinction can be confusing because "simple" and "complicated" are subjective terms, and because it is possible for a compiler (complicated translator) to produce code that is then executed by a complicated virtual machine (interpreter); this is in fact precisely what happens by default in Java. We still say that a language is compiled if the translator analyzes it thoroughly (rather than effecting some "mechanical" transformation), and if the intermediate program does not bear a strong resemblance to the source. These two characteristics—thorough analysis and nontrivial transformation—are the hallmarks of compilation.

DESIGN & IMPLEMENTATION

1.2 Compiled and interpreted languages

Certain languages (e.g., Smalltalk and Python) are sometimes referred to as "interpreted languages" because most of their semantic error checking must be performed at run time. Certain other languages (e.g., Fortran and C) are sometimes referred to as "compiled languages" because almost all of their semantic error checking can be performed statically. This terminology isn't strictly correct: interpreters for C and Fortran can be built easily, and a compiler can generate code to perform even the most extensive dynamic semantic checks. That said, language design has a profound effect on "compilability."

In practice one sees a broad spectrum of implementation strategies:

EXAMPLE 1.10

Preprocessing

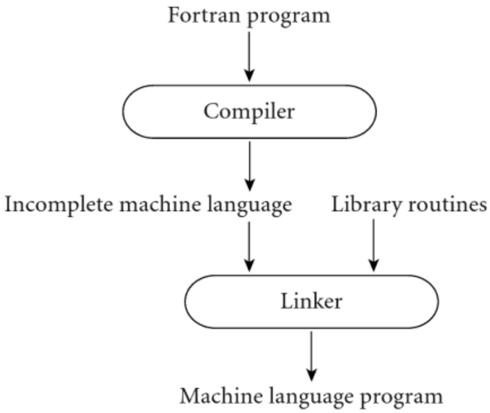
- Most interpreted languages employ an initial translator (a *preprocessor*) that removes comments and white space, and groups characters together into *tokens* such as keywords, identifiers, numbers, and symbols. The translator may also expand abbreviations in the style of a macro assembler. Finally, it may identify higher-level syntactic structures, such as loops and subroutines. The goal is to produce an intermediate form that mirrors the structure of the source, but can be interpreted more efficiently.

  In some very early implementations of Basic, the manual actually suggested removing comments from a program in order to improve its performance. These implementations were pure interpreters; they would re-read (and then ignore) the comments every time they executed a given part of the program. They had no initial translator.

EXAMPLE 1.11

Library routines and linking

- The typical Fortran implementation comes close to pure compilation. The compiler translates Fortran source into machine language. Usually, however, it counts on the existence of a *library* of subroutines that are not part of the original program. Examples include mathematical functions (`sin`, `cos`, `log`, etc.) and I/O. The compiler relies on a separate program, known as a *linker*, to merge the appropriate library routines into the final program:



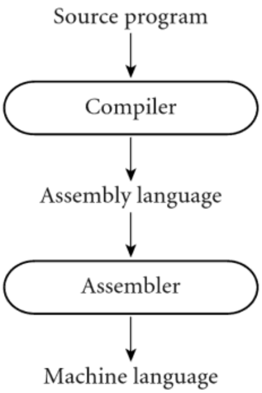
  In some sense, one may think of the library routines as extensions to the hardware instruction set. The compiler can then be thought of as generating code for a virtual machine that includes the capabilities of both the hardware and the library.

  In a more literal sense, one can find interpretation in the Fortran routines for formatted output. Fortran permits the use of `format` statements that control the alignment of output in columns, the number of significant digits and type of scientific notation for floating-point numbers, inclusion/suppression of leading zeros, and so on. Programs can compute their own formats on the fly. The output library routines include a format interpreter. A similar interpreter can be found in the `printf` routine of C and its descendants.

EXAMPLE 1.12

Post-compilation assembly

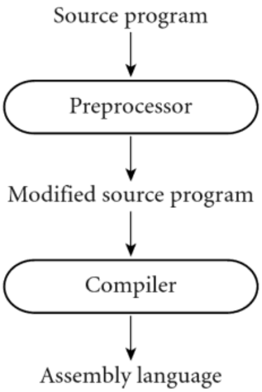
Many compilers generate assembly language instead of machine language. This convention facilitates debugging, since assembly language is easier for people to read, and isolates the compiler from changes in the format of machine language files that may be mandated by new releases of the operating system (only the assembler must be changed, and it is shared by many compilers):



EXAMPLE 1.13

The C preprocessor

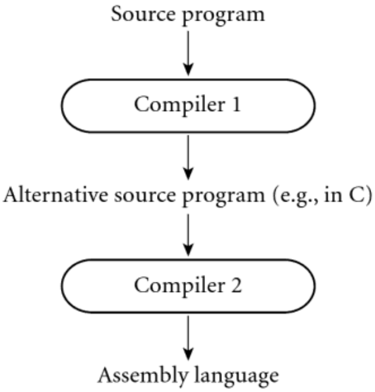
Compilers for C (and for many other languages running under Unix) begin with a preprocessor that removes comments and expands macros. The preprocessor can also be instructed to delete portions of the code itself, providing a *conditional compilation* facility that allows several versions of a program to be built from the same source:



EXAMPLE 1.14

Source-to-source translation

A surprising number of compilers generate output in some high-level language—commonly C or some simplified version of the input language. Such *source-to-source* translation is particularly common in research languages and during the early stages of language development. One famous example was AT&T's original compiler for C++. This was indeed a true compiler, though it generated C instead of assembler: it performed a complete analysis of the syntax and semantics of the C++ source program, and with very few exceptions generated all of the error messages that a programmer would see prior to running the program. In fact, programmers were generally unaware that the C compiler was being used behind the scenes. The C++ compiler did not invoke the C compiler unless it had generated C code that would pass through the second round of compilation without producing any error messages:



Occasionally one would hear the C++ compiler referred to as a preprocessor, presumably because it generated high-level output that was in turn compiled. I consider this a misuse of the term: compilers attempt to "understand" their source; preprocessors do not. Preprocessors perform transformations based on simple pattern matching, and may well produce output that will generate error messages when run through a subsequent stage of translation.

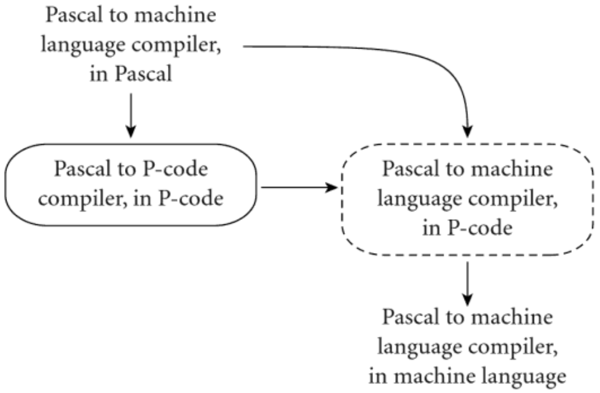
EXAMPLE 1.15
Bootstrapping

Many compilers are *self-hosting*: they are written in the language they compile—Ada compilers in Ada, C compilers in C. This raises an obvious question: how does one compile the compiler in the first place? The answer is to use a technique known as *bootstrapping*, a term derived from the intentionally ridiculous notion of lifting oneself off the ground by pulling on one's bootstraps. In a nutshell, one starts with a simple implementation—often an interpreter—and uses it to build progressively more sophisticated versions. We can illustrate the idea with an historical example.

Many early Pascal compilers were built around a set of tools distributed by Niklaus Wirth. These included the following:

– A Pascal compiler, written in Pascal, that would generate output in *P-code*, a stack-based language similar to the *bytecode* of modern Java compilers
– The same compiler, already translated into P-code
– A P-code interpreter, written in Pascal

To get Pascal up and running on a local machine, the user of the tool set needed only to translate the P-code interpreter (by hand) into some locally available language. This translation was not a difficult task; the interpreter was small. By running the P-code version of the compiler on top of the P-code interpreter, one could then compile arbitrary Pascal programs into P-code, which could in turn be run on the interpreter. To get a faster implementation, one could modify the Pascal version of the Pascal compiler to generate a locally available variety of assembly or machine language, instead of generating P-code (a somewhat more difficult task). This compiler could then be bootstrapped—run through itself—to yield a machine-code version of the compiler:


Pascal to machine language compiler, in Pascal
Pascal to P-code compiler, in P-code
Pascal to machine language compiler, in P-code
Pascal to machine language compiler, in machine language

In a more general context, suppose we were building one of the first compilers for a new programming language. Assuming we have a C compiler on our target system, we might start by writing, in a simple subset of C, a compiler for an equally simple subset of our new programming language. Once this compiler was working, we could hand-translate the C code into (the subset of) our new language, and then run the new source through the compiler itself. After that, we could repeatedly extend the compiler to accept a larger subset

DESIGN & IMPLEMENTATION

1.3 The early success of Pascal

The P-code-based implementation of Pascal, and its use of bootstrapping, are largely responsible for the language's remarkable success in academic circles in the 1970s. No single hardware platform or operating system of that era dominated the computer landscape the way the x86, Linux, and Windows do today.[8] Wirth's toolkit made it possible to get an implementation of Pascal up and running on almost any platform in a week or so. It was one of the first great successes in system portability.

[8] Throughout this book we will use the term "x86" to refer to the instruction set architecture of the Intel 8086 and its descendants, including the various Pentium, "Core," and Xeon processors. Intel calls this architecture the IA-32, but x86 is a more generic term that encompasses the offerings of competitors such as AMD as well.

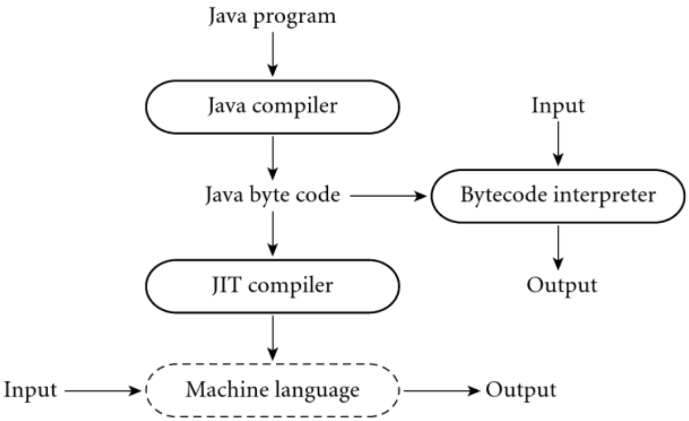
of the new programming language, bootstrap it again, and use the extended language to implement an even larger subset. “Self-hosting” implementations of this sort are actually quite common.

EXAMPLE 1.16
Compiling interpreted languages

One will sometimes find compilers for languages (e.g., Lisp, Prolog, Smalltalk) that permit a lot of late binding, and are traditionally interpreted. These compilers must be prepared, in the general case, to generate code that performs much of the work of an interpreter, or that makes calls into a library that does that work instead. In important special cases, however, the compiler can generate code that makes reasonable assumptions about decisions that won’t be finalized until run time. If these assumptions prove to be valid the code will run very fast. If the assumptions are not correct, a dynamic check will discover the inconsistency, and revert to the interpreter.

EXAMPLE 1.17
Dynamic and just-in-time compilation

In some cases a programming system may deliberately delay compilation until the last possible moment. One example occurs in language implementations (e.g., for Lisp or Prolog) that invoke the compiler on the fly, to translate newly created source into machine language, or to optimize the code for a particular input set. Another example occurs in implementations of Java. The Java language definition defines a machine-independent intermediate form known as Java *bytecode*. Bytecode is the standard format for distribution of Java programs; it allows programs to be transferred easily over the Internet, and then run on any platform. The first Java implementations were based on byte-code interpreters, but modern implementations obtain significantly better performance with a *just-in-time* compiler that translates bytecode into machine language immediately before each execution of the program:



C#, similarly, is intended for just-in-time translation. The main C# compiler produces *Common Intermediate Language* (CIL), which is then translated into machine language immediately prior to execution. CIL is deliberately language independent, so it can be used for code produced by a variety of front-end compilers. We will explore the Java and C# implementations in detail in Section 16.1.

EXAMPLE 1.18

Microcode (firmware)

On some machines (particularly those designed before the mid-1980s), the assembly-level instruction set is not actually implemented in hardware, but in fact runs on an interpreter. The interpreter is written in low-level instructions called *microcode* (or *firmware*), which is stored in read-only memory and executed by the hardware. Microcode and microprogramming are considered further in Section C-5.4.1.

As some of these examples make clear, a compiler does not necessarily translate from a high-level programming language into machine language. Some compilers, in fact, accept inputs that we might not immediately think of as programs at all. Text formatters like TEX, for example, compile high-level document descriptions into commands for a laser printer or phototypesetter. (Many laser printers themselves contain pre-installed interpreters for the Postscript page-description language.) Query language processors for database systems translate languages like SQL into primitive operations on files. There are even compilers that translate logic-level circuit specifications into photographic masks for computer chips. Though the focus in this book is on imperative programming languages, the term "compilation" applies whenever we translate automatically from one nontrivial language to another, with full analysis of the meaning of the input.

1.5 Programming Environments

Compilers and interpreters do not exist in isolation. Programmers are assisted in their work by a host of other tools. Assemblers, debuggers, preprocessors, and linkers were mentioned earlier. Editors are familiar to every programmer. They may be augmented with cross-referencing facilities that allow the programmer to find the point at which an object is defined, given a point at which it is used. Pretty printers help enforce formatting conventions. Style checkers enforce syntactic or semantic conventions that may be tighter than those enforced by the compiler (see Exploration 1.14). Configuration management tools help keep track of dependences among the (many versions of) separately compiled modules in a large software system. Perusal tools exist not only for text but also for intermediate languages that may be stored in binary. Profilers and other performance analysis tools often work in conjunction with debuggers to help identify the pieces of a program that consume the bulk of its computation time.

In older programming environments, tools may be executed individually, at the explicit request of the user. If a running program terminates abnormally with a "bus error" (invalid address) message, for example, the user may choose to invoke a debugger to examine the "core" file dumped by the operating system. He or she may then attempt to identify the program bug by setting breakpoints, enabling tracing and so on, and running the program again under the control of the debugger. Once the bug is found, the user will invoke the editor to make an appropriate change. He or she will then recompile the modified program, possibly with the help of a configuration manager.

Modern environments provide more integrated tools. When an invalid address error occurs in an integrated development environment (IDE), a new window is likely to appear on the user's screen, with the line of source code at which the error occurred highlighted. Breakpoints and tracing can then be set in this window without explicitly invoking a debugger. Changes to the source can be made without explicitly invoking an editor. If the user asks to rerun the program after making changes, a new version may be built without explicitly invoking the compiler or configuration manager.

The editor for an IDE may incorporate knowledge of language syntax, providing templates for all the standard control structures, and checking syntax as it is typed in. Internally, the IDE is likely to maintain not only a program's source and object code, but also a partially compiled internal representation. When the source is edited, the internal representation will be updated automatically—often incrementally (without reparsing large portions of the source). In some cases, structural changes to the program may be implemented first in the internal representation, and then automatically reflected in the source.

IDEs are fundamental to Smalltalk—it is nearly impossible to separate the language from its graphical environment—and have been routinely used for Common Lisp since the 1980s. With the ubiquity of graphical interfaces, integrated environments have largely displaced command-line tools for many languages and systems. Popular open-source IDEs include Eclipse and NetBeans. Commercial systems include the Visual Studio environment from Microsoft and the XCode environment from Apple. Much of the appearance of integration can also be achieved within sophisticated editors such as `emacs`.

✓ CHECK YOUR UNDERSTANDING

11. Explain the distinction between interpretation and compilation. What are the comparative advantages and disadvantages of the two approaches?

12. Is Java compiled or interpreted (or both)? How do you know?

13. What is the difference between a compiler and a preprocessor?

14. What was the intermediate form employed by the original AT&T C++ compiler?

DESIGN & IMPLEMENTATION

1.4 Powerful development environments

Sophisticated development environments can be a two-edged sword. The quality of the Common Lisp environment has arguably contributed to its widespread acceptance. On the other hand, the particularity of the graphical environment for Smalltalk (with its insistence on specific fonts, window styles, etc.) made it difficult to port the language to systems accessed through a textual interface, or to graphical systems with a different "look and feel."

15. What is P-code?

16. What is bootstrapping?

17. What is a just-in-time compiler?

18. Name two languages in which a program can write new pieces of itself "on the fly."

19. Briefly describe three "unconventional" compilers—compilers whose purpose is not to prepare a high-level program for execution on a general-purpose processor.

20. List six kinds of tools that commonly support the work of a compiler within a larger programming environment.

21. Explain how an integrated development environment (IDE) differs from a collection of command-line tools.

1.6 An Overview of Compilation

Compilers are among the most well-studied computer programs. We will consider them repeatedly throughout the rest of the book, and in chapters 2, 4, 15, and 17 in particular. The remainder of this section provides an introductory overview.

EXAMPLE 1.19

Phases of compilation and interpretation

In a typical compiler, compilation proceeds through a series of well-defined *phases*, shown in Figure 1.3. Each phase discovers information of use to later phases, or transforms the program into a form that is more useful to the subsequent phase.

The first few phases (up through semantic analysis) serve to figure out the meaning of the source program. They are sometimes called the *front end* of the compiler. The last few phases serve to construct an equivalent target program. They are sometimes called the *back end* of the compiler.

An interpreter (Figure 1.4) shares the compiler's front-end structure, but "executes" (interprets) the intermediate form directly, rather than translating it into machine language. The execution typically takes the form of a set of mutually recursive subroutines that traverse ("walk") the syntax tree, "executing" its nodes in program order. Many compiler and interpreter phases can be created automatically from a formal description of the source and/or target languages. ■

One will sometimes hear compilation described as a series of *passes*. A pass is a phase or set of phases that is serialized with respect to the rest of compilation: it does not start until previous phases have completed, and it finishes before any subsequent phases start. If desired, a pass may be written as a separate program, reading its input from a file and writing its output to a file. Compilers are commonly divided into passes so that the front end may be shared by compilers

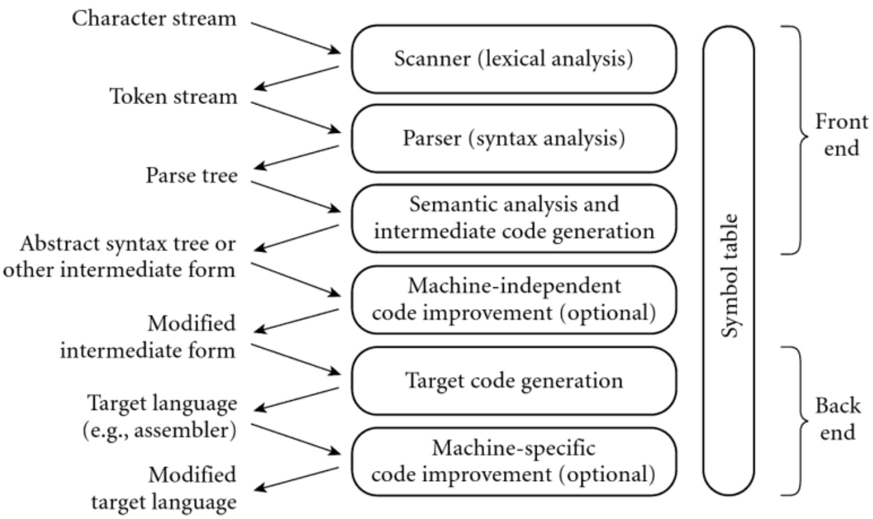

Character stream
Token stream
Parse tree
Abstract syntax tree or other intermediate form
Modified intermediate form
Target language (e.g., assembler)
Modified target language
Scanner (lexical analysis)
Parser (syntax analysis)
Semantic analysis and intermediate code generation
Machine-independent code improvement (optional)
Target code generation
Machine-specific code improvement (optional)
Symbol table
Front end
Back end

Figure 1.3 **Phases of compilation.** Phases are listed on the right and the forms in which information is passed between phases are listed on the left. The symbol table serves throughout compilation as a repository for information about identifiers.

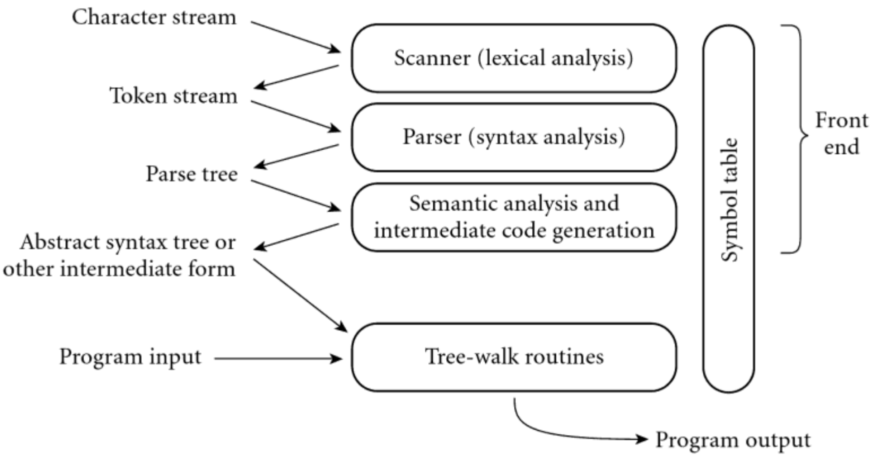


Figure 1.4 **Phases of interpretation.** The front end is essentially the same as that of a compiler. The final phase "executes" the intermediate form, typically using a set of mutually recursive subroutines that walk the syntax tree.

for more than one machine (target language), and so that the back end may be shared by compilers for more than one source language. In some implementations the front end and the back end may be separated by a "middle end" that is responsible for language- and machine-independent code improvement. Prior to the dramatic increases in memory sizes of the mid to late 1980s, compilers were also sometimes divided into passes to minimize memory usage: as each pass completed, the next could reuse its code space.

1.6.1 Lexical and Syntax Analysis

EXAMPLE 1.20
GCD program in C

Consider the greatest common divisor (GCD) problem introduced at the beginning of this chapter, and shown as a function in Figure 1.2. Hypothesizing trivial I/O routines and recasting the function as a stand-alone program, our code might look like this in C:

```
int main() {
    int i = getint(), j = getint();
    while (i != j) {
        if (i > j) i = i - j;
        else j = j - i;
    }
    putint(i);
}
```

EXAMPLE 1.21
GCD program tokens

Scanning and parsing serve to recognize the structure of the program, without regard to its meaning. The scanner reads characters (‘i’, ‘n’, ‘t’, ‘ ’, ‘m’, ‘a’, ‘i’, ‘n’, ‘(’, ‘)’, etc.) and groups them into *tokens*, which are the smallest meaningful units of the program. In our example, the tokens are

```
int      main     (        )        {        int      i        =
getint   (        )        ,        j        =        getint   (
)        ;        while    (        i        !=       j        )
{        if       (        i        >        j        )        i
=        i        -        j        ;        else     j        =
j        -        i        ;        }        putint   (        i
)        ;        }
```

Scanning is also known as *lexical analysis*. The principal purpose of the scanner is to simplify the task of the parser, by reducing the size of the input (there are many more characters than tokens) and by removing extraneous characters like white space. The scanner also typically removes comments and tags tokens with line and column numbers, to make it easier to generate good diagnostics in later phases. One could design a parser to take characters instead of tokens as input—dispensing with the scanner—but the result would be awkward and slow.

EXAMPLE 1.22
Context-free grammar and parsing

Parsing organizes tokens into a *parse tree* that represents higher-level constructs (statements, expressions, subroutines, and so on) in terms of their constituents. Each construct is a node in the tree; its constituents are its children. The root of the tree is simply “*program*”; the leaves, from left to right, are the tokens received from the scanner. Taken as a whole, the tree shows how the tokens fit together to make a valid program. The structure relies on a set of potentially recursive rules known as a *context-free grammar*. Each rule has an arrow sign (⟶) with the construct name on the left and a possible expansion on the right.[9] In C, for example, a `while` loop consists of the keyword `while` followed by a parenthesized Boolean expression and a statement:

iteration-statement ⟶ `while` `(` *expression* `)` *statement*

The statement, in turn, is often a list enclosed in braces:

statement ⟶ *compound-statement*
compound-statement ⟶ `{` *block-item-list_opt* `}`

where

block-item-list_opt ⟶ *block-item-list*

or

block-item-list_opt ⟶ ϵ

and

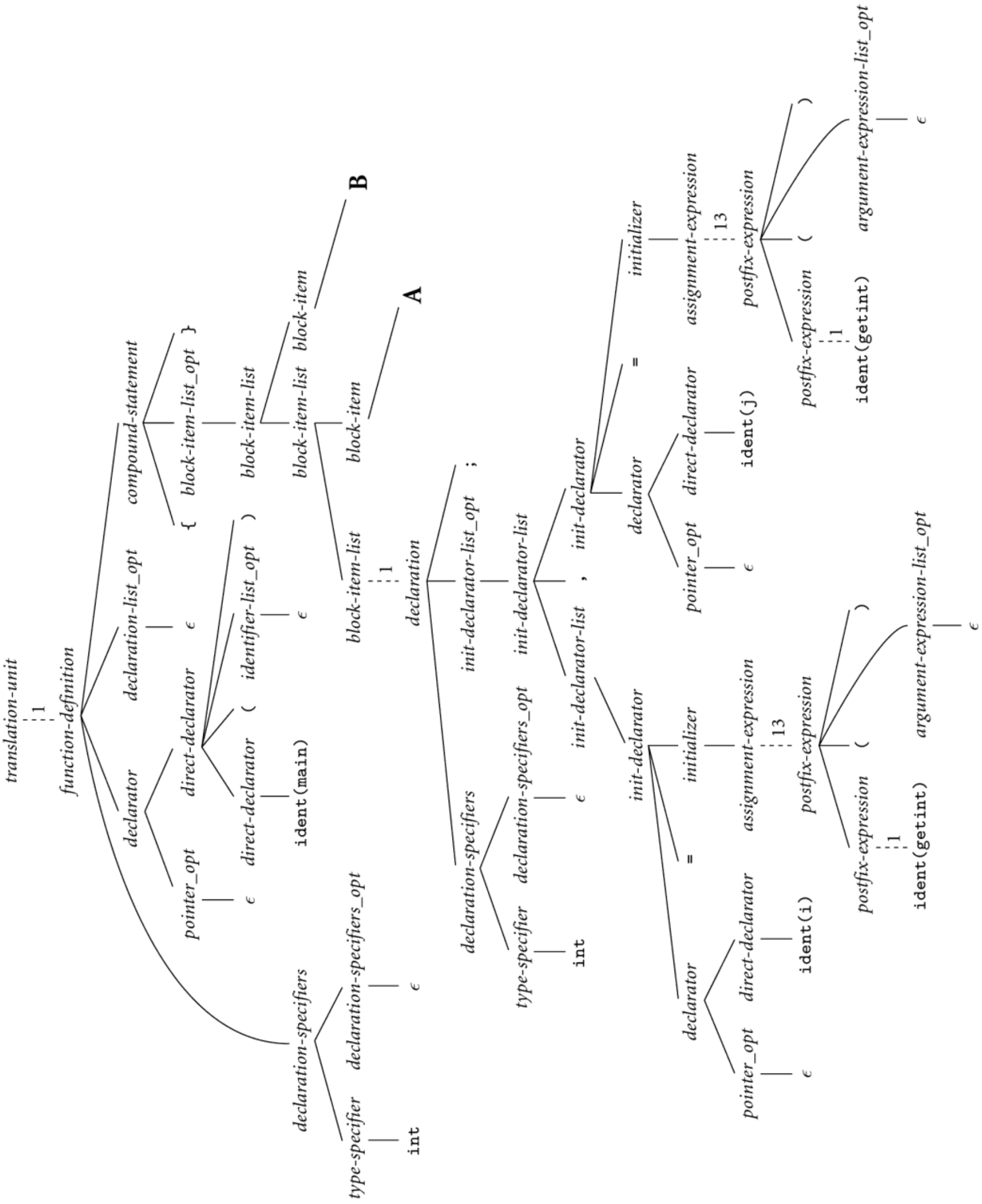
block-item-list ⟶ *block-item*
block-item-list ⟶ *block-item-list* *block-item*
block-item ⟶ *declaration*
block-item ⟶ *statement*

Here ϵ represents the empty string; it indicates that *block-item-list_opt* can simply be deleted. Many more grammar rules are needed, of course, to explain the full structure of a program.

EXAMPLE 1.23
GCD program parse tree

A context-free grammar is said to define the *syntax* of the language; parsing is therefore known as *syntax analysis*. There are many possible grammars for C (an infinite number, in fact); the fragment shown above is taken from the sample grammar contained in the official language definition [Int99]. A full parse tree for our GCD program (based on a full grammar not shown here) appears in Figure 1.5. While the size of the tree may seem daunting, its details aren't particularly important at this point in the text. What *is* important is that (1) each individual branching point represents the application of a single grammar rule, and (2) the resulting complexity is more a reflection of the grammar than it is of the input program. Much of the bulk stems from (a) the use of such artificial "constructs" as *block_item-list* and *block_item-list_opt* to generate lists of arbitrary

[9] Theorists also study *context-sensitive* grammars, in which the allowable expansions of a construct (the applicable rules) depend on the context in which the construct appears (i.e., on constructs to the left and right). Context sensitivity is important for natural languages like English, but it is almost never used in programming language design.


translation-unit
1
function-definition
declaration-specifiers
type-specifier
int
declaration-specifiers_opt
ϵ
declarator
pointer_opt
ϵ
direct-declarator
direct-declarator
ident(main)
(
identifier-list_opt
ϵ
)
declaration-list_opt
ϵ
compound-statement
{
block-item-list_opt
}
block-item-list
block-item-list
block-item-list
1
declaration
declaration-specifiers
type-specifier
int
declaration-specifiers_opt
ϵ
init-declarator-list_opt
init-declarator-list
init-declarator-list
init-declarator
declarator
pointer_opt
ϵ
direct-declarator
ident(i)
=
initializer
assignment-expression
13
postfix-expression
postfix-expression
1
ident(getint)
(
argument-expression-list_opt
ϵ
)
,
init-declarator
declarator
pointer_opt
ϵ
direct-declarator
ident(j)
=
initializer
assignment-expression
13
postfix-expression
postfix-expression
1
ident(getint)
(
argument-expression-list_opt
ϵ
)
;
block-item
A
block-item
B

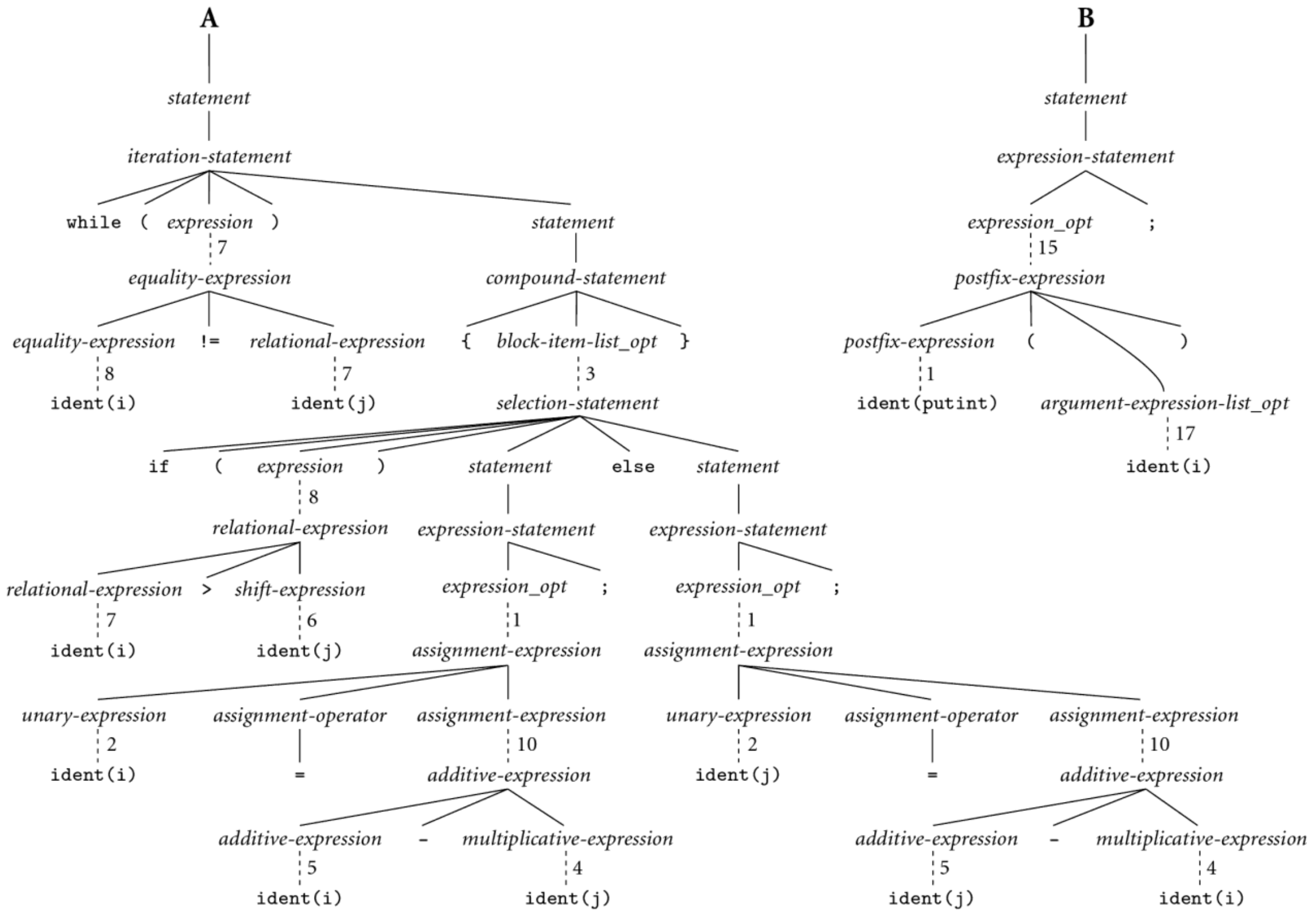


Figure 1.5 Parse tree for the GCD program. The symbol ϵ represents the empty string. Dotted lines indicate a chain of one-for-one replacements, elided to save space; the adjacent number indicates the number of omitted nodes. While the details of the tree aren't important to the current chapter, the sheer *amount* of detail is: it comes from having to fit the (much simpler) source code into the hierarchical structure of a context-free grammar.

length, and (b) the use of the equally artificial *assignment-expression*, *additive-expression*, *multiplicative-expression*, and so on, to capture precedence and associativity in arithmetic expressions. We shall see in the following subsection that much of this complexity can be discarded once parsing is complete. ■

In the process of scanning and parsing, the compiler or interpreter checks to see that all of the program's tokens are well formed, and that the sequence of tokens conforms to the syntax defined by the context-free grammar. Any malformed tokens (e.g., `123abc` or `$@foo` in C) should cause the scanner to produce an error message. Any syntactically invalid token sequence (e.g., `A = X Y Z` in C) should lead to an error message from the parser.

1.6.2 Semantic Analysis and Intermediate Code Generation

Semantic analysis is the discovery of *meaning* in a program. Among other things, the semantic analyzer recognizes when multiple occurrences of the same identifier are meant to refer to the same program entity, and ensures that the uses are consistent. In most languages it also tracks the *types* of both identifiers and expressions, both to verify consistent usage and to guide the generation of code in the back end of a compiler.

To assist in its work, the semantic analyzer typically builds and maintains a *symbol table* data structure that maps each identifier to the information known about it. Among other things, this information includes the identifier's type, internal structure (if any), and scope (the portion of the program in which it is valid).

Using the symbol table, the semantic analyzer enforces a large variety of rules that are not captured by the hierarchical structure of the context-free grammar and the parse tree. In C, for example, it checks to make sure that

- Every identifier is declared before it is used.
- No identifier is used in an inappropriate context (calling an integer as a subroutine, adding a string to an integer, referencing a field of the wrong type of `struct`, etc.).
- Subroutine calls provide the correct number and types of arguments.
- Labels on the arms of a `switch` statement are distinct constants.
- Any function with a non-`void` return type `returns` a value explicitly.

In many front ends, the work of the semantic analyzer takes the form of *semantic action routines*, invoked by the parser when it realizes that it has reached a particular point within a grammar rule.

Of course, not all semantic rules can be checked at compile time (or in the front end of an interpreter). Those that can are referred to as the *static semantics* of the language. Those that must be checked at run time (or in the later phases of an interpreter) are referred to as the *dynamic semantics* of the language. C has very little in the way of dynamic checks (its designers opted for performance over safety). Examples of rules that other languages enforce at run time include:

- Variables are never used in an expression unless they have been given a value.[10]
- Pointers are never dereferenced unless they refer to a valid object.
- Array subscript expressions lie within the bounds of the array.
- Arithmetic operations do not overflow.

When it cannot enforce rules statically, a compiler will often produce code to perform appropriate checks at run time, aborting the program or generating an *exception* if one of the checks then fails. (Exceptions will be discussed in Section 9.4.) Some rules, unfortunately, may be unacceptably expensive or impossible to enforce, and the language implementation may simply fail to check them. In Ada, a program that breaks such a rule is said to be *erroneous*; in C its behavior is said to be *undefined*.

EXAMPLE 1.24
GCD program abstract syntax tree

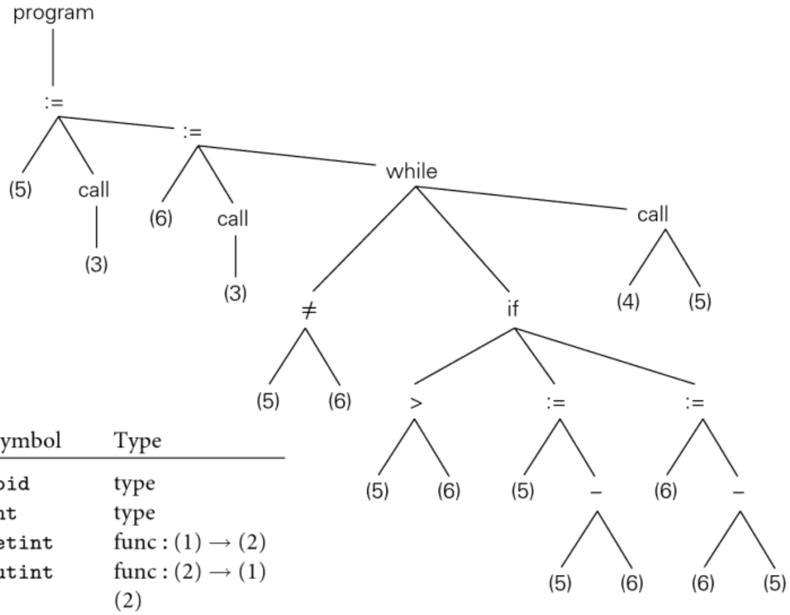
A parse tree is sometimes known as a *concrete syntax tree*, because it demonstrates, completely and concretely, how a particular sequence of tokens can be derived under the rules of the context-free grammar. Once we know that a token sequence is valid, however, much of the information in the parse tree is irrelevant to further phases of compilation. In the process of checking static semantic rules, the semantic analyzer typically transforms the parse tree into an *abstract syntax tree* (otherwise known as an *AST*, or simply a *syntax tree*) by removing most of the "artificial" nodes in the tree's interior. The semantic analyzer also *annotates* the remaining nodes with useful information, such as pointers from identifiers to their symbol table entries. The annotations attached to a particular node are known as its *attributes*. A syntax tree for our GCD program is shown in Figure 1.6. ■

EXAMPLE 1.25
Interpreting the syntax tree

Many interpreters use an annotated syntax tree to represent the running program: "execution" then amounts to tree traversal. In our GCD program, an interpreter would start at the root of Figure 1.6 and visit, in order, the statements on the main spine of the tree. At the first ":=" node, the interpreter would notice that the right child is a call: it would therefore call the `getint` routine (found in slot 3 of the symbol table) and assign the result into `i` (found in slot 5 of the symbol table). At the second ":=" node the interpreter would similarly assign the result of `getint` into `j`. At the while node it would repeatedly evaluate the left ("≠") child and, if the result was true, recursively walk the tree under the right (if) child. Finally, once the while node's left child evaluated to false, the interpreter would move on to the final call node, and output its result. ■

In many compilers, the annotated syntax tree constitutes the intermediate form that is passed from the front end to the back end. In other compilers, semantic analysis ends with a traversal of the tree (typically single pass) that generates some other intermediate form. One common such form consists of a *control flow graph* whose nodes resemble fragments of assembly language for a simple

[10] As we shall see in Section 6.1.3, Java and C# actually do enforce initialization at compile time, but only by adopting a conservative set of rules for "definite assignment," outlawing programs for which correctness is difficult or impossible to verify at compile time.



Index	Symbol	Type
1	`void`	type
2	`int`	type
3	`getint`	func : (1) → (2)
4	`putint`	func : (2) → (1)
5	`i`	(2)
6	`j`	(2)

Figure 1.6 Syntax tree and symbol table for the GCD program. Note the contrast to Figure 1.5: the syntax tree retains just the essential structure of the program, omitting details that were needed only to drive the parsing algorithm.

idealized machine. We will consider this option further in Chapter 15, where a control flow graph for our GCD program appears in Figure 15.3. In a suite of related compilers, the front ends for several languages and the back ends for several machines would share a common intermediate form.

1.6.3 Target Code Generation

EXAMPLE 1.26
GCD program assembly code

The code generation phase of a compiler translates the intermediate form into the target language. Given the information contained in the syntax tree, generating correct code is usually not a difficult task (generating *good* code is harder, as we shall see in Section 1.6.4). To generate assembly or machine language, the code generator traverses the symbol table to assign locations to variables, and then traverses the intermediate representation of the program, generating loads and stores for variable references, interspersed with appropriate arithmetic operations, tests, and branches. Naive code for our GCD example appears in Figure 1.7, in x86 assembly language. It was generated automatically by a simple pedagogical compiler.

The assembly language mnemonics may appear a bit cryptic, but the comments on each line (not generated by the compiler!) should make the correspon-

```
    pushl   %ebp                # \
    movl    %esp, %ebp          #  ) reserve space for local variables
    subl    $16, %esp           # /
    call    getint              # read
    movl    %eax, -8(%ebp)      # store i
    call    getint              # read
    movl    %eax, -12(%ebp)     # store j
A:  movl    -8(%ebp), %edi      # load i
    movl    -12(%ebp), %ebx     # load j
    cmpl    %ebx, %edi          # compare
    je      D                   # jump if i == j
    movl    -8(%ebp), %edi      # load i
    movl    -12(%ebp), %ebx     # load j
    cmpl    %ebx, %edi          # compare
    jle     B                   # jump if i < j
    movl    -8(%ebp), %edi      # load i
    movl    -12(%ebp), %ebx     # load j
    subl    %ebx, %edi          # i = i - j
    movl    %edi, -8(%ebp)      # store i
    jmp     C
B:  movl    -12(%ebp), %edi     # load j
    movl    -8(%ebp), %ebx      # load i
    subl    %ebx, %edi          # j = j - i
    movl    %edi, -12(%ebp)     # store j
C:  jmp     A
D:  movl    -8(%ebp), %ebx      # load i
    push    %ebx                # push i (pass to putint)
    call    putint              # write
    addl    $4, %esp            # pop i
    leave                       # deallocate space for local variables
    mov     $0, %eax            # exit status for program
    ret                         # return to operating system
```

Figure 1.7 Naive x86 assembly language for the GCD program.

dence between Figures 1.6 and 1.7 generally apparent. A few hints: `esp`, `ebp`, `eax`, `ebx`, and `edi` are registers (special storage locations, limited in number, that can be accessed very quickly). `-8(%ebp)` refers to the memory location 8 bytes before the location whose address is in register `ebp`; in this program, `ebp` serves as a *base* from which we can find variables `i` and `j`. The argument to a subroutine `call` instruction is passed by pushing it onto a stack, for which `esp` is the top-of-stack pointer. The return value comes back in register `eax`. Arithmetic operations overwrite their second argument with the result of the operation.[11]

[11] As noted in footnote 1, these are GNU assembler conventions; Microsoft and Intel assemblers specify arguments in the opposite order.

Often a code generator will save the symbol table for later use by a symbolic debugger, by including it in a nonexecutable part of the target code.

1.6.4 Code Improvement

Code improvement is often referred to as *optimization*, though it seldom makes anything optimal in any absolute sense. It is an optional phase of compilation whose goal is to transform a program into a new version that computes the same result more efficiently—more quickly or using less memory, or both.

Some improvements are machine independent. These can be performed as transformations on the intermediate form. Other improvements require an understanding of the target machine (or of whatever will execute the program in the target language). These must be performed as transformations on the target program. Thus code improvement often appears twice in the list of compiler phases: once immediately after semantic analysis and intermediate code generation, and again immediately after target code generation.

EXAMPLE 1.27
GCD program optimization

Applying a good code improver to the code in Figure 1.7 produces the code shown in Example 1.2. Comparing the two programs, we can see that the improved version is quite a lot shorter. Conspicuously absent are most of the loads and stores. The machine-independent code improver is able to verify that `i` and `j` can be kept in registers throughout the execution of the main loop. (This would not have been the case if, for example, the loop contained a call to a subroutine that might reuse those registers, or that might try to modify `i` or `j`.) The machine-specific code improver is then able to assign `i` and `j` to actual registers of the target machine. For modern microprocessors, with complex internal behavior, compilers can usually generate better code than can human assembly language programmers.

CHECK YOUR UNDERSTANDING

22. List the principal phases of compilation, and describe the work performed by each.

23. List the phases that are also executed as part of interpretation.

24. Describe the form in which a program is passed from the scanner to the parser; from the parser to the semantic analyzer; from the semantic analyzer to the intermediate code generator.

25. What distinguishes the front end of a compiler from the back end?

26. What is the difference between a phase and a pass of compilation? Under what circumstances does it make sense for a compiler to have multiple passes?

27. What is the purpose of the compiler's symbol table?

28. What is the difference between static and dynamic semantics?

29. On modern machines, do assembly language programmers still tend to write better code than a good compiler can? Why or why not?

1.7 Summary and Concluding Remarks

In this chapter we introduced the study of programming language design and implementation. We considered why there are so many languages, what makes them successful or unsuccessful, how they may be categorized for study, and what benefits the reader is likely to gain from that study. We noted that language design and language implementation are intimately tied to one another. Obviously an implementation must conform to the rules of the language. At the same time, a language designer must consider how easy or difficult it will be to implement various features, and what sort of performance is likely to result.

Language implementations are commonly differentiated into those based on interpretation and those based on compilation. We noted, however, that the difference between these approaches is fuzzy, and that most implementations include a bit of each. As a general rule, we say that a language is compiled if execution is preceded by a translation step that (1) fully analyzes both the structure (syntax) and meaning (semantics) of the program, and (2) produces an equivalent program in a significantly different form. The bulk of the implementation material in this book pertains to compilation.

Compilers are generally structured as a series of *phases*. The first few phases—scanning, parsing, and semantic analysis—serve to analyze the source program. Collectively these phases are known as the compiler's *front end*. The final few phases—target code generation and machine-specific code improvement—are known as the *back end*. They serve to build a target program—preferably a fast one—whose semantics match those of the source. Between the front end and the back end, a good compiler performs extensive machine-independent code improvement; the phases of this "middle end" typically comprise the bulk of the code of the compiler, and account for most of its execution time.

Chapters 3, 6, 7, 8, 9, and 10 form the core of the rest of this book. They cover fundamental issues of language design, both from the point of view of the programmer and from the point of view of the language implementor. To support the discussion of implementations, Chapters 2 and 4 describe compiler front ends in more detail than has been possible in this introduction. Chapter 5 provides an overview of assembly-level architecture. Chapters 15 through 17 discuss compiler back ends, including assemblers and linkers, run-time systems, and code improvement techniques. Additional language paradigms are covered in Chapters 11 through 14. Appendix A lists the principal programming languages mentioned in the text, together with a genealogical chart and bibliographic references. Appendix B contains a list of "Design & Implementation" sidebars; Appendix C contains a list of numbered examples.

1.8 Exercises

1.1 Errors in a computer program can be classified according to when they are detected and, if they are detected at compile time, what part of the compiler detects them. Using your favorite imperative language, give an example of each of the following.

(a) A lexical error, detected by the scanner

(b) A syntax error, detected by the parser

(c) A static semantic error, detected by semantic analysis

(d) A dynamic semantic error, detected by code generated by the compiler

(e) An error that the compiler can neither catch nor easily generate code to catch (this should be a violation of the language definition, not just a program bug)

1.2 Consider again the Pascal tool set distributed by Niklaus Wirth (Example 1.15). After successfully building a machine language version of the Pascal compiler, one could in principle discard the P-code interpreter and the P-code version of the compiler. Why might one choose *not* to do so?

1.3 Imperative languages like Fortran and C are typically compiled, while scripting languages, in which many issues cannot be settled until run time, are typically interpreted. Is interpretation simply what one "has to do" when compilation is infeasible, or are there actually some *advantages* to interpreting a language, even when a compiler is available?

1.4 The `gcd` program of Example 1.20 might also be written

```
int main() {
    int i = getint(), j = getint();
    while (i != j) {
        if (i > j) i = i % j;
        else j = j % i;
    }
    putint(i);
}
```

Does this program compute the same result? If not, can you fix it? Under what circumstances would you expect one or the other to be faster?

1.5 Expanding on Example 1.25, trace an interpretation of the `gcd` program on the inputs 12 and 8. Which syntax tree nodes are visited, in which order?

1.6 Both interpretation and code generation can be performed by traversal of a syntax tree. Compare these two kinds of traversals. In what ways are they similar/different?

1.7 In your local implementation of C, what is the limit on the size of integers? What happens in the event of arithmetic overflow? What are the implications of size limits on the portability of programs from one machine/compiler to another? How do the answers to these questions differ for Java? For Ada? For Pascal? For Scheme? (You may need to find a manual.)

1.8 The Unix `make` utility allows the programmer to specify *dependences* among the separately compiled pieces of a program. If file *A* depends on file *B* and file *B* is modified, `make` deduces that *A* must be recompiled, in case any of the changes to *B* would affect the code produced for *A*. How accurate is this sort of dependence management? Under what circumstances will it lead to unnecessary work? Under what circumstances will it fail to recompile something that needs to be recompiled?

1.9 Why is it difficult to tell whether a program is correct? How do you go about finding bugs in your code? What kinds of bugs are revealed by testing? What kinds of bugs are not? (For more formal notions of program correctness, see the bibliographic notes at the end of Chapter 4.)

1.9 Explorations

1.10 (a) What was the first programming language you learned? If you chose it, why did you do so? If it was chosen for you by others, why do you think they chose it? What parts of the language did you find the most difficult to learn?

(b) For the language with which you are most familiar (this may or may not be the first one you learned), list three things you wish had been differently designed. Why do you think they were designed the way they were? How would you fix them if you had the chance to do it over? Would there be any negative consequences, for example in terms of compiler complexity or program execution speed?

1.11 Get together with a classmate whose principal programming experience is with a language in a different category of Figure 1.1. (If your experience is mostly in C, for example, you might search out someone with experience in Lisp.) Compare notes. What are the easiest and most difficult aspects of programming, in each of your experiences? Pick a simple problem (e.g., sorting, or identification of connected components in a graph) and solve it using each of your favorite languages. Which solution is more elegant (do the two of you agree)? Which is faster? Why?

1.12 (a) If you have access to a Unix system, compile a simple program with the `-S` command-line flag. Add comments to the resulting assembly language file to explain the purpose of each instruction.

(b) Now use the `-o` command-line flag to generate a *relocatable object file*. Using appropriate local tools (look in particular for `nm`, `objdump`, or a symbolic debugger like gdb or dbx), identify the machine language corresponding to each line of assembler.

(c) Using nm, objdump, or a similar tool, identify the *undefined external symbols* in your object file. Now run the compiler to completion, to produce an *executable* file. Finally, run nm or objdump again to see what has happened to the symbols in part (b). Where did they come from—how did the linker resolve them?

(d) Run the compiler to completion one more time, using the -v command-line flag. You should see messages describing the various subprograms invoked during the compilation process (some compilers use a different letter for this option; check the man page). The subprograms may include a preprocessor, separate passes of the compiler itself (often two), probably an assembler, and the linker. If possible, run these subprograms yourself, individually. Which of them produce the files described in the previous subquestions? Explain the purpose of the various command-line flags with which the subprograms were invoked.

1.13 Write a program that commits a dynamic semantic error (e.g., division by zero, access off the end of an array, dereference of a null pointer). What happens when you run this program? Does the compiler give you options to control what happens? Devise an experiment to evaluate the cost of run-time semantic checks. If possible, try this exercise with more than one language or compiler.

1.14 C has a reputation for being a relatively "unsafe" high-level language. For example: it allows the programmer to mix operands of different sizes and types in many more ways than its "safer" cousins. The Unix lint utility can be used to search for potentially unsafe constructs in C programs. In effect, many of the rules that are enforced by the compiler in other languages are optional in C, and are enforced (if desired) by a separate program. What do you think of this approach? Is it a good idea? Why or why not?

1.15 Using an Internet search engine or magazine indexing service, read up on the history of Java and C#, including the conflict between Sun and Microsoft over Java standardization. Some have claimed that C# was, at least in part, an attempt by Microsoft to undermine the spread of Java. Others point to philosophical and practical differences between the languages, and argue that C# more than stands on its merits. In hindsight, how would you characterize Microsoft's decision to pursue an alternative to Java?

1.10 Bibliographic Notes

The compiler-oriented chapters of this book attempt to convey a sense of what the compiler does, rather than explaining how to build one. A much greater level of detail can be found in other texts. Leading options include the work of Aho et al. [ALSU07], Cooper and Torczon [CT04], and Fischer et al. [FCL10]. Other excellent, though less current texts include those of Appel [App97] and Grune et al. [GBJ$^+$12]. Popular texts on programming language design include those of Louden [LL12], Sebesta [Seb15], and Sethi [Set96].

Some of the best information on the history of programming languages can be found in the proceedings of conferences sponsored by the Association for Computing Machinery in 1978, 1993, and 2007 [Wex78, Ass93, Ass07]. Another excellent reference is Horowitz's 1987 text [Hor87]. A broader range of historical material can be found in the quarterly *IEEE Annals of the History of Computing*. Given the importance of personal taste in programming language design, it is inevitable that some language comparisons should be marked by strongly worded opinions. Early examples include the writings of Dijkstra [Dij82], Hoare [Hoa81], Kernighan [Ker81], and Wirth [Wir85a].

Much modern software development takes place in integrated programming environments. Influential precursors to these environments include the Genera Common Lisp environment from Symbolics Corp. [WMWM87] and the Smalltalk [Gol84], Interlisp [TM81], and Cedar [SZBH86] environments at the Xerox Palo Alto Research Center.

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2 Programming Language Syntax

Unlike natural languages such as English or Chinese, computer languages must be precise. Both their form (syntax) and meaning (semantics) must be specified without ambiguity, so that both programmers and computers can tell what a program is supposed to do. To provide the needed degree of precision, language designers and implementors use formal syntactic and semantic notation. To facilitate the discussion of language features in later chapters, we will cover this notation first: syntax in the current chapter and semantics in Chapter 4.

EXAMPLE 2.1

Syntax of Arabic numerals

As a motivating example, consider the Arabic numerals with which we represent numbers. These numerals are composed of digits, which we can enumerate as follows ('|' means "or"):

$$digit \longrightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}$$

Digits are the syntactic building blocks for numbers. In the usual notation, we say that a natural number is represented by an arbitrary-length (nonempty) string of digits, beginning with a nonzero digit:

$$non\_zero\_digit \longrightarrow \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}$$
$$natural\_number \longrightarrow non\_zero\_digit\ digit\ *$$

Here the "Kleene[1] star" metasymbol (*) is used to indicate zero or more repetitions of the symbol to its left. ■

Of course, digits are only symbols: ink blobs on paper or pixels on a screen. They carry no meaning in and of themselves. We add semantics to digits when we say that they represent the natural numbers from zero to nine, as defined by mathematicians. Alternatively, we could say that they represent colors, or the days of the week in a decimal calendar. These would constitute alternative semantics for the same syntax. In a similar fashion, we define the semantics of natural numbers by associating a base-10, place-value interpretation with each

[1] Stephen Kleene (1909–1994), a mathematician at the University of Wisconsin, was responsible for much of the early development of the theory of computation, including much of the material in Section C-2.4.

string of digits. Similar syntax rules and semantic interpretations can be devised for rational numbers, (limited-precision) real numbers, arithmetic, assignments, control flow, declarations, and indeed all of programming languages.

Distinguishing between syntax and semantics is useful for at least two reasons. First, different programming languages often provide features with very similar semantics but very different syntax. It is generally much easier to learn a new language if one is able to identify the common (and presumably familiar) semantic ideas beneath the unfamiliar syntax. Second, there are some very efficient and elegant algorithms that a compiler or interpreter can use to discover the syntactic structure (but not the semantics!) of a computer program, and these algorithms can be used to drive the rest of the compilation or interpretation process.

In the current chapter we focus on syntax: how we specify the structural rules of a programming language, and how a compiler identifies the structure of a given input program. These two tasks—specifying syntax rules and figuring out how (and whether) a given program was built according to those rules—are distinct. The first is of interest mainly to programmers, who want to write valid programs. The second is of interest mainly to compilers, which need to analyze those programs. The first task relies on *regular expressions* and *context-free grammars*, which specify how to generate valid programs. The second task relies on *scanners* and *parsers*, which recognize program structure. We address the first of these tasks in Section 2.1, the second in Sections 2.2 and 2.3.

In Section 2.4 (largely on the companion site) we take a deeper look at the formal theory underlying scanning and parsing. In theoretical parlance, a scanner is a *deterministic finite automaton* (DFA) that recognizes the tokens of a programming language. A parser is a deterministic *push-down automaton* (PDA) that recognizes the language's context-free syntax. It turns out that one can generate scanners and parsers automatically from regular expressions and context-free grammars. This task is performed by tools like Unix's `lex` and `yacc`,[2] among others. Possibly nowhere else in computer science is the connection between theory and practice so clear and so compelling.

2.1 Specifying Syntax: Regular Expressions and Context-Free Grammars

Formal specification of syntax requires a set of rules. How complicated (expressive) the syntax can be depends on the kinds of rules we are allowed to use. It turns out that what we intuitively think of as tokens can be constructed from individual characters using just three kinds of formal rules: concatenation, alternation (choice among a finite set of alternatives), and so-called "Kleene closure"

[2] At many sites, `lex` and `yacc` have been superseded by the GNU `flex` and `bison` tools, which provide a superset of the original functionality.

(repetition an arbitrary number of times). Specifying most of the rest of what we intuitively think of as syntax requires one additional kind of rule: recursion (creation of a construct from simpler instances of the same construct). Any set of strings that can be defined in terms of the first three rules is called a *regular set*, or sometimes a *regular language*. Regular sets are generated by *regular expressions* and recognized by scanners. Any set of strings that can be defined if we add recursion is called a *context-free language* (CFL). Context-free languages are generated by *context-free grammars* (CFGs) and recognized by parsers. (Terminology can be confusing here. The meaning of the word "language" varies greatly, depending on whether we're talking about "formal" languages [e.g., regular or context-free], or programming languages. A formal language is just a set of strings, with no accompanying semantics.)

2.1.1 Tokens and Regular Expressions

Tokens are the basic building blocks of programs—the shortest strings of characters with individual meaning. Tokens come in many *kinds*, including keywords, identifiers, symbols, and constants of various types. Some kinds of token (e.g., the increment operator) correspond to only one string of characters. Others (e.g., *identifier*) correspond to a set of strings that share some common form. (In most languages, keywords are special strings of characters that have the right form to be identifiers, but are reserved for special purposes.) We will use the word "token" informally to refer to both the generic kind (an identifier, the increment operator) and the specific string (`foo`, `++`); the distinction between these should be clear from context.

EXAMPLE 2.2

Lexical structure of C11

Some languages have only a few kinds of token, of fairly simple form. Other languages are more complex. C, for example, has more than 100 kinds of tokens, including 44 keywords (`double`, `if`, `return`, `struct`, etc.); identifiers (`my_variable`, `your_type`, `sizeof`, `printf`, etc.); integer (0765, 0x1f5, 501), floating-point (6.022e23), and character (`'x'`, `'\''`, `'\0170'`) constants; string literals (`"snerk"`, `"say \"hi\"\n"`); 54 "punctuators" (`+`, `]`, `->`, `*=`, `:`, `||`, etc.), and two different forms of comments. There are provisions for international character sets, string literals that span multiple lines of source code, constants of varying precision (width), alternative "spellings" for symbols that are missing on certain input devices, and preprocessor macros that build tokens from smaller pieces. Other large, modern languages (Java, Ada) are similarly complex. ■

To specify tokens, we use the notation of *regular expressions*. A regular expression is one of the following:

1. A character
2. The empty string, denoted ϵ
3. Two regular expressions next to each other, meaning any string generated by the first one followed by (concatenated with) any string generated by the second one

4. Two regular expressions separated by a vertical bar (|), meaning any string generated by the first one *or* any string generated by the second one
5. A regular expression followed by a Kleene star, meaning the concatenation of zero or more strings generated by the expression in front of the star

Parentheses are used to avoid ambiguity about where the various subexpressions start and end.[3]

EXAMPLE 2.3

Syntax of numeric constants

Consider, for example, the syntax of numeric constants accepted by a simple hand-held calculator:

$$\begin{aligned}
&\textit{number} \longrightarrow \textit{integer} \mid \textit{real} \\
&\textit{integer} \longrightarrow \textit{digit}\ \textit{digit}\,* \\
&\textit{real} \longrightarrow \textit{integer}\ \textit{exponent} \mid \textit{decimal}\ (\,\textit{exponent} \mid \epsilon\,) \\
&\textit{decimal} \longrightarrow \textit{digit}\,*\ (\ \texttt{.}\ \ \textit{digit} \mid \textit{digit}\ \ \texttt{.}\ )\ \textit{digit}\,* \\
&\textit{exponent} \longrightarrow (\,\texttt{e} \mid \texttt{E}\,)\ (\,\texttt{+} \mid \texttt{-} \mid \epsilon\,)\ \textit{integer} \\
&\textit{digit} \longrightarrow \texttt{0} \mid \texttt{1} \mid \texttt{2} \mid \texttt{3} \mid \texttt{4} \mid \texttt{5} \mid \texttt{6} \mid \texttt{7} \mid \texttt{8} \mid \texttt{9}
\end{aligned}$$

The symbols to the left of the ⟶ signs provide names for the regular expressions. One of these (*number*) will serve as a token name; the others are simply

DESIGN & IMPLEMENTATION

2.1 Contextual keywords

In addition to distinguishing between keywords and identifiers, some languages define so-called *contextual keywords*, which function as keywords in certain specific places in a program, but as identifiers elsewhere. In C#, for example, the word `yield` can appear immediately before `return` or `break`—a place where an identifier can never appear. In this context, it is interpreted as a keyword; anywhere else it is an identifier. It is therefore perfectly acceptable to have a local variable named `yield`: the compiler can distinguish it from the keyword by where it appears in the program.

C++11 has a small handful of contextual keywords. C# 4.0 has 26. Most were introduced in the course of revising the language to create a new standard version. Given a large user community, any short, intuitively appealing word is likely to have been used as an identifier by someone, in some existing program. Making that word a contextual keyword in the new version of the language, rather than a full keyword, reduces the risk that existing programs will suddenly fail to compile.

[3] Some authors use λ to represent the empty string. Some use a period (.), rather than juxtaposition, to indicate concatenation. Some use a plus sign (+), rather than a vertical bar, to indicate alternation.

for convenience in building larger expressions.[4] Note that while we have allowed definitions to build on one another, nothing is ever defined in terms of itself, even indirectly. Such recursive definitions are the distinguishing characteristic of context-free grammars, described in Section 2.1.2. To generate a valid number, we expand out the sub-definitions and then scan the resulting expression from left to right, choosing among alternatives at each vertical bar, and choosing a number of repetitions at each Kleene star. Within each repetition we may make different choices at vertical bars, generating different substrings. ■

Character Sets and Formatting Issues

Upper- and lowercase letters in identifiers and keywords are considered distinct in some languages (e.g., Perl, Python, and Ruby; C and its descendants), and identical in others (e.g., Ada, Common Lisp, and Fortran). Thus `foo`, `Foo`, and `FOO` all represent the same identifier in Ada, but different identifiers in C. Modula-2 and Modula-3 require keywords and predefined (built-in) identifiers to be written in uppercase; C and its descendants require them to be written in lowercase. A few languages allow only letters and digits in identifiers. Most allow underscores. A few (notably Lisp) allow a variety of additional characters. Some languages (e.g., Java and C#) have standard (but optional) conventions on the use of upper- and lowercase letters in names.[5]

With the globalization of computing, non-Latin character sets have become increasingly important. Many modern languages, including C, C++, Ada 95, Java, C#, and Fortran 2003 have introduced explicit support for multibyte character sets, generally based on the Unicode and ISO/IEC 10646 international standards. Most modern programming languages allow non-Latin characters to appear within comments and character strings; an increasing number allow them in identifiers as well. Conventions for portability across character sets and for *localization* to a given character set can be surprisingly complex, particularly when various forms of backward compatibility are required (the C99 Rationale devotes five full pages to this subject [Int03a, pp. 19–23]); for the most part we ignore such issues here.

Some language implementations impose limits on the maximum length of identifiers, but most avoid such unnecessary restrictions. Most modern languages are also more or less *free format*, meaning that a program is simply a sequence of tokens: what matters is their order with respect to one another, not their physical position within a printed line or page. “White space” (blanks, tabs, carriage returns, and line and page feed characters) between tokens is usually ignored, except to the extent that it is needed to separate one token from the next.

[4] We have assumed here that all numeric constants are simply “numbers.” In many programming languages, integer and real constants are separate kinds of token. Their syntax may also be more complex than indicated here, to support such features are multiple lengths or nondecimal bases.

[5] For the sake of consistency we do not always obey such conventions in this book: most examples follow the common practice of C programmers, in which underscores, rather than capital letters, separate the “subwords” of names.

There are a few noteworthy exceptions to these rules. Some language implementations limit the maximum length of a line, to allow the compiler to store the current line in a fixed-length buffer. Dialects of Fortran prior to Fortran 90 use a *fixed format*, with 72 characters per line (the width of a paper punch card, on which programs were once stored), and with different columns within the line reserved for different purposes. Line breaks serve to separate statements in several other languages, including Go, Haskell, Python, and Swift. Haskell and Python also give special significance to indentation. The body of a loop, for example, consists of precisely those subsequent lines that are indented farther than the header of the loop.

Other Uses of Regular Expressions

Many readers will be familiar with regular expressions from the `grep` family of tools in Unix, the search facilities of various text editors, or such scripting languages and tools as Perl, Python, Ruby, `awk`, and `sed`. Most of these provide a rich set of extensions to the notation of regular expressions. Some extensions, such as shorthand for "zero or one occurrences" or "anything other than white space," do not change the power of the notation. Others, such as the ability to require a second occurrence, later in the input string, of the same character sequence that matched an earlier part of the expression, increase the power of the notation, so that it is no longer restricted to generating regular sets. Still other extensions are designed not to increase the expressiveness of the notation but rather to tie it to other language facilities. In many tools, for example, one can bracket portions of a regular expression in such a way that when a string is matched against it the contents of the corresponding substrings are assigned into named local variables. We will return to these issues in Section 14.4.2, in the context of scripting languages.

2.1.2 Context-Free Grammars

EXAMPLE 2.4

Syntactic nesting in expressions

Regular expressions work well for defining tokens. They are unable, however, to specify *nested* constructs, which are central to programming languages. Consider for example the structure of an arithmetic expression:

DESIGN & IMPLEMENTATION

2.2 Formatting restrictions

Formatting limitations inspired by implementation concerns—as in the punch-card-oriented rules of Fortran 77 and its predecessors—have a tendency to become unwanted anachronisms as implementation techniques improve. Given the tendency of certain word processors to "fill" or auto-format text, the line break and indentation rules of languages like Haskell, Occam, and Python are somewhat controversial.

$$
\begin{aligned}
\mathit{expr} \;&\longrightarrow\; \texttt{id} \mid \texttt{number} \mid \texttt{-}\ \mathit{expr} \mid \texttt{(}\ \mathit{expr}\ \texttt{)} \\
&\qquad \mid \mathit{expr}\ \mathit{op}\ \mathit{expr} \\
\mathit{op} \;&\longrightarrow\; \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/}
\end{aligned}
$$

Here the ability to define a construct in terms of itself is crucial. Among other things, it allows us to ensure that left and right parentheses are matched, something that cannot be accomplished with regular expressions (see Section C-2.4.3 for more details). The arrow symbol (⟶) means "can have the form"; for brevity it is sometimes pronounced "goes to." ■

Each of the rules in a context-free grammar is known as a *production*. The symbols on the left-hand sides of the productions are known as *variables*, or *nonterminals*. There may be any number of productions with the same left-hand side. Symbols that are to make up the strings derived from the grammar are known as *terminals* (shown here in `typewriter` font). They cannot appear on the left-hand side of any production. In a programming language, the terminals of the context-free grammar are the language's tokens. One of the nonterminals, usually the one on the left-hand side of the first production, is called the *start symbol*. It names the construct defined by the overall grammar.

The notation for context-free grammars is sometimes called Backus-Naur Form (BNF), in honor of John Backus and Peter Naur, who devised it for the definition of the Algol-60 programming language [NBB$^+$63].[6] Strictly speaking, the Kleene star and meta-level parentheses of regular expressions are not allowed in BNF, but they do not change the expressive power of the notation, and are commonly included for convenience. Sometimes one sees a "Kleene plus" ($^+$) as well; it indicates one or more instances of the symbol or group of symbols in front of it.[7] When augmented with these extra operators, the notation is often called extended BNF (EBNF). The construct

EXAMPLE 2.5
Extended BNF (EBNF)

$$\mathit{id\_list} \;\longrightarrow\; \texttt{id}\ (\ \texttt{,}\ \texttt{id}\ )^*$$

is shorthand for

$$
\begin{aligned}
\mathit{id\_list} \;&\longrightarrow\; \texttt{id} \\
\mathit{id\_list} \;&\longrightarrow\; \mathit{id\_list}\ \texttt{,}\ \texttt{id}
\end{aligned}
$$

"Kleene plus" is analogous. Note that the parentheses here are metasymbols. In Example 2.4 they were part of the language being defined, and were written in fixed-width font.[8]

[6] John Backus (1924–2007) was also the inventor of Fortran. He spent most of his professional career at IBM Corporation, and was named an IBM Fellow in 1987. He received the ACM Turing Award in 1977.

[7] Some authors use curly braces ({ }) to indicate zero or more instances of the symbols inside. Some use square brackets ([ ]) to indicate zero or one instances of the symbols inside—that is, to indicate that those symbols are optional.

[8] To avoid confusion, some authors place quote marks around any single character that is part of the language being defined: $\mathit{id\_list} \longrightarrow \texttt{id}\ (\ \text{','}\ \texttt{id}\ )^*$; $\mathit{expr} \longrightarrow \text{'('}\ \mathit{expr}\ \text{')'}$. In both regular and extended BNF, many authors use ::= instead of ⟶.

Like the Kleene star and parentheses, the vertical bar is in some sense superfluous, though it was provided in the original BNF. The construct

$$\mathit{op} \longrightarrow \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/}$$

can be considered shorthand for

$$\begin{aligned}
\mathit{op} &\longrightarrow \texttt{+} \\
\mathit{op} &\longrightarrow \texttt{-} \\
\mathit{op} &\longrightarrow \texttt{*} \\
\mathit{op} &\longrightarrow \texttt{/}
\end{aligned}$$

which is also sometimes written

$$\begin{aligned}
\mathit{op} &\longrightarrow \texttt{+} \\
&\longrightarrow \texttt{-} \\
&\longrightarrow \texttt{*} \\
&\longrightarrow \texttt{/}
\end{aligned}$$

Many tokens, such as `id` and `number` above, have many possible spellings (i.e., may be represented by many possible strings of characters). The parser is oblivious to these; it does not distinguish one identifier from another. The semantic analyzer does distinguish them, however; the scanner must save the spelling of each such "interesting" token for later use.

2.1.3 Derivations and Parse Trees

A context-free grammar shows us how to generate a syntactically valid string of terminals: Begin with the start symbol. Choose a production with the start symbol on the left-hand side; replace the start symbol with the right-hand side of that production. Now choose a nonterminal *A* in the resulting string, choose a production *P* with *A* on its left-hand side, and replace *A* with the right-hand side of *P*. Repeat this process until no nonterminals remain.

EXAMPLE 2.6

Derivation of `slope * x + intercept`

As an example, we can use our grammar for expressions to generate the string "`slope * x + intercept`":

$$\begin{aligned}
\mathit{expr} &\Longrightarrow \mathit{expr}\ \mathit{op}\ \underline{\mathit{expr}} \\
&\Longrightarrow \mathit{expr}\ \underline{\mathit{op}}\ \texttt{id} \\
&\Longrightarrow \underline{\mathit{expr}}\ \texttt{+ id} \\
&\Longrightarrow \mathit{expr}\ \mathit{op}\ \underline{\mathit{expr}}\ \texttt{+ id} \\
&\Longrightarrow \mathit{expr}\ \underline{\mathit{op}}\ \texttt{id + id} \\
&\Longrightarrow \underline{\mathit{expr}}\ \texttt{* id + id} \\
&\Longrightarrow \underset{\texttt{(slope)}}{\texttt{id}}\ \texttt{*}\ \underset{\texttt{(x)}}{\texttt{id}}\ \texttt{+}\ \underset{\texttt{(intercept)}}{\texttt{id}}
\end{aligned}$$

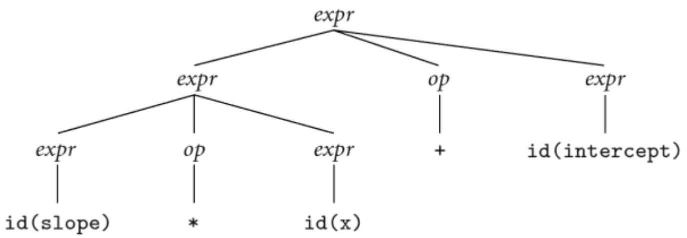


Figure 2.1 Parse tree for `slope * x + intercept` (grammar in Example 2.4).

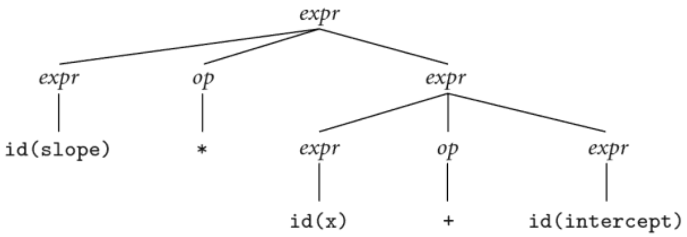


Figure 2.2 Alternative (less desirable) parse tree for `slope * x + intercept` (grammar in Example 2.4). The fact that more than one tree exists implies that our grammar is ambiguous.

The $\Longrightarrow$ metasymbol is often pronounced "derives." It indicates that the right-hand side was obtained by using a production to replace some nonterminal in the left-hand side. At each line we have underlined the symbol A that is replaced in the following line.

A series of replacement operations that shows how to derive a string of terminals from the start symbol is called a *derivation*. Each string of symbols along the way is called a *sentential form*. The final sentential form, consisting of only terminals, is called the *yield* of the derivation. We sometimes elide the intermediate steps and write *expr* $\Longrightarrow^*$ `slope * x + intercept`, where the metasymbol $\Longrightarrow^*$ means "derives after zero or more replacements." In this particular derivation, we have chosen at each step to replace the right-most nonterminal with the right-hand side of some production. This replacement strategy leads to a *right-most* derivation. There are many other possible derivations, including *left-most* and options in-between.

We saw in Chapter 1 that we can represent a derivation graphically as a *parse tree*. The root of the parse tree is the start symbol of the grammar. The leaves of the tree are its yield. Each internal node, together with its children, represents the use of a production.

EXAMPLE 2.7

Parse trees for `slope * x + intercept`

A parse tree for our example expression appears in Figure 2.1. This tree is not unique. At the second level of the tree, we could have chosen to turn the operator into a `*` instead of a `+`, and to further expand the expression on the right, rather than the one on the left (see Figure 2.2). A grammar that allows the construction of more than one parse tree for some string of terminals is said to be *ambiguous*. Ambiguity turns out to be a problem when trying to build a parser: it requires some extra mechanism to drive a choice between equally acceptable alternatives. ■

A moment's reflection will reveal that there are infinitely many context-free grammars for any given context-free language.[9] Some grammars, however, are much more useful than others. In this text we will avoid the use of ambiguous grammars (though most parser generators allow them, by means of *disambiguating* rules). We will also avoid the use of so-called *useless* symbols: nonterminals that cannot generate any string of terminals, or terminals that cannot appear in the yield of any derivation.

When designing the grammar for a programming language, we generally try to find one that reflects the internal structure of programs in a way that is useful to the rest of the compiler. (We shall see in Section 2.3.2 that we also try to find one that can be parsed efficiently, which can be a bit of a challenge.) One place in which structure is particularly important is in arithmetic expressions, where we can use productions to capture the *associativity* and *precedence* of the various operators. Associativity tells us that the operators in most languages group left to right, so that `10 - 4 - 3` means `(10 - 4) - 3` rather than `10 - (4 - 3)`. Precedence tells us that multiplication and division in most languages group more tightly than addition and subtraction, so that `3 + 4 * 5` means `3 + (4 * 5)` rather than `(3 + 4) * 5`. (These rules are not universal; we will consider them again in Section 6.1.1.)

EXAMPLE 2.8

Expression grammar with precedence and associativity

Here is a better version of our expression grammar:

1. *expr* ⟶ *term* | *expr add_op term*
2. *term* ⟶ *factor* | *term mult_op factor*
3. *factor* ⟶ `id` | `number` | `-` *factor* | `(` *expr* `)`
4. *add_op* ⟶ `+` | `-`
5. *mult_op* ⟶ `*` | `/`

This grammar is unambiguous. It captures precedence in the way *factor*, *term*, and *expr* build on one another, with different operators appearing at each level. It captures associativity in the second halves of lines 1 and 2, which build sub*expr*s and sub*term*s to the left of the operator, rather than to the right. In Figure 2.3, we can see how building the notion of precedence into the grammar makes it clear that multiplication groups more tightly than addition in `3 + 4 * 5`, even without parentheses. In Figure 2.4, we can see that subtraction groups more tightly to the left, so that `10 - 4 - 3` would evaluate to `3`, rather than to `9`. ■

[9] Given a specific grammar, there are many ways to create other equivalent grammars. We could, for example, replace A with some new symbol B everywhere it appears in the right-hand side of a production, and then create a new production $B \longrightarrow A$.

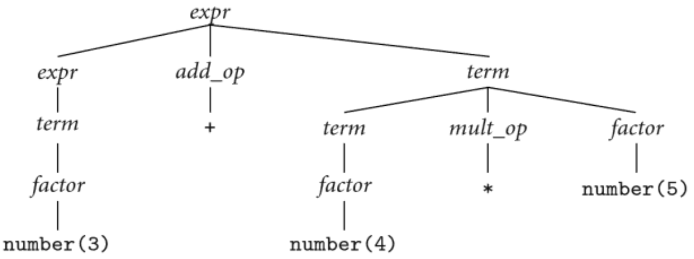


Figure 2.3 **Parse tree for 3 + 4 * 5, with precedence** (grammar in Example 2.8).

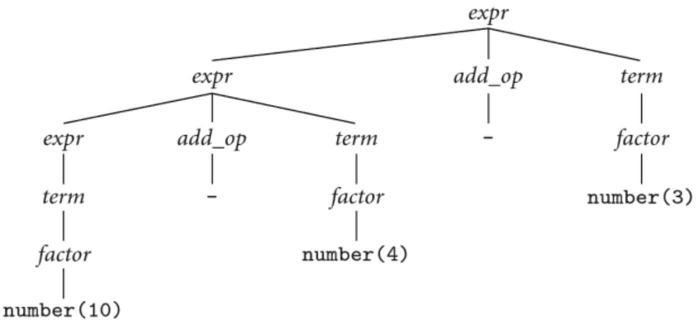


Figure 2.4 **Parse tree for 10 – 4 – 3, with left associativity** (grammar in Example 2.8).

✓ **CHECK YOUR UNDERSTANDING**

1. What is the difference between syntax and semantics?
2. What are the three basic operations that can be used to build complex regular expressions from simpler regular expressions?
3. What additional operation (beyond the three of regular expressions) is provided in context-free grammars?
4. What is *Backus-Naur form*? When and why was it devised?
5. Name a language in which indentation affects program syntax.
6. When discussing context-free languages, what is a *derivation*? What is a *sentential form*?
7. What is the difference between a *right-most* derivation and a *left-most* derivation?
8. What does it mean for a context-free grammar to be *ambiguous*?
9. What are *associativity* and *precedence*? Why are they significant in parse trees?

2.2 Scanning

Together, the scanner and parser for a programming language are responsible for discovering the syntactic structure of a program. This process of discovery, or *syntax analysis*, is a necessary first step toward translating the program into an equivalent program in the target language. (It's also the first step toward interpreting the program directly. In general, we will focus on compilation, rather than interpretation, for the remainder of the book. Most of what we shall discuss either has an obvious application to interpretation, or is obviously irrelevant to it.)

By grouping input characters into tokens, the scanner dramatically reduces the number of individual items that must be inspected by the more computationally intensive parser. In addition, the scanner typically removes comments (so the parser doesn't have to worry about them appearing throughout the context-free grammar—see Exercise 2.20); saves the text of "interesting" tokens like identifiers, strings, and numeric literals; and tags tokens with line and column numbers, to make it easier to generate high-quality error messages in subsequent phases.

EXAMPLE 2.9
Tokens for a calculator language

In Examples 2.4 and 2.8 we considered a simple language for arithmetic expressions. In Section 2.3.1 we will extend this to create a simple "calculator language" with input, output, variables, and assignment. For this language we will use the following set of tokens:

assign ⟶ `:=`

plus ⟶ `+`

minus ⟶ `-`

times ⟶ `*`

div ⟶ `/`

lparen ⟶ `(`

rparen ⟶ `)`

id ⟶ *letter* (*letter* | *digit*)*
except for **`read`** and **`write`**

number ⟶ *digit digit* * | *digit* * (`.` *digit* | *digit* `.`) *digit* *

In keeping with Algol and its descendants (and in contrast to the C-family languages), we have used `:=` rather than `=` for assignment. For simplicity, we have omitted the exponential notation found in Example 2.3. We have also listed the tokens `read` and `write` as exceptions to the rule for `id` (more on this in Section 2.2.2). To make the task of the scanner a little more realistic, we borrow the two styles of comment from C:

comment ⟶ `/*` (*non-*`*` | `*` *non-*`/`)* $*^+$ `/`
  | `//` (*non-newline*)* *newline*

Here we have used *non-*`*`, *non-*`/`, and *non-newline* as shorthand for the alternation of all characters other than `*`, `/`, and *newline*, respectively. ■

EXAMPLE 2.10

An ad hoc scanner for calculator tokens

How might we go about recognizing the tokens of our calculator language? The simplest approach is entirely ad hoc. Pseudocode appears in Figure 2.5. We can structure the code however we like, but it seems reasonable to check the simpler and more common cases first, to peek ahead when we need to, and to embed loops for comments and for long tokens such as identifiers and numbers.

After finding a token the scanner returns to the parser. When invoked again it repeats the algorithm from the beginning, using the next available characters of input (including any that were peeked at but not consumed the last time). ■

As a rule, we accept the longest possible token in each invocation of the scanner. Thus `foobar` is always `foobar` and never `f` or `foo` or `foob`. More to the point, in a language like C, `3.14159` is a real number and never `3`, `.`, and `14159`. White space (blanks, tabs, newlines, comments) is generally ignored, except to the extent that it separates tokens (e.g., `foo bar` is different from `foobar`).

Figure 2.5 could be extended fairly easily to outline a scanner for some larger programming language. The result could then be fleshed out, by hand, to create code in some implementation language. Production compilers often use such ad hoc scanners; the code is fast and compact. During language development, however, it is usually preferable to build a scanner in a more structured way, as an explicit representation of a *finite automaton*. Finite automata can be generated automatically from a set of regular expressions, making it easy to regenerate a scanner when token definitions change.

EXAMPLE 2.11

Finite automaton for a calculator scanner

An automaton for the tokens of our calculator language appears in pictorial form in Figure 2.6. The automaton starts in a distinguished initial state. It then moves from state to state based on the next available character of input. When it reaches one of a designated set of final states it recognizes the token associated with that state. The "longest possible token" rule means that the scanner returns to the parser only when the next character cannot be used to continue the current token. ■

DESIGN & IMPLEMENTATION

2.3 Nested comments

Nested comments can be handy for the programmer (e.g., for temporarily "commenting out" large blocks of code). Scanners normally deal only with nonrecursive constructs, however, so nested comments require special treatment. Some languages disallow them. Others require the language implementor to augment the scanner with special-purpose comment-handling code. C and C++ strike a compromise: `/* ... */` style comments are not allowed to nest, but `/* ... */` and `//...` style comments can appear inside each other. The programmer can thus use one style for "normal" comments and the other for "commenting out." (The C99 designers note, however, that conditional compilation (`#if`) is preferable [Int03a, p. 58].)

```
skip any initial white space (spaces, tabs, and newlines)
if cur_char ∈ {'(', ')', '+', '−', '*'}
    return the corresponding single-character token
if cur_char = ':'
    read the next character
    if it is '=' then return assign else announce an error
if cur_char = '/'
    peek at the next character
    if it is '*' or '/'
        read additional characters until "*/" or newline is seen, respectively
        jump back to top of code
    else return div
if cur_char = .
    read the next character
    if it is a digit
        read any additional digits
        return number
    else announce an error
if cur_char is a digit
    read any additional digits and at most one decimal point
    return number
if cur_char is a letter
    read any additional letters and digits
    check to see whether the resulting string is read or write
    if so then return the corresponding token
    else return id
else announce an error
```

Figure 2.5 Outline of an ad hoc scanner for tokens in our calculator language.

2.2.1 Generating a Finite Automaton

While a finite automaton can in principle be written by hand, it is more common to build one automatically from a set of regular expressions, using a *scanner generator* tool. For our calculator language, we should like to covert the regular expressions of Example 2.9 into the automaton of Figure 2.6. That automaton has the desirable property that its actions are *deterministic*: in any given state with a given input character there is never more than one possible outgoing transition (arrow) labeled by that character. As it turns out, however, there is no obvious one-step algorithm to convert a set of regular expressions into an equivalent deterministic finite automaton (DFA). The typical scanner generator implements the conversion as a series of three separate steps.

The first step converts the regular expressions into a *nondeterministic* finite automaton (NFA). An NFA is like a DFA except that (1) there may be more than one transition out of a given state labeled by a given character, and (2) there may be so-called *epsilon transitions*: arrows labeled by the empty string symbol, ϵ. The NFA is said to accept an input string (token) if there exists a path from the start

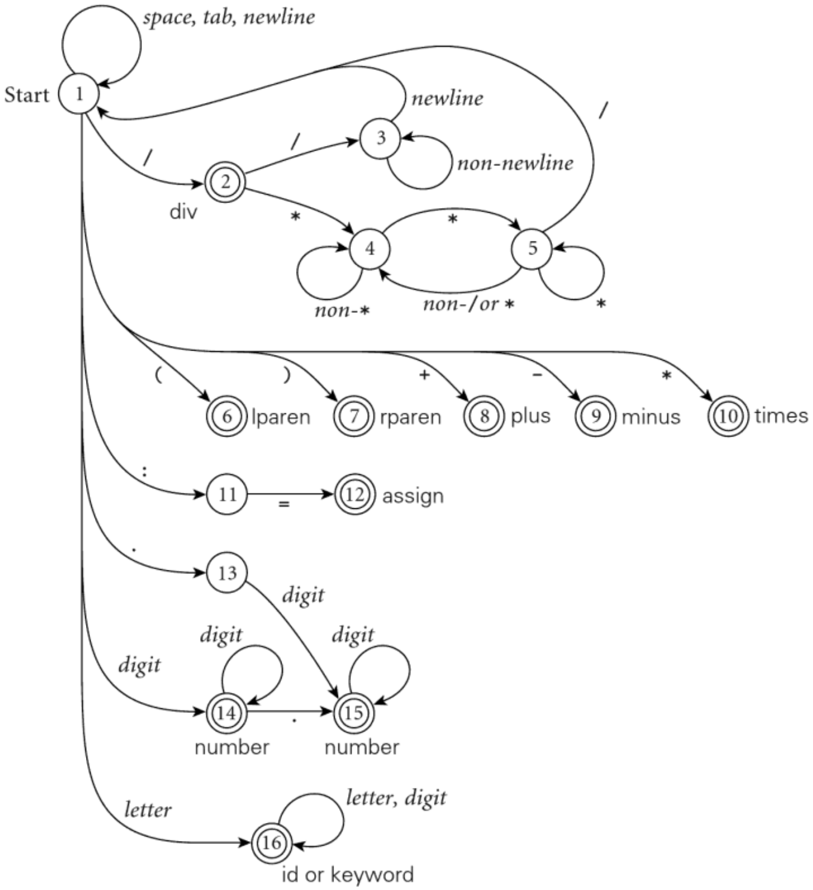


Figure 2.6 Pictorial representation of a scanner for calculator tokens, in the form of a finite automaton. This figure roughly parallels the code in Figure 2.5. States are numbered for reference in Figure 2.12. Scanning for each token begins in the state marked "Start." The *final* states, in which a token is recognized, are indicated by double circles. Comments, when recognized, send the scanner back to its start state, rather than a final state.

state to a final state whose non-epsilon transitions are labeled, in order, by the characters of the token.

To avoid the need to search all possible paths for one that "works," the second step of a scanner generator translates the NFA into an equivalent DFA: an automaton that accepts the same language, but in which there are no epsilon transitions, and no states with more than one outgoing transition labeled by the same character. The third step is a space optimization that generates a final DFA with the minimum possible number of states.

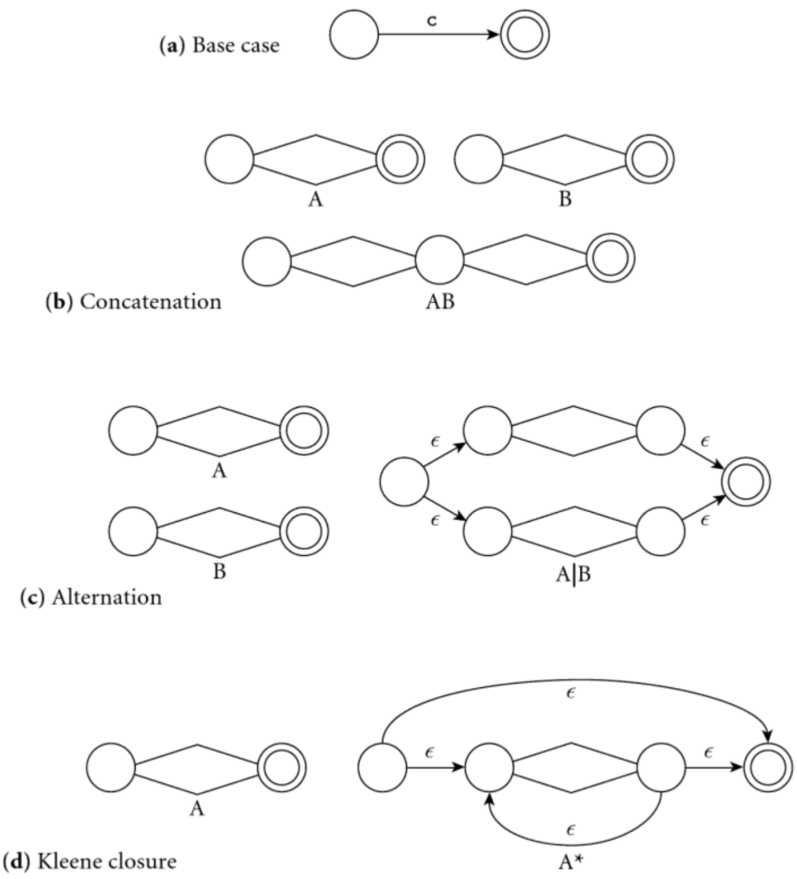


Figure 2.7 **Construction of an NFA equivalent to a given regular expression.** Part (a) shows the base case: the automaton for the single letter c. Parts (b), (c), and (d), respectively, show the constructions for concatenation, alternation, and Kleene closure. Each construction retains a unique start state and a single final state. Internal detail is hidden in the diamond-shaped center regions.

From a Regular Expression to an NFA

EXAMPLE 2.12

Constructing an NFA for a given regular expression

A trivial regular expression consisting of a single character c is equivalent to a simple two-state NFA (in fact, a DFA), illustrated in part (a) of Figure 2.7. Similarly, the regular expression ϵ is equivalent to a two-state NFA whose arc is labeled by ϵ. Starting with this base we can use three subconstructions, illustrated in parts (b) through (d) of the same figure, to build larger NFAs to represent the concatenation, alternation, or Kleene closure of the regular expressions represented by smaller NFAs. Each step preserves three invariants: there are no transitions into the initial state, there is a single final state, and there are no transitions out of the final state. These invariants allow smaller automata to be joined into larger

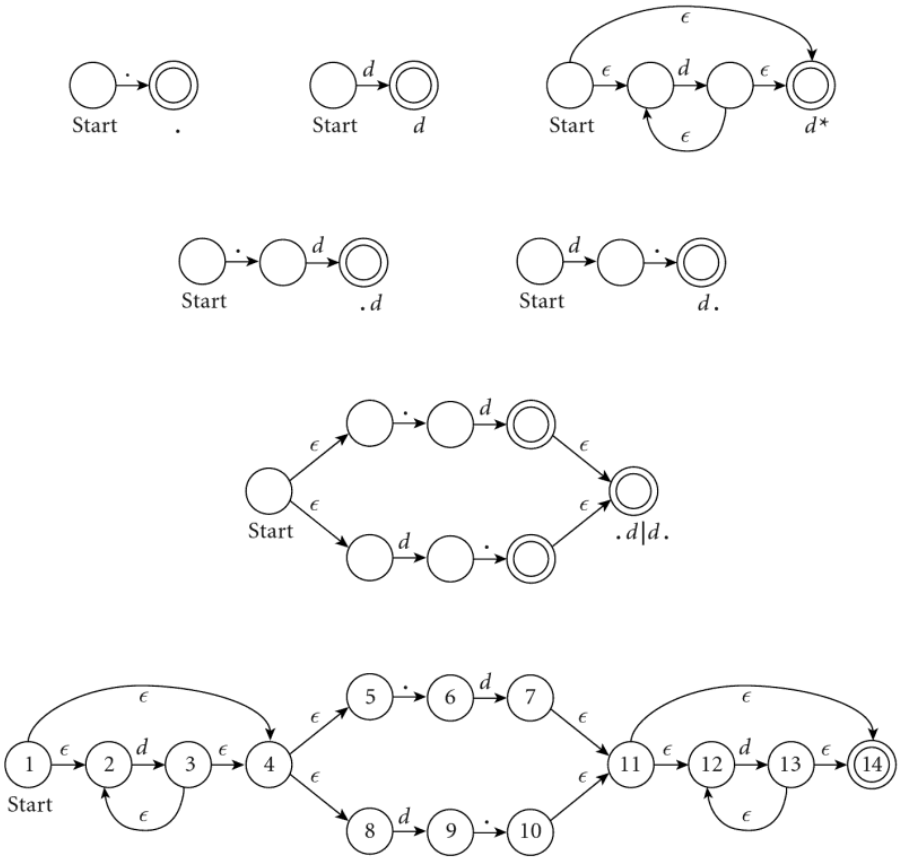


Figure 2.8 Construction of an NFA equivalent to the regular expression $d^*(\ .\ d\ |\ d\ .\ )\ d^*$. In the top row are the primitive automata for . and d, and the Kleene closure construction for d^*. In the second and third rows we have used the concatenation and alternation constructions to build $.\ d$, $d\ .$, and $(\ .\ d\ |\ d\ .\ )$. The fourth row uses concatenation again to complete the NFA. We have labeled the states in the final automaton for reference in subsequent figures.

ones without any ambiguity about where to create the connections, and without creating any unexpected paths. ■

EXAMPLE 2.13
NFA for $d^*(\ .\ d\ |\ d\ .\ )\ d^*$

To make these constructions concrete, we consider a small but nontrivial example—the *decimal* strings of Example 2.3. These consist of a string of decimal digits containing a single decimal point. With only one digit, the point can come at the beginning or the end: $(\ .\ d\ |\ d\ .\ )$, where for brevity we use d to represent any decimal digit. Arbitrary numbers of digits can then be added at the beginning or the end: $d^*(\ .\ d\ |\ d\ .\ )\ d^*$. Starting with this regular expression and using the constructions of Figure 2.7, we illustrate the construction of an equivalent NFA in Figure 2.8. ■

From an NFA to a DFA

EXAMPLE 2.14
DFA for d*(.d | d.) d*

With no way to “guess” the right transition to take from any given state, any practical implementation of an NFA would need to explore all possible transitions, concurrently or via backtracking. To avoid such a complex and time-consuming strategy, we can use a “set of subsets” construction to transform the NFA into an equivalent DFA. The key idea is for the state of the DFA after reading a given input to represent the *set* of states that the NFA might have reached on the same input. We illustrate the construction in Figure 2.9 using the NFA from Figure 2.8. Initially, before it consumes any input, the NFA may be in State 1, or it may make epsilon transitions to States 2, 4, 5, or 8. We thus create an initial State *A* for our DFA to represent this set. On an input of *d*, our NFA may move from State 2 to State 3, or from State 8 to State 9. It has no other transitions on this input from any of the states in *A*. From State 3, however, the NFA may make epsilon transitions to any of States 2, 4, 5, or 8. We therefore create DFA State *B* as shown.

On a ., our NFA may move from State 5 to State 6. There are no other transitions on this input from any of the states in *A*, and there are no epsilon transitions out of State 6. We therefore create the singleton DFA State *C* as shown. None of States *A*, *B*, or *C* is marked as final, because none contains a final state of the original NFA.

Returning to State *B* of the growing DFA, we note that on an input of *d* the original NFA may move from State 2 to State 3, or from State 8 to State 9. From State 3, in turn, it may move to States 2, 4, 5, or 8 via epsilon transitions. As these are exactly the states already in *B*, we create a self-loop in the DFA. Given a ., on the other hand, the original NFA may move from State 5 to State 6, or from State 9 to State 10. From State 10, in turn, it may move to States 11, 12, or 14 via epsilon transitions. We therefore create DFA State *D* as shown, with a transition on . from *B* to *D*. State *D* is marked as final because it contains state 14 of the original NFA. That is, given input *d*., there exists a path from the start state to the end state of the original NFA. Continuing our enumeration of state sets, we end up creating three more, labeled *E*, *F*, and *G* in Figure 2.9. Like State *D*, these all contain State 14 of the original NFA, and thus are marked as final. ■

In our example, the DFA ends up being smaller than the NFA, but this is only because our regular language is so simple. In theory, the number of states in the DFA may be exponential in the number of states in the NFA, but this extreme is also uncommon in practice. For a programming language scanner, the DFA tends to be larger than the NFA, but not outlandishly so. We consider space complexity in more detail in Section C-2.4.1.

Minimizing the DFA

EXAMPLE 2.15
Minimal DFA for d*(.d | d.) d*

Starting from a regular expression, we have now constructed an equivalent DFA. Though this DFA has seven states, a bit of thought suggests that a smaller one should exist. In particular, once we have seen both a *d* and a ., the only valid transitions are on *d*, and we ought to be able to make do with a single final state.

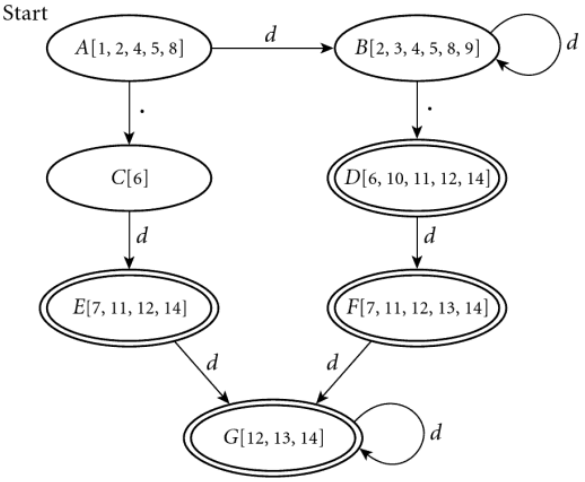


Figure 2.9 **A DFA equivalent to the NFA at the bottom of Figure 2.8.** Each state of the DFA represents the *set* of states that the NFA could be in after seeing the same input.

We can formalize this intuition, allowing us to apply it to any DFA, via the following inductive construction.

Initially we place the states of the (not necessarily minimal) DFA into two equivalence classes: final states and nonfinal states. We then repeatedly search for an equivalence class $\mathcal{X}$ and an input symbol c such that when given c as input, the states in $\mathcal{X}$ make transitions to states in $k > 1$ different equivalence classes. We then partition $\mathcal{X}$ into k classes in such a way that all states in a given new class would move to a member of the same old class on c. When we are unable to find a class to partition in this fashion we are done.

In our example, the original placement puts States *D*, *E*, *F*, and *G* in one class (final states) and States *A*, *B*, and *C* in another, as shown in the upper left of Figure 2.10. Unfortunately, the start state has ambiguous transitions on both *d* and . . To address the *d* ambiguity, we split *ABC* into *AB* and *C*, as shown in the upper right. New State *AB* has a self-loop on *d*; new State *C* moves to State *DEFG*. State *AB* still has an ambiguity on ., however, which we resolve by splitting it into States *A* and *B*, as shown at the bottom of the figure. At this point there are no further ambiguities, and we are left with a four-state minimal DFA. ■

2.2.2 Scanner Code

We can implement a scanner that explicitly captures the "circles-and-arrows" structure of a DFA in either of two main ways. One embeds the automaton in the control flow of the program using gotos or nested case (switch) statements; the other, described in the following subsection, uses a table and a driver. As a general rule, handwritten automata tend to use nested case statements, while

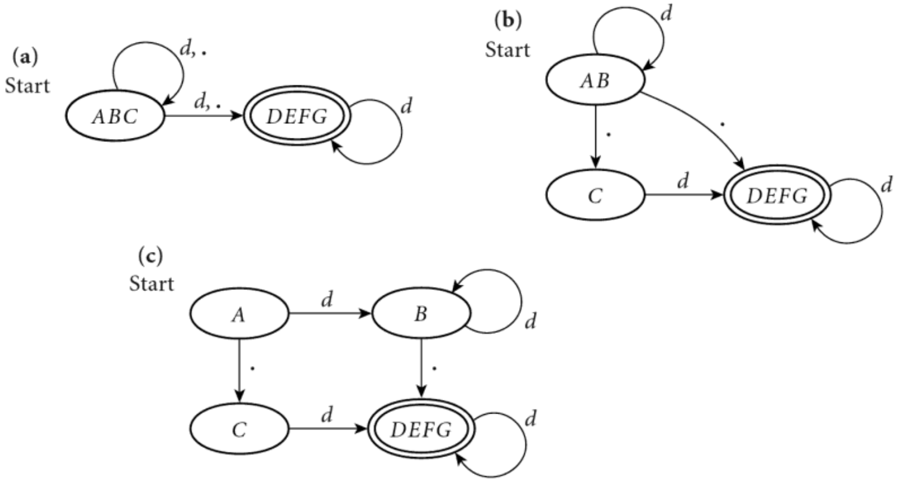


Figure 2.10 **Minimization of the DFA of Figure 2.9.** In each step we split a set of states to eliminate a transition ambiguity.

most automatically generated automata use tables. Tables are hard to create by hand, but easier than code to create from within a program. Likewise, nested case statements are easier to write and to debug than the ad hoc approach of Figure 2.5, if not quite as efficient. Unix's `lex/flex` tool produces C language output containing tables and a customized driver.

EXAMPLE 2.16

Nested case **statement automaton**

The nested case statement style of automaton has the following general structure:

```
state := 1                    –– start state
loop
    read cur_char
    case state of
        1 : case cur_char of
                ‘ ’, ‘\t’, ‘\n’ :  . . .
                ‘a’. . . ‘z’ :     . . .
                ‘0’. . . ‘9’ :     . . .
                ‘>’ :              . . .
                . . .
        2 : case cur_char of
                . . .
            . . .
        n: case cur_char of
                . . .
```

The outer case statement covers the states of the finite automaton. The inner case statements cover the transitions out of each state. Most of the inner clauses simply set a new state. Some return from the scanner with the current token. (If the current character should not be part of that token, it is pushed back onto the input stream before returning.) ■

Two aspects of the code typically deviate from the strict form of a formal finite automaton. One is the handling of keywords. The other is the need to peek ahead when a token can validly be extended by two or more additional characters, but not by only one.

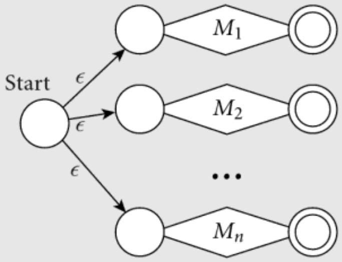
As noted at the beginning of Section 2.1.1, keywords in most languages look just like identifiers, but are reserved for a special purpose (some authors use the term *reserved word* instead of keyword). It is possible to write a finite automaton that distinguishes between keywords and identifiers, but it requires a *lot* of states (see Exercise 2.3). Most scanners, both handwritten and automatically generated, therefore treat keywords as "exceptions" to the rule for identifiers. Before return-

DESIGN & IMPLEMENTATION

2.4 Recognizing multiple kinds of token

One of the chief ways in which a scanner differs from a formal DFA is that it *identifies* tokens in addition to recognizing them. That is, it not only determines whether characters constitute a valid token; it also indicates *which one.* In practice, this means that it must have separate final states for every kind of token. We glossed over this issue in our RE-to-DFA constructions.

To build a scanner for a language with n different kinds of tokens, we begin with an NFA of the sort suggested in the figure here. Given NFAs $M_i, 1 \leq i \leq n$ (one automaton for each kind of token), we create a new start state with epsilon transitions to the start states of the M_is. In contrast to the alternation construction of Figure 2.7(c), however, we do *not* create a single final state; we keep the existing ones, each labeled by the token for which it is final. We then apply the NFA-to-DFA construction as before. (If final states for different tokens in the NFA ever end up in the same state of the DFA, then we have ambiguous token definitions. These may be resolved by changing the regular expressions from which the NFAs were derived, or by wrapping additional logic around the DFA.)



In the DFA minimization construction, instead of starting with two equivalence classes (final and nonfinal states), we begin with $n + 1$, including a separate class for final states for each of the kinds of token. Exercise 2.5 explores this construction for a scanner that recognizes both the *integer* and *decimal* types of Example 2.3.

ing an identifier to the parser, the scanner looks it up in a hash table or trie (a tree of branching paths) to make sure it isn't really a keyword.[10]

EXAMPLE 2.17

The nontrivial prefix problem

Whenever one legitimate token is a prefix of another, the "longest possible token" rule says that we should continue scanning. If some of the intermediate strings are not valid tokens, however, we can't tell whether a longer token is possible without looking more than one character ahead. This problem arises with dot characters (periods) in C. Suppose the scanner has just seen a `3` and has a dot coming up in the input. It needs to peek at characters beyond the dot in order to distinguish between `3.14` (a single token designating a real number), `3 . foo` (three tokens that the scanner should accept, even though the parser will object to seeing them in that order), and `3 ... foo` (again not syntactically valid, but three separate tokens nonetheless). In general, upcoming characters that a scanner must examine in order to make a decision are known as its *look-ahead*. In Section 2.3 we will see a similar notion of look-ahead *tokens* in parsing.

EXAMPLE 2.18

Look-ahead in Fortran scanning

In messier languages, a scanner may need to look an arbitrary distance ahead. In Fortran IV, for example, `DO 5 I = 1,25` is the header of a loop (it executes the statements up to the one labeled `5` for values of `I` from 1 to 25), while `DO 5 I = 1.25` is an assignment statement that places the value `1.25` into the variable `DO5I`. Spaces are ignored in (pre-Fortran 90) Fortran input, even in the middle of variable names. Moreover, variables need not be declared, and the terminator for a `DO` loop is simply a label, which the parser can ignore. After seeing `DO`, the scanner cannot tell whether the `5` is part of the current token until it reaches the comma or dot. It has been widely (but apparently incorrectly) claimed that NASA's Mariner 1 space probe was lost due to accidental replacement of a comma with a dot in a case similar to this one in flight control software.[11] Dialects of Fortran starting with Fortran 77 allow (in fact encourage) the use of alternative

DESIGN & IMPLEMENTATION

2.5 Longest possible tokens

A little care in syntax design—avoiding tokens that are nontrivial prefixes of other tokens—can dramatically simplify scanning. In straightforward cases of prefix ambiguity, the scanner can enforce the "longest possible token" rule automatically. In Fortran, however, the rules are sufficiently complex that no purely lexical solution suffices. Some of the problems, and a possible solution, are discussed in an article by Dyadkin [Dya95].

[10] Many languages include *predefined* identifiers (e.g., for standard library functions), but these are not keywords. The programmer can redefine them, so the scanner must treat them the same as other identifiers. Contextual keywords, similarly, must be treated by the scanner as identifiers.

[11] In actuality, the faulty software for Mariner 1 appears to have stemmed from a missing "bar" punctuation mark (indicating an average) in handwritten notes from which the software was derived [Cer89, pp. 202–203]. The Fortran `DO` loop error does appear to have occurred in at least one piece of NASA software, but no serious harm resulted [Web89].

syntax for loop headers, in which an extra comma makes misinterpretation less likely: `DO 5,I = 1,25`. ■

In C, the dot character problem can easily be handled as a special case. In languages requiring larger amounts of look-ahead, the scanner can take a more general approach. In any case of ambiguity, it assumes that a longer token will be possible, but remembers that a shorter token could have been recognized at some point in the past. It also buffers all characters read beyond the end of the shorter token. If the optimistic assumption leads the scanner into an error state, it "unreads" the buffered characters so that they will be seen again later, and returns the shorter token.

2.2.3 Table-Driven Scanning

EXAMPLE 2.19
Table-driven scanning

In the preceding subsection we sketched how control flow—a loop and nested `case` statements—can be used to represent a finite automaton. An alternative approach represents the automaton as a data structure: a two-dimensional *transition table*. A driver program (Figure 2.11) uses the current state and input character to index into the table. Each entry in the table specifies whether to move to a new state (and if so, which one), return a token, or announce an error. A second table indicates, for each state, whether we might be at the end of a token (and if so, which one). Separating this second table from the first allows us to notice when we pass a state that might have been the end of a token, so we can back up if we hit an error state. Example tables for our calculator tokens appear in Figure 2.12.

Like a handwritten scanner, the table-driven code of Figure 2.11 looks tokens up in a table of keywords immediately before returning. An outer loop serves to filter out comments and "white space"—spaces, tabs, and newlines. ■

2.2.4 Lexical Errors

The code in Figure 2.11 explicitly recognizes the possibility of *lexical errors*. In some cases the next character of input may be neither an acceptable continuation of the current token nor the start of another token. In such cases the scanner must print an error message and perform some sort of recovery so that compilation can continue, if only to look for additional errors. Fortunately, lexical errors are relatively rare—most character sequences do correspond to token sequences—and relatively easy to handle. The most common approach is simply to (1) throw away the current, invalid token; (2) skip forward until a character is found that can legitimately begin a new token; (3) restart the scanning algorithm; and (4) count on the error-recovery mechanism of the parser to cope with any cases in which the resulting sequence of tokens is not syntactically valid. Of course the need for error recovery is not unique to table-driven scanners; any scanner must cope with errors. We did not show the code in Figure 2.5, but it would have to be there in practice.

```
state = 0 . . number_of_states
token = 0 . . number_of_tokens
scan_tab : array [char, state] of record
    action : (move, recognize, error)
    new_state : state
token_tab : array [state] of token          –– what to recognize
keyword_tab : set of record
    k_image : string
    k_token : token
–– these three tables are created by a scanner generator tool

tok : token
cur_char : char
remembered_chars : list of char
repeat
    cur_state : state := start_state
    image : string := null
    remembered_state : state := 0          –– none
    loop
        read cur_char
        case scan_tab[cur_char, cur_state].action
            move:
                if token_tab[cur_state] $\ne$ 0
                    –– this could be a final state
                    remembered_state := cur_state
                    remembered_chars := $\epsilon$
                add cur_char to remembered_chars
                cur_state := scan_tab[cur_char, cur_state].new_state
            recognize:
                tok := token_tab[cur_state]
                unread cur_char          –– push back into input stream
                exit inner loop
            error:
                if remembered_state $\ne$ 0
                    tok := token_tab[remembered_state]
                    unread remembered_chars
                    remove remembered_chars from image
                    exit inner loop
                –– else print error message and recover; probably start over
        append cur_char to image
    –– end inner loop
until tok $\notin$ {white_space, comment}
look image up in keyword_tab and replace tok with appropriate keyword if found
return ⟨tok, image⟩
```

Figure 2.11 **Driver for a table-driven scanner,** with code to handle the ambiguous case in which one valid token is a prefix of another, but some intermediate string is not.

						Current input character								
State	*space, tab*	*newline*	/	*	(	)	+	–	:	=	.	*digit*	*letter*	*other*	
1	17	17	2	10	6	7	8	9	11	–	13	14	16	–	
2	–	–	3	4	–	–	–	–	–	–	–	–	–	–	div
3	3	18	3	3	3	3	3	3	3	3	3	3	3	3	
4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	
5	4	4	18	5	4	4	4	4	4	4	4	4	4	4	
6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	lparen
7	–	–	–	–	–	–	–	–	–	–	–	–	–	–	rparen
8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	plus
9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	minus
10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	times
11	–	–	–	–	–	–	–	–	–	12	–	–	–	–	
12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	assign
13	–	–	–	–	–	–	–	–	–	–	–	15	–	–	
14	–	–	–	–	–	–	–	–	–	–	15	14	–	–	number
15	–	–	–	–	–	–	–	–	–	–	–	15	–	–	number
16	–	–	–	–	–	–	–	–	–	–	–	16	16	–	identifier
17	17	17	–	–	–	–	–	–	–	–	–	–	–	–	white_space
18	–	–	–	–	–	–	–	–	–	–	–	–	–	–	comment

Figure 2.12 **Scanner tables for the calculator language.** These could be used by the code of Figure 2.11. States are numbered as in Figure 2.6, except for the addition of two states—17 and 18—to "recognize" white space and comments. The right-hand column represents table token_tab; the rest of the figure is scan_tab. Numbers in the table indicate an entry for which the corresponding action is move. Dashes appear where there is no way to extend the current token: if the corresponding entry in token_tab is nonempty, then action is recognize; otherwise, action is error. Table keyword_tab (not shown) contains the strings `read` and `write`.

The code in Figure 2.11 also shows that the scanner must return both the kind of token found and its character-string image (spelling); again this requirement applies to all types of scanners. For some tokens the character-string image is redundant: all semicolons look the same, after all, as do all `while` keywords. For other tokens, however (e.g., identifiers, character strings, and numeric constants), the image is needed for semantic analysis. It is also useful for error messages: "undeclared identifier" is not as nice as "`foo` has not been declared."

2.2.5 Pragmas

Some languages and language implementations allow a program to contain constructs called *pragmas* that provide directives or hints to the compiler. Pragmas that do not change program semantics—only the compilation process—are sometimes called *significant comments*. In some languages the name is also appropriate because, like comments, pragmas can appear anywhere in the source program. In this case they are usually processed by the scanner: allowing them anywhere in the grammar would greatly complicate the parser. In most languages, however, pragmas are permitted only at certain well-defined places in the grammar. In this case they are best processed by the parser or semantic analyzer.

Pragmas that serve as directives may

- Turn various kinds of run-time checks (e.g., pointer or subscript checking) on or off
- Turn certain code improvements on or off (e.g., on in inner loops to improve performance; off otherwise to improve compilation speed)
- Enable or disable performance profiling (statistics gathering to identify program bottlenecks)

Some directives "cross the line" and change program semantics. In Ada, for example, the `unchecked` pragma can be used to disable type checking. In OpenMP, which we will consider in Chapter 13, pragmas specify significant parallel extensions to Fortran, C and C++: creating, scheduling, and synchronizing threads. In this case the principal rationale for expressing the extensions as pragmas rather than more deeply integrated changes is to sharply delineate the boundary between the core language and the extensions, and to share a common set of extensions across languages.

Pragmas that serve (merely) as hints provide the compiler with information about the source program that may allow it to do a better job:

- Variable `x` is very heavily used (it may be a good idea to keep it in a register).
- Subroutine `F` is a pure function: its only effect on the rest of the program is the value it returns.
- Subroutine `S` is not (indirectly) recursive (its storage may be statically allocated).
- 32 bits of precision (instead of 64) suffice for floating-point variable `x`.

The compiler may ignore these in the interest of simplicity, or in the face of contradictory information.

Standard syntax for pragmas was introduced in C++11 (where they are known as "attributes"). A function that prints an error message and terminates execution, for example, can be labeled `[[noreturn]]`, to allow the compiler to optimize code around calls, or to issue more helpful error or warning messages. As of this writing, the set of supported attributes can be extended by vendors (by modifying the compiler), but not by ordinary programmers. The extent to which these attributes should be limited to hints (rather than directives) has been somewhat controversial. New pragmas in Java (which calls them "annotations") and C# (which calls them "attributes") *can* be defined by the programmer; we will return to these in Section 16.3.1.

CHECK YOUR UNDERSTANDING

10. List the tasks performed by the typical scanner.
11. What are the advantages of an automatically generated scanner, in comparison to a handwritten one? Why do many commercial compilers use a handwritten scanner anyway?
12. Explain the difference between deterministic and nondeterministic finite automata. Why do we prefer the deterministic variety for scanning?
13. Outline the constructions used to turn a set of regular expressions into a minimal DFA.
14. What is the "longest possible token" rule?
15. Why must a scanner sometimes "peek" at upcoming characters?
16. What is the difference between a *keyword* and an *identifier*?
17. Why must a scanner save the text of tokens?
18. How does a scanner identify lexical errors? How does it respond?
19. What is a *pragma*?

2.3 Parsing

The parser is the heart of a typical compiler. It calls the scanner to obtain the tokens of the input program, assembles the tokens together into a syntax tree, and passes the tree (perhaps one subroutine at a time) to the later phases of the compiler, which perform semantic analysis and code generation and improvement. In effect, the parser is "in charge" of the entire compilation process; this style of compilation is sometimes referred to as *syntax-directed translation*.

As noted in the introduction to this chapter, a context-free grammar (CFG) is a *generator* for a CF language. A parser is a language *recognizer*. It can be shown that for any CFG we can create a parser that runs in $O(n^3)$ time, where n is the length of the input program.[12] There are two well-known parsing algorithms that achieve this bound: Earley's algorithm [Ear70] and the Cocke-Younger-Kasami (CYK) algorithm [Kas65, You67]. Cubic time is much too slow for parsing sizable programs, but fortunately not all grammars require such a general and slow parsing algorithm. There are large classes of grammars for which we can build parsers that run in linear time. The two most important of these classes are called LL and LR (Figure 2.13).

[12] In general, an algorithm is said to run in time $O(f(n))$, where n is the length of the input, if its running time $t(n)$ is proportional to $f(n)$ in the worst case. More precisely, we say $t(n) = O(f(n)) \iff \exists\, c, m\, [n > m \longrightarrow t(n) < cf(n)]$.

Class	Direction of scanning	Derivation discovered	Parse tree construction	Algorithm used
LL	left-to-right	left-most	top-down	predictive
LR	left-to-right	right-most	bottom-up	shift-reduce

Figure 2.13 Principal classes of linear-time parsing algorithms.

LL stands for "Left-to-right, Left-most derivation." LR stands for "Left-to-right, Right-most derivation." In both classes the input is read left-to-right, and the parser attempts to discover (construct) a derivation of that input. For LL parsers, the derivation will be left-most; for LR parsers, right-most. We will cover LL parsers first. They are generally considered to be simpler and easier to understand. They can be written by hand or generated automatically from an appropriate grammar by a parser-generating tool. The class of LR grammars is larger (i.e., more grammars are LR than LL), and some people find the structure of the LR grammars more intuitive, especially in the handling of arithmetic expressions. LR parsers are almost always constructed by a parser-generating tool. Both classes of parsers are used in production compilers, though LR parsers are more common.

LL parsers are also called "top-down," or "predictive" parsers. They construct a parse tree from the root down, predicting at each step which production will be used to expand the current node, based on the next available token of input. LR parsers are also called "bottom-up" parsers. They construct a parse tree from the leaves up, recognizing when a collection of leaves or other nodes can be joined together as the children of a single parent.

EXAMPLE 2.20
Top-down and bottom-up parsing

We can illustrate the difference between top-down and bottom-up parsing by means of a simple example. Consider the following grammar for a comma-separated list of identifiers, terminated by a semicolon:

id_list ⟶ `id` *id_list_tail*
id_list_tail ⟶ `, id` *id_list_tail*
id_list_tail ⟶ `;`

These are the productions that would normally be used for an identifier list in a top-down parser. They can also be parsed bottom-up (most top-down grammars can be). In practice they would not be used in a bottom-up parser, for reasons that will become clear in a moment, but the ability to handle them either way makes them good for this example.

Progressive stages in the top-down and bottom-up construction of a parse tree for the string `A, B, C;` appear in Figure 2.14. The top-down parser begins by predicting that the root of the tree (*id_list*) will expand to `id` *id_list_tail*. It then matches the `id` against a token obtained from the scanner. (If the scanner produced something different, the parser would announce a syntax error.) The parser then moves down into the first (in this case only) nonterminal child and predicts that *id_list_tail* will expand to `, id` *id_list_tail*. To make this prediction it needs

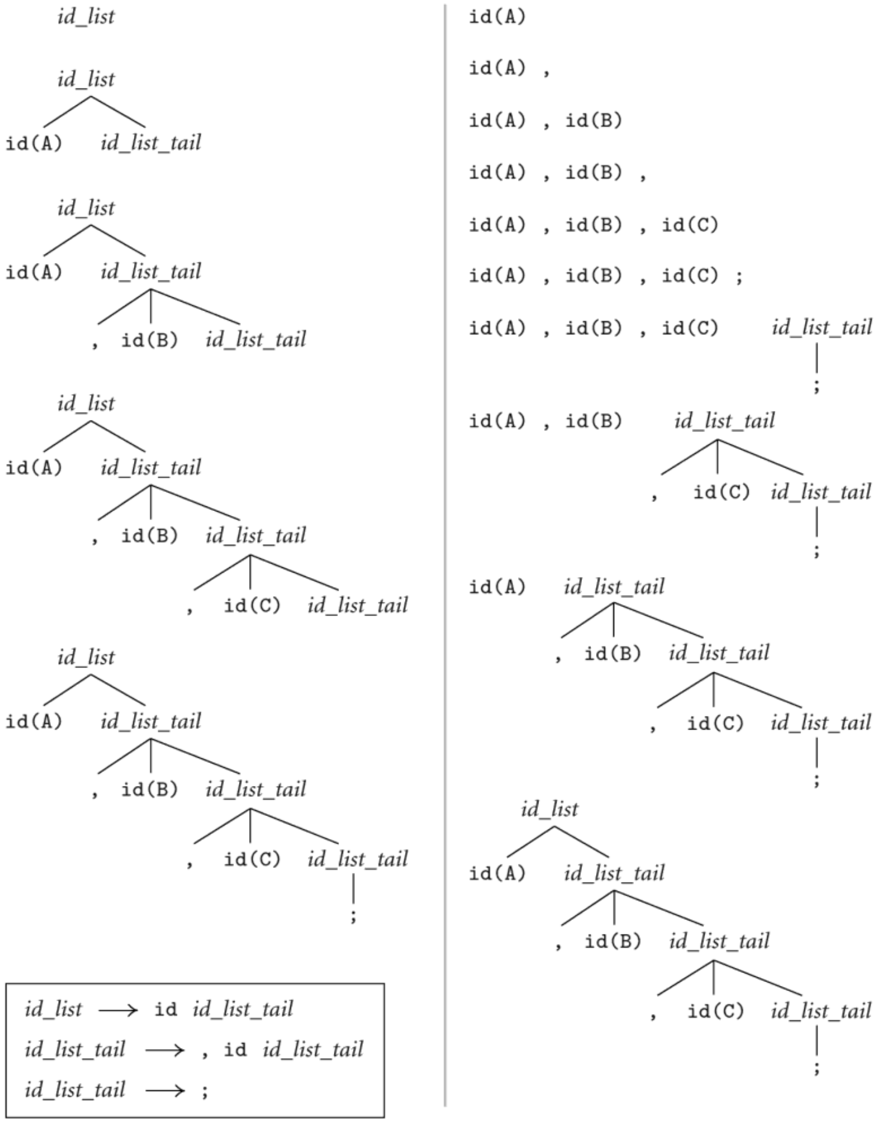


Figure 2.14 **Top-down (*left*) and bottom-up parsing (*right*)** of the input string `A, B, C;`. Grammar appears at lower left.

to peek at the upcoming token (a comma), which allows it to choose between the two possible expansions for *id_list_tail*. It then matches the comma and the `id` and moves down into the next *id_list_tail*. In a similar, recursive fashion, the top-down parser works down the tree, left-to-right, predicting and expanding nodes and tracing out a left-most derivation of the fringe of the tree.

The bottom-up parser, by contrast, begins by noting that the left-most leaf of the tree is an `id`. The next leaf is a comma and the one after that is another `id`. The parser continues in this fashion, shifting new leaves from the scanner into a forest of partially completed parse tree fragments, until it realizes that some of those fragments constitute a complete right-hand side. In this grammar, that doesn't occur until the parser has seen the semicolon—the right-hand side of *id_list_tail* ⟶ `;` . With this right-hand side in hand, the parser reduces the semicolon to an *id_list_tail*. It then reduces `, id` *id_list_tail* into another *id_list_tail*. After doing this one more time it is able to reduce `id` *id_list_tail* into the root of the parse tree, *id_list*.

At no point does the bottom-up parser predict what it will see next. Rather, it shifts tokens into its forest until it recognizes a right-hand side, which it then reduces to a left-hand side. Because of this behavior, bottom-up parsers are sometimes called *shift-reduce* parsers. Moving up the figure, from bottom to top, we can see that the shift-reduce parser traces out a right-most derivation, in reverse. Because bottom-up parsers were the first to receive careful formal study, right-most derivations are sometimes called *canonical*. ■

There are several important subclasses of LR parsers, including SLR, LALR, and "full LR." SLR and LALR are important for their ease of implementation, full LR for its generality. LL parsers can also be grouped into SLL and "full LL" subclasses. We will cover the differences among them only briefly here; for further information see any of the standard compiler-construction or parsing theory textbooks [App97, ALSU07, AU72, CT04, FCL10, GBJ$^+$12].

One commonly sees LL or LR (or whatever) written with a number in parentheses after it: LL(2) or LALR(1), for example. This number indicates how many tokens of look-ahead are required in order to parse. Most real compilers use just one token of look-ahead, though more can sometimes be helpful. The open-source ANTLR tool, in particular, uses multitoken look-ahead to enlarge the class of languages amenable to top-down parsing [PQ95]. In Section 2.3.1 we will look at LL(1) grammars and handwritten parsers in more detail. In Sections 2.3.3 and 2.3.4 we will consider automatically generated LL(1) and LR(1) (actually SLR(1)) parsers.

EXAMPLE 2.21
Bounding space with a bottom-up grammar

The problem with our example grammar, for the purposes of bottom-up parsing, is that it forces the compiler to shift all the tokens of an *id_list* into its forest before it can reduce any of them. In a very large program we might run out of space. Sometimes there is nothing that can be done to avoid a lot of shifting. In this case, however, we can use an alternative grammar that allows the parser to reduce prefixes of the *id_list* into nonterminals as it goes along:

id_list ⟶ *id_list_prefix* `;`
id_list_prefix ⟶ *id_list_prefix* `, id`
⟶ `id`

This grammar cannot be parsed top-down, because when we see an `id` on the input and we're expecting an *id_list_prefix*, we have no way to tell which of the two

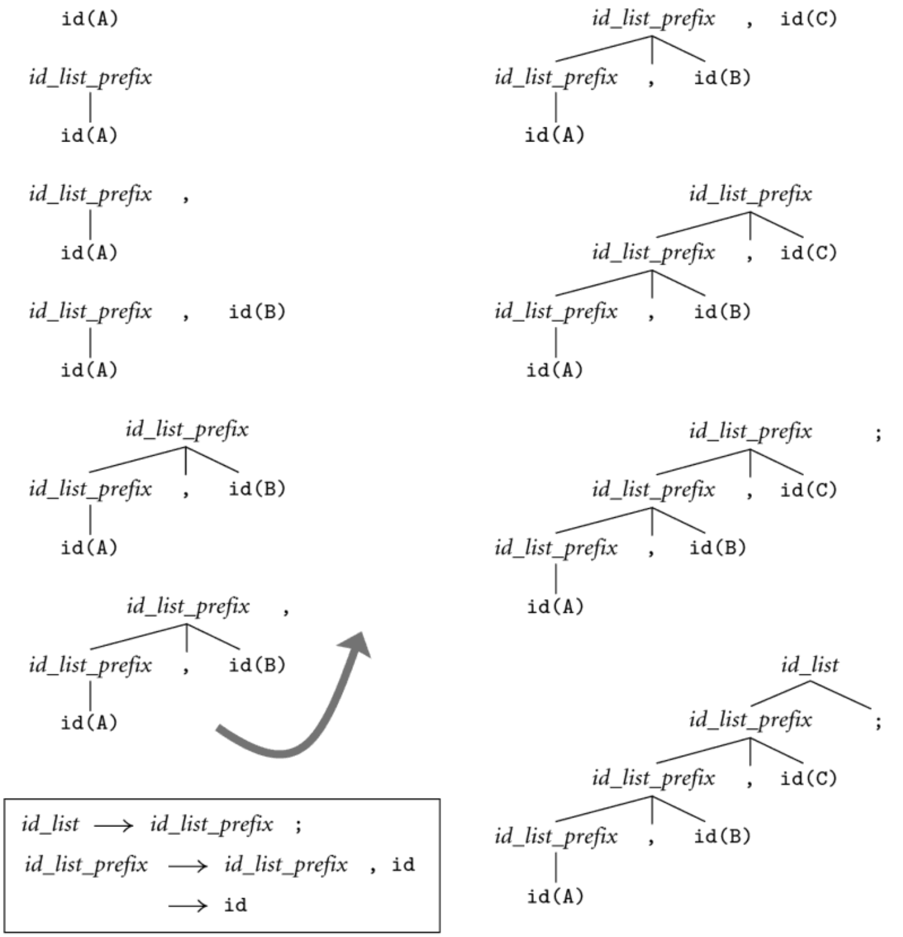


Figure 2.15 Bottom-up parse of `A, B, C;` using a grammar (lower left) that allows lists to be collapsed incrementally.

possible productions we should predict (more on this dilemma in Section 2.3.2). As shown in Figure 2.15, however, the grammar works well bottom-up. ■

2.3.1 Recursive Descent

EXAMPLE 2.22
Top-down grammar for a calculator language

To illustrate top-down (predictive) parsing, let us consider the grammar for a simple "calculator" language, shown in Figure 2.16. The calculator allows values to be read into named variables, which may then be used in expressions. Expressions in turn may be written to the output. Control flow is strictly linear (no loops, `if` statements, or other jumps). In a pattern that will repeat in many of our examples, we have included an initial *augmenting* production, *program* ⟶ *stmt_list* `$$`,

program ⟶ *stmt_list* `$$`
stmt_list ⟶ *stmt stmt_list* | ϵ
stmt ⟶ `id := ` *expr* | `read id` | `write` *expr*
expr ⟶ *term term_tail*
term_tail ⟶ *add_op term term_tail* | ϵ
term ⟶ *factor factor_tail*
factor_tail ⟶ *mult_op factor factor_tail* | ϵ
factor ⟶ `(` *expr* `)` | `id` | `number`
add_op ⟶ `+` | `-`
mult_op ⟶ `*` | `/`

Figure 2.16 LL(1) grammar for a simple calculator language.

which arranges for the "real" body of the program (*stmt_list*) to be followed by a special *end marker* token, `$$`. The end marker is produced by the scanner at the end of the input. Its presence allows the parser to terminate cleanly once it has seen the entire program, and to decline to accept programs with extra garbage tokens at the end. As in regular expressions, we use the symbol ϵ to denote the empty string. A production with ϵ on the right-hand side is sometimes called an *epsilon production*.

It may be helpful to compare the *expr* portion of Figure 2.16 to the expression grammar of Example 2.8. Most people find that previous, LR grammar to be significantly more intuitive. It suffers, however, from a problem similar to that of the *id_list* grammar of Example 2.21: if we see an `id` on the input when expecting an *expr*, we have no way to tell which of the two possible productions to predict. The grammar of Figure 2.16 avoids this problem by merging the common prefixes of right-hand sides into a single production, and by using new symbols (*term_tail* and *factor_tail*) to generate additional operators and operands as required. The transformation has the unfortunate side effect of placing the operands of a given operator in separate right-hand sides. In effect, we have sacrificed grammatical elegance in order to be able to parse predictively.

So how do we parse a string with our calculator grammar? We saw the basic idea in Figure 2.14. We start at the top of the tree and predict needed productions on the basis of the current left-most nonterminal in the tree and the current input token. We can formalize this process in one of two ways. The first, described in the remainder of this subsection, is to build a *recursive descent parser* whose subroutines correspond, one-one, to the nonterminals of the grammar. Recursive descent parsers are typically constructed by hand, though the ANTLR parser generator constructs them automatically from an input grammar. The second approach, described in Section 2.3.3, is to build an *LL parse table* which is then read by a driver program. Table-driven parsers are almost always constructed automatically by a parser generator. These two options—recursive descent and table-driven—are reminiscent of the nested `case` statements and table-driven approaches to building a scanner that we saw in Sections 2.2.2 and 2.2.3. It should be emphasized that they implement the same basic parsing algorithm.

Handwritten recursive descent parsers are most often used when the language to be parsed is relatively simple, or when a parser-generator tool is not available. There are exceptions, however. In particular, recursive descent appears in recent versions of the GNU compiler collection (`gcc`). Earlier versions used `bison` to create a bottom-up parser automatically. The change was made in part for performance reasons and in part to enable the generation of higher-quality syntax error messages. (The `bison` code was easier to write, and arguably easier to maintain.)

EXAMPLE 2.23

Recursive descent parser for the calculator language

Pseudocode for a recursive descent parser for our calculator language appears in Figure 2.17. It has a subroutine for every nonterminal in the grammar. It also has a mechanism input_token to inspect the next token available from the scanner and a subroutine (match) to consume and update this token, and in the process verify that it is the one that was expected (as specified by an argument). If match or any of the other subroutines sees an unexpected token, then a syntax error has occurred. For the time being let us assume that the parse_error subroutine simply prints a message and terminates the parse. In Section 2.3.5 we will consider how to recover from such errors and continue to parse the remainder of the input.

EXAMPLE 2.24

Recursive descent parse of a "sum and average" program

Suppose now that we are to parse a simple program to read two numbers and print their sum and average:

```
read A
read B
sum := A + B
write sum
write sum / 2
```

The parse tree for this program appears in Figure 2.18. The parser begins by calling the subroutine program. After noting that the initial token is a `read`, program calls stmt_list and then attempts to match the end-of-file pseudotoken. (In the parse tree, the root, *program*, has two children, *stmt_list* and `$$`.) Procedure stmt_list again notes that the upcoming token is a `read`. This observation allows it to determine that the current node (*stmt_list*) generates *stmt stmt_list* (rather than ϵ). It therefore calls stmt and stmt_list before returning. Continuing in this fashion, the execution path of the parser traces out a left-to-right depth-first traversal of the parse tree. This correspondence between the dynamic execution trace and the structure of the parse tree is the distinguishing characteristic of recursive descent parsing. Note that because the *stmt_list* nonterminal appears in the right-hand side of a *stmt_list* production, the stmt_list subroutine must call itself. This recursion accounts for the name of the parsing technique.

Without additional code (not shown in Figure 2.17), the parser merely verifies that the program is syntactically correct (i.e., that none of the otherwise parse_error clauses in the case statements are executed and that match always sees what it expects to see). To be of use to the rest of the compiler—which must produce an equivalent target program in some other language—the parser must

```
procedure match(expected)
    if input_token = expected then consume_input_token()
    else parse_error

–– this is the start routine:
procedure program()
    case input_token of
        id, read, write, $$ :
            stmt_list()
            match($$)
        otherwise parse_error

procedure stmt_list()
    case input_token of
        id, read, write : stmt(); stmt_list()
        $$ : skip        –– epsilon production
        otherwise parse_error

procedure stmt()
    case input_token of
        id : match(id); match(:=); expr()
        read : match(read); match(id)
        write : match(write); expr()
        otherwise parse_error

procedure expr()
    case input_token of
        id, number, ( : term(); term_tail()
        otherwise parse_error

procedure term_tail()
    case input_token of
        +, - : add_op(); term(); term_tail()
        ), id, read, write, $$ :
            skip        –– epsilon production
        otherwise parse_error

procedure term()
    case input_token of
        id, number, ( : factor(); factor_tail()
        otherwise parse_error
```

Figure 2.17 **Recursive descent parser for the calculator language.** Execution begins in procedure program. The recursive calls trace out a traversal of the parse tree. Not shown is code to save this tree (or some similar structure) for use by later phases of the compiler. *(continued)*

```
procedure factor_tail()
    case input_token of
        *, / : mult_op(); factor(); factor_tail()
        +, -, ), id, read, write, $$ :
            skip        -- epsilon production
        otherwise parse_error

procedure factor()
    case input_token of
        id : match(id)
        number : match(number)
        ( : match((); expr(); match())
        otherwise parse_error

procedure add_op()
    case input_token of
        + : match(+)
        - : match(-)
        otherwise parse_error

procedure mult_op()
    case input_token of
        * : match(*)
        / : match(/)
        otherwise parse_error
```

Figure 2.17 *(continued)*

save the parse tree or some other representation of program fragments as an explicit data structure. To save the parse tree itself, we can allocate and link together records to represent the children of a node immediately before executing the recursive subroutines and match invocations that represent those children. We shall need to pass each recursive routine an argument that points to the record that is to be expanded (i.e., whose children are to be discovered). Procedure match will also need to save information about certain tokens (e.g., character-string representations of identifiers and literals) in the leaves of the tree.

As we saw in Chapter 1, the parse tree contains a great deal of irrelevant detail that need not be saved for the rest of the compiler. It is therefore rare for a parser to construct a full parse tree explicitly. More often it produces an abstract syntax tree or some other more terse representation. In a recursive descent compiler, a syntax tree can be created by allocating and linking together records in only a subset of the recursive calls.

The trickiest part of writing a recursive descent parser is figuring out which tokens should label the arms of the case statements. Each arm represents one production: one possible expansion of the symbol for which the subroutine was named. The tokens that label a given arm are those that *predict* the production. A token X may predict a production for either of two reasons: (1) the right-hand

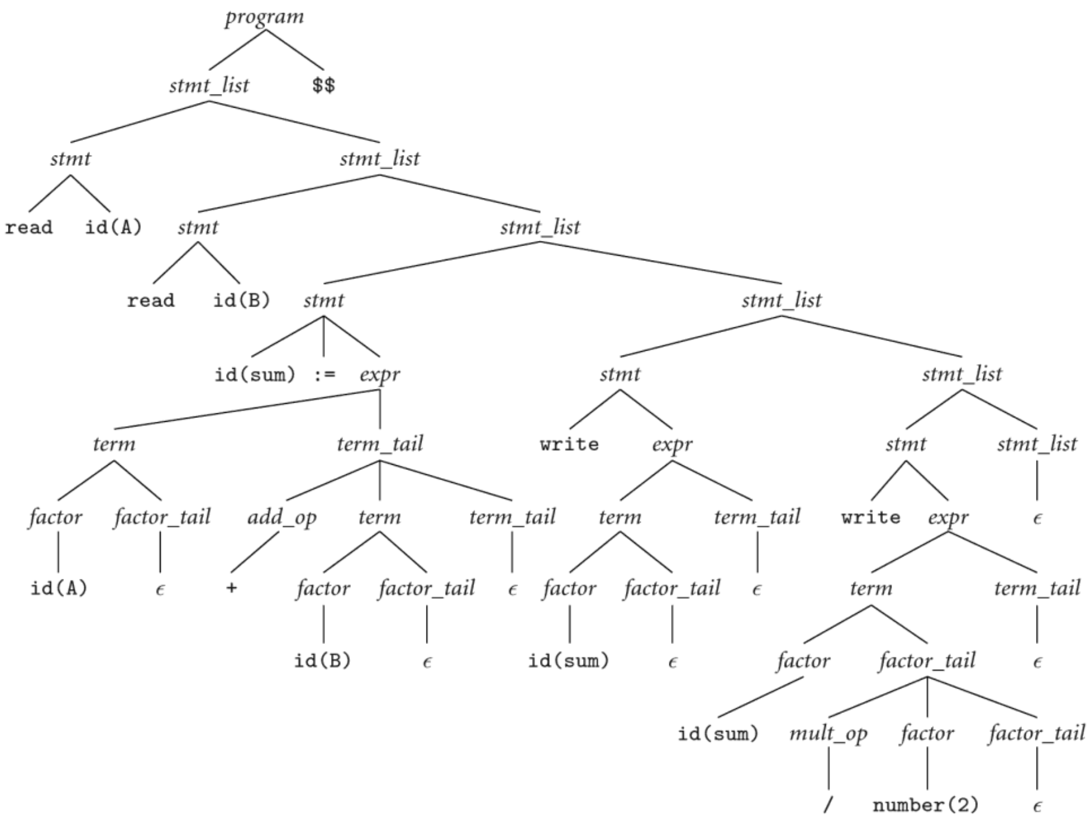


Figure 2.18 Parse tree for the sum-and-average program of Example 2.24, using the grammar of Figure 2.16.

side of the production, when recursively expanded, may yield a string beginning with X, or (2) the right-hand side may yield nothing (i.e., it is ϵ, or a string of nonterminals that may recursively yield ϵ), and X may begin the yield of what comes *next*. We will formalize this notion of prediction in Section 2.3.3, using sets called FIRST and FOLLOW, and show how to derive them automatically from an LL(1) CFG.

✓ **CHECK YOUR UNDERSTANDING**

20. What is the inherent "big-O" complexity of parsing? What is the complexity of parsers used in real compilers?

21. Summarize the difference between LL and LR parsing. Which one of them is also called "bottom-up"? "Top-down"? Which one is also called "predictive"? "Shift-reduce"? What do "LL" and "LR" stand for?

22. What kind of parser (top-down or bottom-up) is most common in production compilers?

23. Why are right-most derivations sometimes called *canonical*?

24. What is the significance of the "1" in LR(1)?

25. Why might we want (or need) different grammars for different parsing algorithms?

26. What is an *epsilon production*?

27. What are *recursive descent* parsers? Why are they used mostly for small languages?

28. How might a parser construct an explicit parse tree or syntax tree?

2.3.2 Writing an LL(1) Grammar

When designing a recursive-descent parser, one has to acquire a certain facility in writing and modifying LL(1) grammars. The two most common obstacles to "LL(1)-ness" are *left recursion* and *common prefixes*.

EXAMPLE 2.25
Left recursion

A grammar is said to be left recursive if there is a nonterminal A such that $A \Longrightarrow^{+} A\ \alpha$ for some α.[13] The trivial case occurs when the first symbol on the right-hand side of a production is the same as the symbol on the left-hand side. Here again is the grammar from Example 2.21, which cannot be parsed top-down:

$$
\begin{aligned}
\textit{id\_list} &\longrightarrow \textit{id\_list\_prefix}\ \texttt{;}\\
\textit{id\_list\_prefix} &\longrightarrow \textit{id\_list\_prefix}\ \texttt{,}\ \texttt{id}\\
&\longrightarrow \texttt{id}
\end{aligned}
$$

The problem is in the second and third productions; in the *id_list_prefix* parsing routine, with `id` on the input, a predictive parser cannot tell which of the productions it should use. (Recall that left recursion is *desirable* in bottom-up grammars, because it allows recursive constructs to be discovered incrementally, as in Figure 2.15.) ■

EXAMPLE 2.26
Common prefixes

Common prefixes occur when two different productions with the same left-hand side begin with the same symbol or symbols. Here is an example that commonly appears in languages descended from Algol:

[13] Following conventional notation, we use uppercase Roman letters near the beginning of the alphabet to represent nonterminals, uppercase Roman letters near the end of the alphabet to represent arbitrary grammar symbols (terminals or nonterminals), lowercase Roman letters near the beginning of the alphabet to represent terminals (tokens), lowercase Roman letters near the end of the alphabet to represent token strings, and lowercase Greek letters to represent strings of arbitrary symbols.

stmt ⟶ `id := ` *expr*

⟶ `id (` *argument_list* `)` -- procedure call

With `id` at the beginning of both right-hand sides, we cannot choose between them on the basis of the upcoming token. ■

Both left recursion and common prefixes can be removed from a grammar mechanically. The general case is a little tricky (Exercise 2.25), because the prediction problem may be an indirect one (e.g., $S \longrightarrow A\ \alpha$ and $A \longrightarrow S\ \beta$, or $S \longrightarrow A\ \alpha$, $S \longrightarrow B\ \beta$, $A \Longrightarrow^* \texttt{c}\ \gamma$, and $B \Longrightarrow^* \texttt{c}\ \delta$). We can see the general idea in the examples above, however.

EXAMPLE 2.27
Eliminating left recursion

Our left-recursive definition of *id_list* can be replaced by the right-recursive variant we saw in Example 2.20:

id_list ⟶ `id` *id_list_tail*

id_list_tail ⟶ `, id` *id_list_tail*

id_list_tail ⟶ `;` ■

EXAMPLE 2.28
Left factoring

Our common-prefix definition of *stmt* can be made LL(1) by a technique called *left factoring*:

stmt ⟶ `id` *stmt_list_tail*

stmt_list_tail ⟶ `:=` *expr* | `(` *argument_list* `)` ■

Of course, simply eliminating left recursion and common prefixes is *not* guaranteed to make a grammar LL(1). There are infinitely many non-LL *languages*—languages for which no LL grammar exists—and the mechanical transformations to eliminate left recursion and common prefixes work on their grammars just fine. Fortunately, the few non-LL languages that arise in practice can generally be handled by augmenting the parsing algorithm with one or two simple heuristics.

EXAMPLE 2.29
Parsing a "dangling `else`"

The best known example of a "not quite LL" construct arises in languages like Pascal, in which the `else` part of an `if` statement is optional. The natural grammar fragment

stmt ⟶ `if` *condition then_clause else_clause* | *other_stmt*

then_clause ⟶ `then` *stmt*

else_clause ⟶ `else` *stmt* | ϵ

is ambiguous (and thus neither LL nor LR); it allows the `else` in `if` $\texttt{C}_1$ `then if` $\texttt{C}_2$ `then` $\texttt{S}_1$ `else` $\texttt{S}_2$ to be paired with either `then`. The less natural grammar fragment

stmt ⟶ *balanced_stmt* | *unbalanced_stmt*

balanced_stmt ⟶ `if` *condition* `then` *balanced_stmt* `else` *balanced_stmt*
| *other_stmt*

unbalanced_stmt ⟶ `if` *condition* `then` *stmt*
| `if` *condition* `then` *balanced_stmt* `else` *unbalanced_stmt*

can be parsed bottom-up but not top-down (there is *no* pure top-down grammar for Pascal else statements). A *balanced_stmt* is one with the same number of thens and elses. An *unbalanced_stmt* has more thens. ■

The usual approach, whether parsing top-down or bottom-up, is to use the ambiguous grammar together with a "disambiguating rule," which says that in the case of a conflict between two possible productions, the one to use is the one that occurs first, textually, in the grammar. In the ambiguous fragment above, the fact that *else_clause* ⟶ else *stmt* comes before *else_clause* ⟶ ϵ ends up pairing the else with the nearest then.

EXAMPLE 2.30

"Dangling else" program bug

Better yet, a language designer can avoid this sort of problem by choosing different syntax. The ambiguity of the *dangling else* problem in Pascal leads to problems not only in parsing, but in writing and maintaining correct programs. Most Pascal programmers at one time or another ended up writing a program like this one:

```
if P <> nil then
    if P^.val = goal then
        foundIt := true
else
    endOfList := true
```

Indentation notwithstanding, the Pascal manual states that an else clause matches the closest unmatched then—in this case the inner one—which is clearly not what the programmer intended. To get the desired effect, the Pascal programmer needed to write

```
if P <> nil then begin
    if P^.val = goal then
        foundIt := true
end
else
    endOfList := true
```

■

EXAMPLE 2.31

End markers for structured statements

Many other Algol-family languages (including Modula, Modula-2, and Oberon, all more recent inventions of Pascal's designer, Niklaus Wirth) require explicit *end markers* on all structured statements. The grammar fragment for if statements in Modula-2 looks something like this:

DESIGN & IMPLEMENTATION

2.6 The dangling else

A simple change in language syntax—eliminating the dangling else—not only reduces the chance of programming errors, but also significantly simplifies parsing. For more on the dangling else problem, see Exercise 2.24 and Section 6.4.

stmt ⟶ `IF` *condition* *then_clause* *else_clause* `END` | *other_stmt*
then_clause ⟶ `THEN` *stmt_list*
else_clause ⟶ `ELSE` *stmt_list* | ϵ

The addition of the `END` eliminates the ambiguity.

Modula-2 uses `END` to terminate all its structured statements. Ada and Fortran 77 end an `if` with `end if` (and a `while` with `end while`, etc.). Algol 68 creates its terminators by spelling the initial keyword backward (`if`... `fi`, `case`... `esac`, `do`... `od`, etc.).

EXAMPLE 2.32
The need for `elsif`

One problem with end markers is that they tend to bunch up. In Pascal one could write

```
if A = B then ...
else if A = C then ...
else if A = D then ...
else if A = E then ...
else ...
```

With end markers this becomes

```
if A = B then ...
else if A = C then ...
else if A = D then ...
else if A = E then ...
else ...
end end end end
```

To avoid this awkwardness, languages with end markers generally provide an `elsif` keyword (sometimes spelled `elif`):

```
if A = B then ...
elsif A = C then ...
elsif A = D then ...
elsif A = E then ...
else ...
end
```

2.3.3 Table-Driven Top-Down Parsing

EXAMPLE 2.33
Driver and table for top-down parsing

In a recursive descent parser, each arm of a case statement corresponds to a production, and contains parsing routine and match calls corresponding to the symbols on the right-hand side of that production. At any given point in the parse, if we consider the calls beyond the program counter (the ones that have yet to occur) in the parsing routine invocations currently in the call stack, we obtain a list of the symbols that the parser expects to see between here and the end of the program. A table-driven top-down parser maintains an explicit stack containing this same list of symbols.

```
terminal = 1 . . number_of_terminals
non_terminal = number_of_terminals + 1 . . number_of_symbols
symbol = 1 . . number_of_symbols
production = 1 . . number_of_productions

parse_tab : array [non_terminal, terminal] of record
    action : (predict, error)
    prod : production
prod_tab : array [production] of list of symbol
–– these two tables are created by a parser generator tool

parse_stack : stack of symbol

parse_stack.push(start_symbol)
loop
    expected_sym : symbol := parse_stack.pop()
    if expected_sym ∈ terminal
        match(expected_sym)                  –– as in Figure 2.17
        if expected_sym = $$ then return     –– success!
    else
        if parse_tab[expected_sym, input_token].action = error
            parse_error
        else
            prediction : production := parse_tab[expected_sym, input_token].prod
            foreach sym : symbol in reverse prod_tab[prediction]
                parse_stack.push(sym)
```

Figure 2.19 Driver for a table-driven LL(1) parser.

Pseudocode for such a parser appears in Figure 2.19. The code is language independent. It requires a language-*dependent* parsing table, generally produced by an automatic tool. For the calculator grammar of Figure 2.16, the table appears in Figure 2.20.

EXAMPLE 2.34

Table-driven parse of the "sum and average" program

To illustrate the algorithm, Figure 2.21 shows a trace of the stack and the input over time, for the sum-and-average program of Example 2.24. The parser iterates around a loop in which it pops the top symbol off the stack and performs the following actions: If the popped symbol is a terminal, the parser attempts to match it against an incoming token from the scanner. If the match fails, the parser announces a syntax error and initiates some sort of error recovery (see Section 2.3.5). If the popped symbol is a nonterminal, the parser uses that nonterminal together with the next available input token to index into a two-dimensional table that tells it which production to predict (or whether to announce a syntax error and initiate recovery).

Initially, the parse stack contains the start symbol of the grammar (in our case, *program*). When it predicts a production, the parser pushes the right-hand-side symbols onto the parse stack in reverse order, so the first of those symbols ends up at top-of-stack. The parse completes successfully when we match the end marker

Top-of-stack	**Current input token**											
nonterminal	`id`	`number`	`read`	`write`	`:=`	`(`	`)`	`+`	`-`	`*`	`/`	`$$`
program	1	–	1	1	–	–	–	–	–	–	–	1
stmt_list	2	–	2	2	–	–	–	–	–	–	–	3
stmt	4	–	5	6	–	–	–	–	–	–	–	–
expr	7	7	–	–	–	7	–	–	–	–	–	–
term_tail	9	–	9	9	–	–	9	8	8	–	–	9
term	10	10	–	–	–	10	–	–	–	–	–	–
factor_tail	12	–	12	12	–	–	12	12	12	11	11	12
factor	14	15	–	–	–	13	–	–	–	–	–	–
add_op	–	–	–	–	–	–	–	16	17	–	–	–
mult_op	–	–	–	–	–	–	–	–	–	18	19	–

Figure 2.20 **LL(1) parse table for the calculator language.** Table entries indicate the production to predict (as numbered in Figure 2.23). A dash indicates an error. When the top-of-stack symbol is a terminal, the appropriate action is always to match it against an incoming token from the scanner. An auxiliary table, not shown here, gives the right-hand-side symbols for each production.

token, `$$`. Assuming that `$$` appears only once in the grammar, at the end of the first production, and that the scanner returns this token only at end-of-file, any syntax error is guaranteed to manifest itself either as a failed match or as an error entry in the table.

As we hinted at the end of Section 2.3.1, predict sets are defined in terms of simpler sets called FIRST and FOLLOW, where FIRST(A) is the set of all tokens that could be the start of an A and FOLLOW(A) is the set of all tokens that could come after an A in some valid program. If we extend the domain of FIRST in the obvious way to include *strings* of symbols, we then say that the predict set of a production $A \longrightarrow \beta$ is FIRST(β), plus FOLLOW(A) if $\beta \Longrightarrow^* \epsilon$. For notational convenience, we define the predicate EPS such that EPS(β) $\equiv \beta \Longrightarrow^* \epsilon$.

EXAMPLE 2.35
Predict sets for the calculator language

We can illustrate the algorithm to construct these sets using our calculator grammar (Figure 2.16). We begin with "obvious" facts about the grammar and build on them inductively. If we recast the grammar in plain BNF (no EBNF '|' constructs), then it has 19 productions. The "obvious" facts arise from adjacent pairs of symbols in right-hand sides. In the first production, we can see that `$$` $\in$ FOLLOW(*stmt_list*). In the third (*stmt_list* $\longrightarrow \epsilon$), EPS(*stmt_list*) = true. In the fourth production (*stmt* $\longrightarrow$ `id` `:=` *expr*), `id` $\in$ FIRST(*stmt*) (also `:=` $\in$ FOLLOW(`id`), but it turns out we don't need FOLLOW sets for nonterminals). In the fifth and sixth productions (*stmt* $\longrightarrow$ `read` `id` | `write` *expr*), {`read`, `write`} $\subset$ FIRST(*stmt*). The complete set of "obvious" facts appears in Figure 2.22.

From the "obvious" facts we can deduce a larger set of facts during a second pass over the grammar. For example, in the second production (*stmt_list* $\longrightarrow$ *stmt stmt_list*) we can deduce that {`id`, `read`, `write`} $\subset$ FIRST(*stmt_list*), because we already know that {`id`, `read`, `write`} $\subset$ FIRST(*stmt*), and a *stmt_list* can

Parse stack	**Input stream**	**Comment**
program	`read A read B` ...	initial stack contents
stmt_list `$$`	`read A read B` ...	predict *program* ⟶ *stmt_list* `$$`
stmt stmt_list `$$`	`read A read B` ...	predict *stmt_list* ⟶ *stmt stmt_list*
`read id` *stmt_list* `$$`	`read A read B` ...	predict *stmt* ⟶ `read id`
`id` *stmt_list* `$$`	`A read B` ...	match `read`
stmt_list `$$`	`read B sum :=` ...	match `id`
stmt stmt_list `$$`	`read B sum :=` ...	predict *stmt_list* ⟶ *stmt stmt_list*
`read id` *stmt_list* `$$`	`read B sum :=` ...	predict *stmt* ⟶ `read id`
`id` *stmt_list* `$$`	`B sum :=` ...	match `read`
stmt_list `$$`	`sum := A + B` ...	match `id`
stmt stmt_list `$$`	`sum := A + B` ...	predict *stmt_list* ⟶ *stmt stmt_list*
`id :=` *expr stmt_list* `$$`	`sum := A + B` ...	predict *stmt* ⟶ `id :=` *expr*
`:=` *expr stmt_list* `$$`	`:= A + B` ...	match `id`
expr stmt_list `$$`	`A + B` ...	match `:=`
term term_tail stmt_list `$$`	`A + B` ...	predict *expr* ⟶ *term term_tail*
factor factor_tail term_tail stmt_list `$$`	`A + B` ...	predict *term* ⟶ *factor factor_tail*
`id` *factor_tail term_tail stmt_list* `$$`	`A + B` ...	predict *factor* ⟶ `id`
factor_tail term_tail stmt_list `$$`	`+ B write sum` ...	match `id`
term_tail stmt_list `$$`	`+ B write sum` ...	predict *factor_tail* ⟶ ϵ
add_op term term_tail stmt_list `$$`	`+ B write sum` ...	predict *term_tail* ⟶ *add_op term term_tail*
`+` *term term_tail stmt_list* `$$`	`+ B write sum` ...	predict *add_op* ⟶ `+`
term term_tail stmt_list `$$`	`B write sum` ...	match `+`
factor factor_tail term_tail stmt_list `$$`	`B write sum` ...	predict *term* ⟶ *factor factor_tail*
`id` *factor_tail term_tail stmt_list* `$$`	`B write sum` ...	predict *factor* ⟶ `id`
factor_tail term_tail stmt_list `$$`	`write sum` ...	match `id`
term_tail stmt_list `$$`	`write sum write` ...	predict *factor_tail* ⟶ ϵ
stmt_list `$$`	`write sum write` ...	predict *term_tail* ⟶ ϵ
stmt stmt_list `$$`	`write sum write` ...	predict *stmt_list* ⟶ *stmt stmt_list*
`write` *expr stmt_list* `$$`	`write sum write` ...	predict *stmt* ⟶ `write` *expr*
expr stmt_list `$$`	`sum write sum / 2`	match `write`
term term_tail stmt_list `$$`	`sum write sum / 2`	predict *expr* ⟶ *term term_tail*
factor factor_tail term_tail stmt_list `$$`	`sum write sum / 2`	predict *term* ⟶ *factor factor_tail*
`id` *factor_tail term_tail stmt_list* `$$`	`sum write sum / 2`	predict *factor* ⟶ `id`
factor_tail term_tail stmt_list `$$`	`write sum / 2`	match `id`
term_tail stmt_list `$$`	`write sum / 2`	predict *factor_tail* ⟶ ϵ
stmt_list `$$`	`write sum / 2`	predict *term_tail* ⟶ ϵ
stmt stmt_list `$$`	`write sum / 2`	predict *stmt_list* ⟶ *stmt stmt_list*
`write` *expr stmt_list* `$$`	`write sum / 2`	predict *stmt* ⟶ `write` *expr*
expr stmt_list `$$`	`sum / 2`	match `write`
term term_tail stmt_list `$$`	`sum / 2`	predict *expr* ⟶ *term term_tail*
factor factor_tail term_tail stmt_list `$$`	`sum / 2`	predict *term* ⟶ *factor factor_tail*
`id` *factor_tail term_tail stmt_list* `$$`	`sum / 2`	predict *factor* ⟶ `id`
factor_tail term_tail stmt_list `$$`	`/ 2`	match `id`
mult_op factor factor_tail term_tail stmt_list `$$`	`/ 2`	predict *factor_tail* ⟶ *mult_op factor factor_tail*
`/` *factor factor_tail term_tail stmt_list* `$$`	`/ 2`	predict *mult_op* ⟶ `/`
factor factor_tail term_tail stmt_list `$$`	`2`	match `/`
`number` *factor_tail term_tail stmt_list* `$$`	`2`	predict *factor* ⟶ `number`
factor_tail term_tail stmt_list `$$`		match `number`
term_tail stmt_list `$$`		predict *factor_tail* ⟶ ϵ
stmt_list `$$`		predict *term_tail* ⟶ ϵ
`$$`		predict *stmt_list* ⟶ ϵ

Figure 2.21 Trace of a table-driven LL(1) parse of the sum-and-average program of Example 2.24.

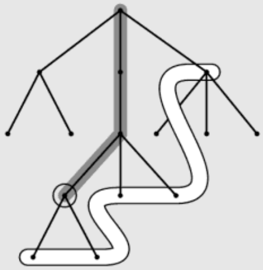
$\mathit{program} \longrightarrow \mathit{stmt\_list}\ \texttt{\$\$}$	$\texttt{\$\$} \in \mathrm{FOLLOW}(\mathit{stmt\_list})$
$\mathit{stmt\_list} \longrightarrow \mathit{stmt}\ \mathit{stmt\_list}$	
$\mathit{stmt\_list} \longrightarrow \epsilon$	$\mathrm{EPS}(\mathit{stmt\_list}) = \text{true}$
$\mathit{stmt} \longrightarrow \texttt{id := } \mathit{expr}$	$\texttt{id} \in \mathrm{FIRST}(\mathit{stmt})$
$\mathit{stmt} \longrightarrow \texttt{read id}$	$\texttt{read} \in \mathrm{FIRST}(\mathit{stmt})$
$\mathit{stmt} \longrightarrow \texttt{write } \mathit{expr}$	$\texttt{write} \in \mathrm{FIRST}(\mathit{stmt})$
$\mathit{expr} \longrightarrow \mathit{term}\ \mathit{term\_tail}$	
$\mathit{term\_tail} \longrightarrow \mathit{add\_op}\ \mathit{term}\ \mathit{term\_tail}$	
$\mathit{term\_tail} \longrightarrow \epsilon$	$\mathrm{EPS}(\mathit{term\_tail}) = \text{true}$
$\mathit{term} \longrightarrow \mathit{factor}\ \mathit{factor\_tail}$	
$\mathit{factor\_tail} \longrightarrow \mathit{mult\_op}\ \mathit{factor}\ \mathit{factor\_tail}$	
$\mathit{factor\_tail} \longrightarrow \epsilon$	$\mathrm{EPS}(\mathit{factor\_tail}) = \text{true}$
$\mathit{factor} \longrightarrow \texttt{(}\ \mathit{expr}\ \texttt{)}$	$\texttt{(} \in \mathrm{FIRST}(\mathit{factor})$ and $\texttt{)} \in \mathrm{FOLLOW}(\mathit{expr})$
$\mathit{factor} \longrightarrow \texttt{id}$	$\texttt{id} \in \mathrm{FIRST}(\mathit{factor})$
$\mathit{factor} \longrightarrow \texttt{number}$	$\texttt{number} \in \mathrm{FIRST}(\mathit{factor})$
$\mathit{add\_op} \longrightarrow \texttt{+}$	$\texttt{+} \in \mathrm{FIRST}(\mathit{add\_op})$
$\mathit{add\_op} \longrightarrow \texttt{-}$	$\texttt{-} \in \mathrm{FIRST}(\mathit{add\_op})$
$\mathit{mult\_op} \longrightarrow \texttt{*}$	$\texttt{*} \in \mathrm{FIRST}(\mathit{mult\_op})$
$\mathit{mult\_op} \longrightarrow \texttt{/}$	$\texttt{/} \in \mathrm{FIRST}(\mathit{mult\_op})$

Figure 2.22 "Obvious" facts (right) about the LL(1) calculator grammar (left).

DESIGN & IMPLEMENTATION

2.7 Recursive descent and table-driven LL parsing

When trying to understand the connection between recursive descent and table-driven LL parsing, it is tempting to imagine that the explicit stack of the table-driven parser mirrors the implicit call stack of the recursive descent parser, but this is not the case.



A better way to visualize the two implementations of top-down parsing is to remember that both are discovering a parse tree via depth-first left-to-right traversal. When we are at a given point in the parse—say the circled node in the tree shown here—the implicit call stack of a recursive descent parser holds a frame for each of the nodes on the path back to the root, created when the routine corresponding to that node was called. (This path is shown in grey.)

But these nodes are immaterial. What matters for the rest of the parse—as shown on the white path here—are the *upcoming calls* on the case statement arms of the recursive descent routines. Those calls—those parse tree nodes—are precisely the contents of the explicit stack of a table-driven LL parser.

FIRST

program {`id`, `read`, `write`, `$$`}
stmt_list {`id`, `read`, `write`}
stmt {`id`, `read`, `write`}
expr {`(`, `id`, `number`}
term_tail {`+`, `-`}
term {`(`, `id`, `number`}
factor_tail {`*`, `/`}
factor {`(`, `id`, `number`}
add_op {`+`, `-`}
mult_op {`*`, `/`}

FOLLOW

program ∅
stmt_list {`$$`}
stmt {`id`, `read`, `write`, `$$`}
expr {`)`, `id`, `read`, `write`, `$$`}
term_tail {`)`, `id`, `read`, `write`, `$$`}
term {`+`, `-`, `)`, `id`, `read`, `write`, `$$`}
factor_tail {`+`, `-`, `)`, `id`, `read`, `write`, `$$`}
factor {`+`, `-`, `*`, `/`, `)`, `id`, `read`, `write`, `$$`}
add_op {`(`, `id`, `number`}
mult_op {`(`, `id`, `number`}

PREDICT

1. *program* ⟶ *stmt_list* `$$` {`id`, `read`, `write`, `$$`}
2. *stmt_list* ⟶ *stmt* *stmt_list* {`id`, `read`, `write`}
3. *stmt_list* ⟶ ϵ {`$$`}
4. *stmt* ⟶ `id := ` *expr* {`id`}
5. *stmt* ⟶ `read id` {`read`}
6. *stmt* ⟶ `write` *expr* {`write`}
7. *expr* ⟶ *term* *term_tail* {`(`, `id`, `number`}
8. *term_tail* ⟶ *add_op* *term* *term_tail* {`+`, `-`}
9. *term_tail* ⟶ ϵ {`)`, `id`, `read`, `write`, `$$`}
10. *term* ⟶ *factor* *factor_tail* {`(`, `id`, `number`}
11. *factor_tail* ⟶ *mult_op* *factor* *factor_tail* {`*`, `/`}
12. *factor_tail* ⟶ ϵ {`+`, `-`, `)`, `id`, `read`, `write`, `$$`}
13. *factor* ⟶ `(` *expr* `)` {`(`}
14. *factor* ⟶ `id` {`id`}
15. *factor* ⟶ `number` {`number`}
16. *add_op* ⟶ `+` {`+`}
17. *add_op* ⟶ `-` {`-`}
18. *mult_op* ⟶ `*` {`*`}
19. *mult_op* ⟶ `/` {`/`}

Figure 2.23 **FIRST, FOLLOW, and PREDICT sets for the calculator language.** FIRST(`c`) = {`c`} ∀ tokens `c`. EPS(A) is true iff A ∈ {*stmt_list*, *term_tail*, *factor_tail*}.

begin with a *stmt*. Similarly, in the first production, we can deduce that `$$` ∈ FIRST(*program*), because we already know that EPS(*stmt_list*) = true.

In the eleventh production (*factor_tail* ⟶ *mult_op factor factor_tail*), we can deduce that {`(`, `id`, `number`} ⊂ FOLLOW(*mult_op*), because we already know that {`(`, `id`, `number`} ⊂ FIRST(*factor*), and *factor* follows *mult_op* in the right-hand side. In the production *expr* ⟶ *term term_tail*, we can deduce that `)` ∈ FOLLOW(*term_tail*), because we already know that `)` ∈ FOLLOW(*expr*), and a *term_tail* can be the last part of an *expr*. In this same production, we can also deduce that `)` ∈ FOLLOW(*term*), because the *term_tail* can generate ϵ (EPS(*term_tail*) = true), allowing a *term* to be the last part of an *expr*.

There is more that we can learn from our second pass through the grammar, but the examples above cover all the different kinds of cases. To complete our calculation, we continue with additional passes over the grammar until we don't learn any more (i.e., we don't add anything to any of the FIRST and FOLLOW sets). We then construct the PREDICT sets. Final versions of all three sets appear in Figure 2.23. The parse table of Figure 2.20 follows directly from PREDICT.

The algorithm to compute EPS, FIRST, FOLLOW, and PREDICT sets appears, a bit more formally, in Figure 2.24. It relies on the following definitions:

```
-- EPS values and FIRST sets for all symbols:
    for all terminals c, EPS(c) := false; FIRST(c) := {c}
    for all nonterminals $X$, EPS($X$) := if $X \longrightarrow \epsilon$ then true else false; FIRST($X$) := $\varnothing$
    repeat
        ⟨outer⟩ for all productions $X \longrightarrow Y_1\ Y_2\ \dots\ Y_k$,
            ⟨inner⟩ for $i$ in 1 . . $k$
                add FIRST($Y_i$) to FIRST($X$)
                if not EPS($Y_i$) (yet) then continue outer loop
            EPS($X$) := true
    until no further progress

-- Subroutines for strings, similar to inner loop above:

    function string_EPS($X_1\ X_2\ \dots\ X_n$)
        for $i$ in 1 . . $n$
            if not EPS($X_i$) then return false
        return true

    function string_FIRST($X_1\ X_2\ \dots\ X_n$)
        return_value := $\varnothing$
        for $i$ in 1 . . $n$
            add FIRST($X_i$) to return_value
            if not EPS($X_i$) then return

-- FOLLOW sets for all symbols:
    for all symbols $X$, FOLLOW($X$) := $\varnothing$
    repeat
        for all productions $A \longrightarrow \alpha\ B\ \beta$,
            add string_FIRST($\beta$) to FOLLOW($B$)
        for all productions $A \longrightarrow \alpha\ B$
                or $A \longrightarrow \alpha\ B\ \beta$, where string_EPS($\beta$) = true,
            add FOLLOW($A$) to FOLLOW($B$)
    until no further progress

-- PREDICT sets for all productions:
    for all productions $A \longrightarrow \alpha$
        PREDICT($A \longrightarrow \alpha$) := string_FIRST($\alpha$) ∪ (if string_EPS($\alpha$) then FOLLOW($A$) else $\varnothing$)
```

Figure 2.24 Algorithm to calculate FIRST, FOLLOW, and PREDICT sets. The grammar is LL(1) if and only if all PREDICT sets for productions with the same left-hand side are disjoint.

$$\text{EPS}(\alpha) \equiv \text{if } \alpha \Longrightarrow^* \epsilon \text{ then true else false}$$
$$\text{FIRST}(\alpha) \equiv \{\texttt{c} : \alpha \Longrightarrow^* \texttt{c}\ \beta\}$$
$$\text{FOLLOW}(A) \equiv \{\texttt{c} : \text{S} \Longrightarrow^+ \alpha\ A\ \texttt{c}\ \beta\}$$
$$\text{PREDICT}(A \longrightarrow \alpha) \equiv \text{FIRST}(\alpha)\ \cup\ (\text{ if EPS}(\alpha) \text{ then FOLLOW}(A) \text{ else } \varnothing\,)$$

The definition of PREDICT assumes that the language has been augmented with an end marker—that is, that FOLLOW(S) = {$$}. Note that FIRST sets and EPS values for strings of length greater than one are calculated on demand; they are not stored explicitly. The algorithm is guaranteed to terminate (i.e., converge on a solution), because the sizes of the FIRST and FOLLOW sets are bounded by the number of terminals in the grammar.

If in the process of calculating PREDICT sets we find that some token belongs to the PREDICT set of more than one production with the same left-hand side, then the grammar is not LL(1), because we will not be able to choose which of the productions to employ when the left-hand side is at the top of the parse stack (or we are in the left-hand side's subroutine in a recursive descent parser) and we see the token coming up in the input. This sort of ambiguity is known as a *predict-predict conflict*; it can arise either because the same token can begin more than one right-hand side, or because it can begin one right-hand side and can also appear after the left-hand side in some valid program, and one possible right-hand side can generate ϵ.

✓ **CHECK YOUR UNDERSTANDING**

29. Describe two common idioms in context-free grammars that cannot be parsed top-down.

30. What is the "dangling `else`" problem? How is it avoided in modern languages?

31. Discuss the similarities and differences between recursive descent and table-driven top-down parsing.

32. What are FIRST and FOLLOW sets? What are they used for?

33. Under what circumstances does a top-down parser predict the production $A \longrightarrow \alpha$?

34. What sorts of "obvious" facts form the basis of FIRST set and FOLLOW set construction?

35. Outline the algorithm used to complete the construction of FIRST and FOLLOW sets. How do we know when we are done?

36. How do we know when a grammar is not LL(1)?

2.3.4 Bottom-Up Parsing

Conceptually, as we saw at the beginning of Section 2.3, a bottom-up parser works by maintaining a forest of partially completed subtrees of the parse tree, which it joins together whenever it recognizes the symbols on the right-hand side of some production used in the right-most derivation of the input string. It creates a new internal node and makes the roots of the joined-together trees the children of that node.

In practice, a bottom-up parser is almost always table-driven. It keeps the roots of its partially completed subtrees on a stack. When it accepts a new token from the scanner, it *shifts* the token into the stack. When it recognizes that the top few symbols on the stack constitute a right-hand side, it *reduces* those symbols to their left-hand side by popping them off the stack and pushing the left-hand side in their place. The role of the stack is the first important difference between top-down and bottom-up parsing: a top-down parser's stack contains a list of what the parser expects to see in the future; a bottom-up parser's stack contains a record of what the parser has already seen in the past.

Canonical Derivations

EXAMPLE 2.36

Derivation of an `id` list

We also noted earlier that the actions of a bottom-up parser trace out a right-most (canonical) derivation in reverse. The roots of the partial subtrees, left-to-right, together with the remaining input, constitute a sentential form of the right-most derivation. On the right-hand side of Figure 2.14, for example, we have the following series of steps:

Stack contents (roots of partial trees)	Remaining input
ϵ	`A, B, C;`
`id (A)`	`, B, C;`
`id (A) ,`	`B, C;`
`id (A) , id (B)`	`, C;`
`id (A) , id (B) ,`	`C;`
`id (A) , id (B) , id (C)`	`;`
`id (A) , id (B) , id (C)` $\underline{\texttt{;}}$	
`id (A) , id (B)` $\underline{\texttt{, id (C)}\ \textit{id\_list\_tail}}$	
`id (A)` $\underline{\texttt{, id (B)}\ \textit{id\_list\_tail}}$	
$\underline{\texttt{id (A)}\ \textit{id\_list\_tail}}$	
id_list	

The last four lines (the ones that don't just shift tokens into the forest) correspond to the right-most derivation:

$$\begin{aligned} \textit{id\_list} &\Longrightarrow \texttt{id}\ \textit{id\_list\_tail} \\ &\Longrightarrow \texttt{id , id}\ \textit{id\_list\_tail} \\ &\Longrightarrow \texttt{id , id , id}\ \textit{id\_list\_tail} \\ &\Longrightarrow \texttt{id , id , id ;} \end{aligned}$$

The symbols that need to be joined together at each step of the parse to represent the next step of the backward derivation are called the *handle* of the sentential form. In the parse trace above, the handles are underlined. ■

EXAMPLE 2.37

Bottom-up grammar for the calculator language

In our *id_list* example, no handles were found until the entire input had been shifted onto the stack. In general this will not be the case. We can obtain a more realistic example by examining an LR version of our calculator language, shown in Figure 2.25. While the LL grammar of Figure 2.16 can be parsed bottom-up, the version in Figure 2.25 is preferable for two reasons. First, it uses a left-recursive production for *stmt_list*. Left recursion allows the parser to collapse long statement lists as it goes along, rather than waiting until the entire list is

1. *program* ⟶ *stmt_list* `$$`
2. *stmt_list* ⟶ *stmt_list stmt*
3. *stmt_list* ⟶ *stmt*
4. *stmt* ⟶ `id :=` *expr*
5. *stmt* ⟶ `read id`
6. *stmt* ⟶ `write` *expr*
7. *expr* ⟶ *term*
8. *expr* ⟶ *expr add_op term*
9. *term* ⟶ *factor*
10. *term* ⟶ *term mult_op factor*
11. *factor* ⟶ `(` *expr* `)`
12. *factor* ⟶ `id`
13. *factor* ⟶ `number`
14. *add_op* ⟶ `+`
15. *add_op* ⟶ `-`
16. *mult_op* ⟶ `*`
17. *mult_op* ⟶ `/`

Figure 2.25 **LR(1) grammar for the calculator language.** Productions have been numbered for reference in future figures.

on the stack and then collapsing it from the end. Second, it uses left-recursive productions for *expr* and *term*. These productions capture left associativity while still keeping an operator and its operands together in the same right-hand side, something we were unable to do in a top-down grammar.

Modeling a Parse with LR Items

EXAMPLE 2.38

Bottom-up parse of the "sum and average" program

Suppose we are to parse the sum-and-average program from Example 2.24:

```
read A
read B
sum := A + B
write sum
write sum / 2
```

The key to success will be to figure out when we have reached the end of a right-hand side—that is, when we have a handle at the top of the parse stack. The trick is to keep track of the set of productions we might be "in the middle of" at any particular time, together with an indication of where in those productions we might be.

When we begin execution, the parse stack is empty and we are at the beginning of the production for *program*. (In general, we can assume that there is only one production with the start symbol on the left-hand side; it is easy to modify any grammar to make this the case.) We can represent our location—more specifically, the location represented by the top of the parse stack—with a $\bullet$ in the right-hand side of the production:

$$\textit{program} \longrightarrow \bullet\ \textit{stmt\_list}\ \texttt{\$\$}$$

When augmented with a $\bullet$, a production is called an LR *item*. Since the $\bullet$ in this item is immediately in front of a nonterminal—namely *stmt_list*—we may be about to see the yield of that nonterminal coming up on the input. This possibility implies that we may be at the beginning of some production with *stmt_list* on the left-hand side:

$$\begin{aligned}
&\textit{program} \longrightarrow \bullet\ \textit{stmt\_list}\ \texttt{\$\$}\\
&\textit{stmt\_list} \longrightarrow \bullet\ \textit{stmt\_list}\ \textit{stmt}\\
&\textit{stmt\_list} \longrightarrow \bullet\ \textit{stmt}
\end{aligned}$$

And, since *stmt* is a nonterminal, we may also be at the beginning of any production whose left-hand side is *stmt*:

$$\begin{aligned}
&\textit{program} \longrightarrow \bullet\ \textit{stmt\_list}\ \texttt{\$\$} &&\text{(State 0)}\\
&\textit{stmt\_list} \longrightarrow \bullet\ \textit{stmt\_list}\ \textit{stmt}\\
&\textit{stmt\_list} \longrightarrow \bullet\ \textit{stmt}\\
&\textit{stmt} \longrightarrow \bullet\ \texttt{id := }\textit{expr}\\
&\textit{stmt} \longrightarrow \bullet\ \texttt{read id}\\
&\textit{stmt} \longrightarrow \bullet\ \texttt{write }\textit{expr}
\end{aligned}$$

Since all of these last productions begin with a terminal, no additional items need to be added to our list. The original item ($\textit{program} \longrightarrow \bullet\ \textit{stmt\_list}\ \texttt{\$\$}$) is called the *basis* of the list. The additional items are its *closure*. The list represents the initial state of the parser. As we shift and reduce, the set of items will change, always indicating which productions *may* be the right one to use next in the derivation of the input string. If we reach a state in which some item has the $\bullet$ at the end of the right-hand side, we can reduce by that production. Otherwise, as in the current situation, we must shift. Note that if we need to shift, but the incoming token cannot follow the $\bullet$ in any item of the current state, then a syntax error has occurred. We will consider error recovery in more detail in Section C-2.3.5.

Our upcoming token is a `read`. Once we shift it onto the stack, we know we are in the following state:

$$\textit{stmt} \longrightarrow \texttt{read}\ \bullet\ \texttt{id} \qquad\qquad \text{(State 1)}$$

This state has a single basis item and an empty closure—the $\bullet$ precedes a terminal. After shifting the `A`, we have

$$\textit{stmt} \longrightarrow \texttt{read id}\ \bullet \qquad\qquad \text{(State 1}'\text{)}$$

We now know that `read id` is the handle, and we must reduce. The reduction pops two symbols off the parse stack and pushes a *stmt* in their place, but what should the new state be? We can see the answer if we imagine moving back in time to the point at which we shifted the `read`—the first symbol of the right-hand side. At that time we were in the state labeled "State 0" above, and the upcoming tokens on the input (though we didn't look at them at the time) were `read id`. We have now consumed these tokens, and we know that they constituted a *stmt*. By pushing a *stmt* onto the stack, we have in essence replaced `read id` with *stmt* on the input stream, and have then "shifted" the nonterminal, rather than its yield, into the stack. Since one of the items in State 0 was

$$\textit{stmt\_list} \longrightarrow \bullet\ \textit{stmt}$$

we now have

$$\textit{stmt\_list} \longrightarrow \textit{stmt}\ \bullet \qquad \text{(State 0}'\text{)}$$

Again we must reduce. We remove the *stmt* from the stack and push a *stmt_list* in its place. Again we can see this as "shifting" a *stmt_list* when in State 0. Since two of the items in State 0 have a *stmt_list* after the •, we don't know (without looking ahead) which of the productions will be the next to be used in the derivation, but we don't have to know. The key advantage of bottom-up parsing over top-down parsing is that we don't need to predict ahead of time which production we shall be expanding.

Our new state is as follows:

$$\begin{array}{lll}
\textit{program} \longrightarrow \textit{stmt\_list}\ \bullet\ \texttt{\$\$} & & \text{(State 2)} \\
\textit{stmt\_list} \longrightarrow \textit{stmt\_list}\ \bullet\ \textit{stmt} & & \\
\textit{stmt} \longrightarrow \bullet\ \texttt{id := }\textit{expr} & & \\
\textit{stmt} \longrightarrow \bullet\ \texttt{read id} & & \\
\textit{stmt} \longrightarrow \bullet\ \texttt{write }\textit{expr} & &
\end{array}$$

The first two productions are the basis; the others are the closure. Since no item has a • at the end, we shift the next token, which happens again to be a `read`, taking us back to State 1. Shifting the `B` takes us to State 1′ again, at which point we reduce. This time however, we go back to State 2 rather than State 0 before shifting the left-hand-side *stmt*. Why? Because we were in State 2 when we began to read the right-hand side.

The Characteristic Finite-State Machine and LR Parsing Variants

An LR-family parser keeps track of the states it has traversed by pushing them into the parse stack, along with the grammar symbols. It is in fact the states (rather than the symbols) that drive the parsing algorithm: they tell us what state we were in at the beginning of a right-hand side. Specifically, when the combination of state and input tells us we need to reduce using production $A \longrightarrow \alpha$, we pop $\textit{length}(\alpha)$ symbols off the stack, together with the record of states we moved through while shifting those symbols. These pops expose the state we were in immediately prior to the shifts, allowing us to return to that state and proceed as if we had seen A in the first place.

We can think of the shift rules of an LR-family parser as the transition function of a finite automaton, much like the automata we used to model scanners. Each state of the automaton corresponds to a list of items that indicate where the parser might be at some specific point in the parse. The transition for input symbol X (which may be either a terminal or a nonterminal) moves to a state whose basis consists of items in which the $\bullet$ has been moved across an X in the right-hand side, plus whatever items need to be added as closure. The lists are constructed by a bottom-up parser generator in order to build the automaton, but are not needed during parsing.

It turns out that the simpler members of the LR family of parsers—LR(0), SLR(1), and LALR(1)—all use the same automaton, called the *characteristic finite-state machine*, or CFSM. Full LR parsers use a machine with (for most grammars) a much larger number of states. The differences between the algorithms lie in how they deal with states that contain a *shift-reduce conflict*—one item with the $\bullet$ in front of a terminal (suggesting the need for a shift) and another with the $\bullet$ at the end of the right-hand side (suggesting the need for a reduction). An LR(0) parser works only when there are no such states. It can be proven that with the addition of an end-marker (i.e., $$), any language that can be deterministically parsed bottom-up has an LR(0) grammar. Unfortunately, the LR(0) grammars for real programming languages tend to be prohibitively large and unintuitive.

SLR (simple LR) parsers peek at upcoming input and use FOLLOW sets to resolve conflicts. An SLR parser will call for a reduction via $A \longrightarrow \alpha$ only if the upcoming token(s) are in FOLLOW(α). It will still see a conflict, however, if the tokens are also in the FIRST set of any of the symbols that follow a $\bullet$ in other items of the state. As it turns out, there are important cases in which a token may follow a given nonterminal somewhere in a valid program, but never in a context described by the current state. For these cases global FOLLOW sets are too crude. LALR (look-ahead LR) parsers improve on SLR by using *local* (state-specific) look-ahead instead.

Conflicts can still arise in an LALR parser when the same set of items can occur on two different paths through the CFSM. Both paths will end up in the same state, at which point state-specific look-ahead can no longer distinguish between them. A full LR parser duplicates states in order to keep paths disjoint when their local look-aheads are different.

LALR parsers are the most common bottom-up parsers in practice. They are the same size and speed as SLR parsers, but are able to resolve more conflicts. Full LR parsers for real programming languages tend to be very large. Several researchers have developed techniques to reduce the size of full-LR tables, but LALR works sufficiently well in practice that the extra complexity of full LR is usually not required. `Yacc/bison` produces C code for an LALR parser.

Bottom-Up Parsing Tables

Like a table-driven LL(1) parser, an SLR(1), LALR(1), or LR(1) parser executes a loop in which it repeatedly inspects a two-dimensional table to find out what action to take. However, instead of using the current input token and top-of-stack nonterminal to index into the table, an LR-family parser uses the current input token and the current parser state (which can be found at the top of the stack). "Shift" table entries indicate the state that should be pushed. "Reduce" table entries indicate the number of states that should be popped and the nonterminal that should be pushed back onto the input stream, to be shifted by the state uncovered by the pops. There is always one popped state for every symbol on the right-hand side of the reducing production. The state to be pushed next can be found by indexing into the table using the uncovered state and the newly recognized nonterminal.

EXAMPLE 2.39

CFSM for the bottom-up calculator grammar

The CFSM for our bottom-up version of the calculator grammar appears in Figure 2.26. States 6, 7, 9, and 13 contain potential shift-reduce conflicts, but all of these can be resolved with global FOLLOW sets. SLR parsing therefore suffices. In State 6, for example, FIRST(add_op) $\cap$ FOLLOW($stmt$) $= \varnothing$. In addition to shift and reduce rules, we allow the parse table as an optimization to contain rules of the form "shift and then reduce." This optimization serves to eliminate trivial states such as $1'$ and $0'$ in Example 2.38, which had only a single item, with the $\bullet$ at the end.

A pictorial representation of the CFSM appears in Figure 2.27. A tabular representation, suitable for use in a table-driven parser, appears in Figure 2.28. Pseudocode for the (language-independent) parser driver appears in Figure 2.29. A trace of the parser's actions on the sum-and-average program appears in Figure 2.30. ■

Handling Epsilon Productions

EXAMPLE 2.40

Epsilon productions in the bottom-up calculator grammar

The careful reader may have noticed that the grammar of Figure 2.25, in addition to using left-recursive rules for *stmt_list*, *expr*, and *term*, differs from the grammar of Figure 2.16 in one other way: it defines a *stmt_list* to be a sequence of one or more *stmt*s, rather than zero or more. (This means, of course, that it defines a different language.) To capture the same language as Figure 2.16, production 3 in Figure 2.25,

$stmt\_list \longrightarrow stmt$

would need to be replaced with

$stmt\_list \longrightarrow \epsilon$ ■

Note that it does in general make sense to have an empty statement list. In the calculator language it simply permits an empty program, which is admittedly silly. In real languages, however, it allows the body of a structured statement to be empty, which can be very useful. One frequently wants one arm of a `case` or multi-way `if`... `then` ... `else` statement to be empty, and an empty `while` loop allows

	State	Transitions
0.	*program* ⟶ • *stmt_list* `$$`	on *stmt_list* shift and goto 2
	stmt_list ⟶ • *stmt_list* *stmt*	
	stmt_list ⟶ • *stmt*	on *stmt* shift and reduce (pop 1 state, push *stmt_list* on input)
	stmt ⟶ • `id` `:=` *expr*	on `id` shift and goto 3
	stmt ⟶ • `read` `id`	on `read` shift and goto 1
	stmt ⟶ • `write` *expr*	on `write` shift and goto 4
1.	*stmt* ⟶ `read` • `id`	on `id` shift and reduce (pop 2 states, push *stmt* on input)
2.	*program* ⟶ *stmt_list* • `$$`	on `$$` shift and reduce (pop 2 states, push *program* on input)
	stmt_list ⟶ *stmt_list* • *stmt*	on *stmt* shift and reduce (pop 2 states, push *stmt_list* on input)
	stmt ⟶ • `id` `:=` *expr*	on `id` shift and goto 3
	stmt ⟶ • `read` `id`	on `read` shift and goto 1
	stmt ⟶ • `write` *expr*	on `write` shift and goto 4
3.	*stmt* ⟶ `id` • `:=` *expr*	on `:=` shift and goto 5
4.	*stmt* ⟶ `write` • *expr*	on *expr* shift and goto 6
	expr ⟶ • *term*	on *term* shift and goto 7
	expr ⟶ • *expr* *add_op* *term*	
	term ⟶ • *factor*	on *factor* shift and reduce (pop 1 state, push *term* on input)
	term ⟶ • *term* *mult_op* *factor*	
	factor ⟶ • `(` *expr* `)`	on `(` shift and goto 8
	factor ⟶ • `id`	on `id` shift and reduce (pop 1 state, push *factor* on input)
	factor ⟶ • `number`	on `number` shift and reduce (pop 1 state, push *factor* on input)
5.	*stmt* ⟶ `id` `:=` • *expr*	on *expr* shift and goto 9
	expr ⟶ • *term*	on *term* shift and goto 7
	expr ⟶ • *expr* *add_op* *term*	
	term ⟶ • *factor*	on *factor* shift and reduce (pop 1 state, push *term* on input)
	term ⟶ • *term* *mult_op* *factor*	
	factor ⟶ • `(` *expr* `)`	on `(` shift and goto 8
	factor ⟶ • `id`	on `id` shift and reduce (pop 1 state, push *factor* on input)
	factor ⟶ • `number`	on `number` shift and reduce (pop 1 state, push *factor* on input)
6.	*stmt* ⟶ `write` *expr* •	on FOLLOW(*stmt*) = {`id`, `read`, `write`, `$$`} reduce (pop 2 states, push *stmt* on input)
	expr ⟶ *expr* • *add_op* *term*	on *add_op* shift and goto 10
	add_op ⟶ • `+`	on `+` shift and reduce (pop 1 state, push *add_op* on input)
	add_op ⟶ • `-`	on `-` shift and reduce (pop 1 state, push *add_op* on input)

Figure 2.26 **CFSM for the calculator grammar (Figure 2.25).** Basis and closure items in each state are separated by a horizontal rule. Trivial reduce-only states have been eliminated by use of "shift and reduce" transitions. *(continued)*

	State	Transitions
7.	*expr* ⟶ *term* •	on FOLLOW(*expr*) = {`id`, `read`, `write`, `$$`, `)`, `+`, `-`} reduce
	term ⟶ *term* • *mult_op* *factor*	(pop 1 state, push *expr* on input)
		on *mult_op* shift and goto 11
	mult_op ⟶ • `*`	on `*` shift and reduce (pop 1 state, push *mult_op* on input)
	mult_op ⟶ • `/`	on `/` shift and reduce (pop 1 state, push *mult_op* on input)
8.	*factor* ⟶ `(` • *expr* `)`	on *expr* shift and goto 12
	expr ⟶ • *term*	on *term* shift and goto 7
	expr ⟶ • *expr* *add_op* *term*	
	term ⟶ • *factor*	on *factor* shift and reduce (pop 1 state, push *term* on input)
	term ⟶ • *term* *mult_op* *factor*	
	factor ⟶ • `(` *expr* `)`	on `(` shift and goto 8
	factor ⟶ • `id`	on `id` shift and reduce (pop 1 state, push *factor* on input)
	factor ⟶ • `number`	on `number` shift and reduce (pop 1 state, push *factor* on input)
9.	*stmt* ⟶ `id` `:=` *expr* •	on FOLLOW (*stmt*) = {`id`, `read`, `write`, `$$`} reduce
	expr ⟶ *expr* • *add_op* *term*	(pop 3 states, push *stmt* on input)
		on *add_op* shift and goto 10
	add_op ⟶ • `+`	on `+` shift and reduce (pop 1 state, push *add_op* on input)
	add_op ⟶ • `-`	on `-` shift and reduce (pop 1 state, push *add_op* on input)
10.	*expr* ⟶ *expr* *add_op* • *term*	on *term* shift and goto 13
	term ⟶ • *factor*	on *factor* shift and reduce (pop 1 state, push *term* on input)
	term ⟶ • *term* *mult_op* *factor*	
	factor ⟶ • `(` *expr* `)`	on `(` shift and goto 8
	factor ⟶ • `id`	on `id` shift and reduce (pop 1 state, push *factor* on input)
	factor ⟶ • `number`	on `number` shift and reduce (pop 1 state, push *factor* on input)
11.	*term* ⟶ *term* *mult_op* • *factor*	on *factor* shift and reduce (pop 3 states, push *term* on input)
	factor ⟶ • `(` *expr* `)`	on `(` shift and goto 8
	factor ⟶ • `id`	on `id` shift and reduce (pop 1 state, push *factor* on input)
	factor ⟶ • `number`	on `number` shift and reduce (pop 1 state, push *factor* on input)
12.	*factor* ⟶ `(` *expr* • `)`	on `)` shift and reduce (pop 3 states, push *factor* on input)
	expr ⟶ *expr* • *add_op* *term*	on *add_op* shift and goto 10
	add_op ⟶ • `+`	on `+` shift and reduce (pop 1 state, push *add_op* on input)
	add_op ⟶ • `-`	on `-` shift and reduce (pop 1 state, push *add_op* on input)
13.	*expr* ⟶ *expr* *add_op* *term* •	on FOLLOW(*expr*) = {`id`, `read`, `write`, `$$`, `)`, `+`, `-`} reduce
	term ⟶ *term* • *mult_op* *factor*	(pop 3 states, push *expr* on input)
		on *mult_op* shift and goto 11
	mult_op ⟶ • `*`	on `*` shift and reduce (pop 1 state, push *mult_op* on input)
	mult_op ⟶ • `/`	on `/` shift and reduce (pop 1 state, push *mult_op* on input)

Figure 2.26 *(continued)*

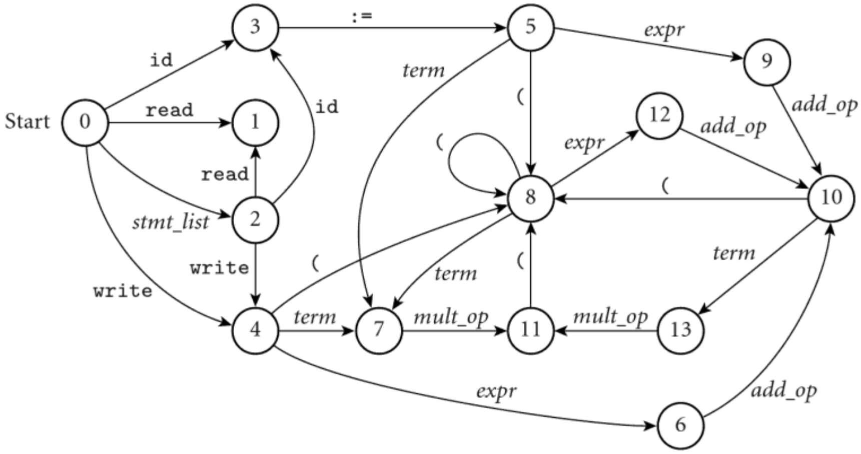


Figure 2.27 Pictorial representation of the CFSM of Figure 2.26. Reduce actions are not shown.

Top-of-stack state								**Current input symbol**											
	sl	*s*	*e*	*t*	*f*	*ao*	*mo*	`id`	`lit`	`r`	`w`	`:=`	`(`	`)`	`+`	`-`	`*`	`/`	`$$`
0	s2	b3	–	–	–	–	–	s3	–	s1	s4	–	–	–	–	–	–	–	–
1	–	–	–	–	–	–	–	b5	–	–	–	–	–	–	–	–	–	–	–
2	–	b2	–	–	–	–	–	s3	–	s1	s4	–	–	–	–	–	–	–	b1
3	–	–	–	–	–	–	–	–	–	–	–	s5	–	–	–	–	–	–	–
4	–	–	s6	s7	b9	–	–	b12	b13	–	–	–	s8	–	–	–	–	–	–
5	–	–	s9	s7	b9	–	–	b12	b13	–	–	–	s8	–	–	–	–	–	–
6	–	–	–	–	–	s10	–	r6	–	r6	r6	–	–	–	b14	b15	–	–	r6
7	–	–	–	–	–	–	s11	r7	–	r7	r7	–	–	r7	r7	r7	b16	b17	r7
8	–	–	s12	s7	b9	–	–	b12	b13	–	–	–	s8	–	–	–	–	–	–
9	–	–	–	–	–	s10	–	r4	–	r4	r4	–	–	–	b14	b15	–	–	r4
10	–	–	–	s13	b9	–	–	b12	b13	–	–	–	s8	–	–	–	–	–	–
11	–	–	–	–	b10	–	–	b12	b13	–	–	–	s8	–	–	–	–	–	–
12	–	–	–	–	–	s10	–	–	–	–	–	–	–	b11	b14	b15	–	–	–
13	–	–	–	–	–	–	s11	r8	–	r8	r8	–	–	r8	r8	r8	b16	b17	r8

Figure 2.28 SLR(1) parse table for the calculator language. Table entries indicate whether to shift (s), reduce (r), or shift and then reduce (b). The accompanying number is the new state when shifting, or the production that has been recognized when (shifting and) reducing. Production numbers are given in Figure 2.25. Symbol names have been abbreviated for the sake of formatting. A dash indicates an error. An auxiliary table, not shown here, gives the left-hand-side symbol and right-hand-side length for each production.

```
state = 1 . . number_of_states
symbol = 1 . . number_of_symbols
production = 1 . . number_of_productions
action_rec = record
    action : (shift, reduce, shift_reduce, error)
    new_state : state
    prod : production

parse_tab : array [symbol, state] of action_rec
prod_tab : array [production] of record
    lhs : symbol
    rhs_len : integer
–– these two tables are created by a parser generator tool

parse_stack : stack of record
    sym : symbol
    st : state

parse_stack.push(⟨null, start_state⟩)
cur_sym : symbol := scan()                  –– get new token from scanner
loop
    cur_state : state := parse_stack.top().st   –– peek at state at top of stack
    if cur_state = start_state and cur_sym = start_symbol
        return                              –– success!
    ar : action_rec := parse_tab[cur_state, cur_sym]
    case ar.action
        shift:
            parse_stack.push(⟨cur_sym, ar.new_state⟩)
            cur_sym := scan()               –– get new token from scanner
        reduce:
            cur_sym := prod_tab[ar.prod].lhs
            parse_stack.pop(prod_tab[ar.prod].rhs_len)
        shift_reduce:
            cur_sym := prod_tab[ar.prod].lhs
            parse_stack.pop(prod_tab[ar.prod].rhs_len−1)
        error:
            parse_error
```

Figure 2.29 Driver for a table-driven SLR(1) parser. We call the scanner directly, rather than using the global input_token of Figures 2.17 and 2.19, so that we can set cur_sym to be an arbitrary symbol. We pass to the pop() routine a parameter that indicates the number of symbols to remove from the stack.

Parse stack	Input stream	Comment
0	`read A read B ...`	
0 `read` ***1***	`A read B ...`	shift `read`
0	*stmt* `read B ...`	shift `id(A)` & reduce by *stmt* ⟶ `read id`
0	*stmt_list* `read B ...`	shift *stmt* & reduce by *stmt_list* ⟶ *stmt*
0 *stmt_list* ***2***	`read B sum ...`	shift *stmt_list*
0 *stmt_list* ***2*** `read` ***1***	`B sum := ...`	shift `read`
0 *stmt_list* ***2***	*stmt* `sum := ...`	shift `id(B)` & reduce by *stmt* ⟶ `read id`
0	*stmt_list* `sum := ...`	shift *stmt* & reduce by *stmt_list* ⟶ *stmt_list stmt*
0 *stmt_list* ***2***	`sum := A ...`	shift *stmt_list*
0 *stmt_list* ***2*** `id` ***3***	`:= A + ...`	shift `id(sum)`
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5***	`A + B ...`	shift `:=`
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5***	*factor* `+ B ...`	shift `id(A)` & reduce by *factor* ⟶ `id`
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5***	*term* `+ B ...`	shift *factor* & reduce by *term* ⟶ *factor*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *term* ***7***	`+ B write ...`	shift *term*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5***	*expr* `+ B write ...`	reduce by *expr* ⟶ *term*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9***	`+ B write ...`	shift *expr*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9***	*add_op* `B write ...`	shift `+` & reduce by *add_op* ⟶ `+`
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9*** *add_op* ***10***	`B write sum ...`	shift *add_op*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9*** *add_op* ***10***	*factor* `write sum ...`	shift `id(B)` & reduce by *factor* ⟶ `id`
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9*** *add_op* ***10***	*term* `write sum ...`	shift *factor* & reduce by *term* ⟶ *factor*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9*** *add_op* ***10*** *term* ***13***	`write sum ...`	shift *term*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5***	*expr* `write sum ...`	reduce by *expr* ⟶ *expr add_op term*
0 *stmt_list* ***2*** `id` ***3*** `:=` ***5*** *expr* ***9***	`write sum ...`	shift *expr*
0 *stmt_list* ***2***	*stmt* `write sum ...`	reduce by *stmt* ⟶ `id :=` *expr*
0	*stmt_list* `write sum ...`	shift *stmt* & reduce by *stmt_list* ⟶ *stmt*
0 *stmt_list* ***2***	`write sum ...`	shift *stmt_list*
0 *stmt_list* ***2*** `write` ***4***	`sum write sum ...`	shift `write`
0 *stmt_list* ***2*** `write` ***4***	*factor* `write sum ...`	shift `id(sum)` & reduce by *factor* ⟶ `id`
0 *stmt_list* ***2*** `write` ***4***	*term* `write sum ...`	shift *factor* & reduce by *term* ⟶ *factor*
0 *stmt_list* ***2*** `write` ***4*** *term* ***7***	`write sum ...`	shift *term*
0 *stmt_list* ***2*** `write` ***4***	*expr* `write sum ...`	reduce by *expr* ⟶ *term*
0 *stmt_list* ***2*** `write` ***4*** *expr* ***6***	`write sum ...`	shift *expr*
0 *stmt_list* ***2***	*stmt* `write sum ...`	reduce by *stmt* ⟶ `write` *expr*
0	*stmt_list* `write sum ...`	shift *stmt* & reduce by *stmt_list* ⟶ *stmt_list stmt*
0 *stmt_list* ***2***	`write sum / ...`	shift *stmt_list*
0 *stmt_list* ***2*** `write` ***4***	`sum / 2 ...`	shift `write`
0 *stmt_list* ***2*** `write` ***4***	*factor* `/ 2 ...`	shift `id(sum)` & reduce by *factor* ⟶ `id`
0 *stmt_list* ***2*** `write` ***4***	*term* `/ 2 ...`	shift *factor* & reduce by *term* ⟶ *factor*
0 *stmt_list* ***2*** `write` ***4*** *term* ***7***	`/ 2 $$`	shift *term*
0 *stmt_list* ***2*** `write` ***4*** *term* ***7***	*mult_op* `2 $$`	shift `/` & reduce by *mult_op* ⟶ `/`
0 *stmt_list* ***2*** `write` ***4*** *term* ***7*** *mult_op* ***11***	`2 $$`	shift *mult_op*
0 *stmt_list* ***2*** `write` ***4*** *term* ***7*** *mult_op* ***11***	*factor* `$$`	shift `number(2)` & reduce by *factor* ⟶ `number`
0 *stmt_list* ***2*** `write` ***4***	*term* `$$`	shift *factor* & reduce by *term* ⟶ *term mult_op factor*
0 *stmt_list* ***2*** `write` ***4*** *term* ***7***	`$$`	shift *term*
0 *stmt_list* ***2*** `write` ***4***	*expr* `$$`	reduce by *expr* ⟶ *term*
0 *stmt_list* ***2*** `write` ***4*** *expr* ***6***	`$$`	shift *expr*
0 *stmt_list* ***2***	*stmt* `$$`	reduce by *stmt* ⟶ `write` *expr*
0	*stmt_list* `$$`	shift *stmt* & reduce by *stmt_list* ⟶ *stmt_list stmt*
0 *stmt_list* ***2***	`$$`	shift *stmt_list*
0	*program*	shift `$$` & reduce by *program* ⟶ *stmt_list* `$$`
[done]		

Figure 2.30 Trace of a table-driven SLR(1) parse of the sum-and-average program. States in the parse stack are shown in boldface type. Symbols in the parse stack are for clarity only; they are not needed by the parsing algorithm. Parsing begins with the initial state of the CFSM (State 0) in the stack. It ends when we reduce by *program* ⟶ *stmt_list* `$$`, uncovering State 0 again and pushing *program* onto the input stream.

a parallel program (or the operating system) to wait for a signal from another process or an I/O device.

EXAMPLE 2.41

CFSM with epsilon productions

If we look at the CFSM for the calculator language, we discover that State 0 is the only state that needs to be changed in order to allow empty statement lists. The item

$$\mathit{stmt\_list} \longrightarrow \bullet\ \mathit{stmt}$$

becomes

$$\mathit{stmt\_list} \longrightarrow \bullet\ \epsilon$$

which is equivalent to

$$\mathit{stmt\_list} \longrightarrow \epsilon\ \bullet$$

or simply

$$\mathit{stmt\_list} \longrightarrow \bullet$$

The entire state is then

$\mathit{program} \longrightarrow \bullet\ \mathit{stmt\_list}$ `$$`	on *stmt_list* shift and goto 2
$\mathit{stmt\_list} \longrightarrow \bullet\ \mathit{stmt\_list}\ \mathit{stmt}$	
$\mathit{stmt\_list} \longrightarrow \bullet$	on `$$` reduce (pop 0 states, push *stmt_list* on input)
$\mathit{stmt} \longrightarrow \bullet$ `id := ` expr	on `id` shift and goto 3
$\mathit{stmt} \longrightarrow \bullet$ `read id`	on `read` shift and goto 1
$\mathit{stmt} \longrightarrow \bullet$ `write` expr	on `write` shift and goto 4

The look-ahead for item

$$\mathit{stmt\_list} \longrightarrow \bullet$$

is FOLLOW(*stmt_list*), which is the end-marker, `$$`. Since `$$` does not appear in the look-aheads for any other item in this state, our grammar is still SLR(1). It is worth noting that epsilon productions commonly prevent a grammar from being LR(0): if such a production shares a state with an item in which the dot precedes a terminal, we won't be able to tell whether to "recognize" ϵ without peeking ahead. ■

✓ CHECK YOUR UNDERSTANDING

37. What is the *handle* of a right sentential form?

38. Explain the significance of the characteristic finite-state machine in LR parsing.

39. What is the significance of the dot ($\bullet$) in an LR item?

40. What distinguishes the *basis* from the *closure* of an LR state?

41. What is a *shift-reduce conflict*? How is it resolved in the various kinds of LR-family parsers?

42. Outline the steps performed by the driver of a bottom-up parser.
43. What kind of parser is produced by `yacc/bison`? By ANTLR?
44. Why are there never any epsilon productions in an LR(0) grammar?

2.3.5 Syntax Errors

EXAMPLE 2.42

A syntax error in C

Suppose we are parsing a C program and see the following code fragment in a context where a statement is expected:

```
A = B : C + D;
```

We will detect a syntax error immediately after the `B`, when the colon appears from the scanner. At this point the simplest thing to do is just to print an error message and halt. This naive approach is generally not acceptable, however: it would mean that every run of the compiler reveals no more than one syntax error. Since most programs, at least at first, contain numerous such errors, we really need to find as many as possible now (we'd also like to continue looking for semantic errors). To do so, we must modify the state of the parser and/or the input stream so that the upcoming token(s) are acceptable. We shall probably want to turn off code generation, disabling the back end of the compiler: since the input is not a valid program, the code will not be of use, and there's no point in spending time creating it.

In general, the term *syntax error recovery* is applied to any technique that allows the compiler, in the face of a syntax error, to continue looking for other errors later in the program. High-quality syntax error recovery is essential in any production-quality compiler. The better the recovery technique, the more likely the compiler will be to recognize additional errors (especially nearby errors) correctly, and the less likely it will be to become confused and announce spurious *cascading errors* later in the program.

IN MORE DEPTH

On the companion site we explore several possible approaches to syntax error recovery. In *panic mode*, the compiler writer defines a small set of "safe symbols" that delimit clean points in the input. Semicolons, which typically end a statement, are a good choice in many languages. When an error occurs, the compiler deletes input tokens until it finds a safe symbol, and then "backs the parser out" (e.g., returns from recursive descent subroutines) until it finds a context in which that symbol might appear. *Phrase-level recovery* improves on this technique by employing different sets of "safe" symbols in different productions of the grammar (right parentheses when in an expression; semicolons when in a declaration). *Context-specific look-ahead* obtains additional improvements by differentiating among the various contexts in which a given production might appear in a syntax tree. To respond gracefully to certain common programming errors, the compiler writer may augment the grammar with *error productions* that capture language-specific idioms that are incorrect but are often written by mistake.

Niklaus Wirth published an elegant implementation of phrase-level and context-specific recovery for recursive descent parsers in 1976 [Wir76, Sec. 5.9]. *Exceptions* (to be discussed further in Section 9.4) provide a simpler alternative if supported by the language in which the compiler is written. For table-driven top-down parsers, Fischer, Milton, and Quiring published an algorithm in 1980 that automatically implements a well-defined notion of *locally least-cost syntax repair*. Locally least-cost repair is also possible in bottom-up parsers, but it is significantly more difficult. Most bottom-up parsers rely on more straightforward phrase-level recovery; a typical example can be found in `yacc/bison`.

2.4 Theoretical Foundations

Our understanding of the relative roles and computational power of scanners, parsers, regular expressions, and context-free grammars is based on the formalisms of *automata theory*. In automata theory, a *formal language* is a set of strings of symbols drawn from a finite *alphabet*. A formal language can be specified either by a set of rules (such as regular expressions or a context-free grammar) that generates the language, or by a *formal machine* that *accepts* (*recognizes*) the language. A formal machine takes strings of symbols as input and outputs either "yes" or "no." A machine is said to accept a language if it says "yes" to all and only those strings that are in the language. Alternatively, a language can be defined as the set of strings for which a particular machine says "yes."

Formal languages can be grouped into a series of successively larger classes known as the *Chomsky hierarchy*.[14] Most of the classes can be characterized in two ways: by the types of rules that can be used to generate the set of strings, or by the type of formal machine that is capable of recognizing the language. As we have seen, *regular languages* are defined by using concatenation, alternation, and Kleene closure, and are recognized by a scanner. *Context-free languages* are a proper superset of the regular languages. They are defined by using concatenation, alternation, and recursion (which subsumes Kleene closure), and are recognized by a parser. A scanner is a concrete realization of a *finite automaton*, a type of formal machine. A parser is a concrete realization of a *push-down automaton*. Just as context-free grammars add recursion to regular expressions, push-down automata add a stack to the memory of a finite automaton. There are additional levels in the Chomsky hierarchy, but they are less directly applicable to compiler construction, and are not covered here.

[14] Noam Chomsky (1928–), a linguist and social philosopher at the Massachusetts Institute of Technology, developed much of the early theory of formal languages.

It can be proven, constructively, that regular expressions and finite automata are equivalent: one can construct a finite automaton that accepts the language defined by a given regular expression, and vice versa. Similarly, it is possible to construct a push-down automaton that accepts the language defined by a given context-free grammar, and vice versa. The grammar-to-automaton constructions are in fact performed by scanner and parser generators such as `lex` and `yacc`. Of course, a real scanner does not accept just one token; it is called in a loop so that it keeps accepting tokens repeatedly. As noted in Sidebar 2.4, this detail is accommodated by having the scanner accept the alternation of all the tokens in the language (with distinguished final states), and by having it continue to consume characters until no longer token can be constructed.

IN MORE DEPTH

On the companion site we consider finite and pushdown automata in more detail. We give an algorithm to convert a DFA into an equivalent regular expression. Combined with the constructions in Section 2.2.1, this algorithm demonstrates the equivalence of regular expressions and finite automata. We also consider the sets of grammars and languages that can and cannot be parsed by the various linear-time parsing algorithms.

2.5 Summary and Concluding Remarks

In this chapter we have introduced the formalisms of regular expressions and context-free grammars, and the algorithms that underlie scanning and parsing in practical compilers. We also mentioned syntax error recovery, and presented a quick overview of relevant parts of automata theory. Regular expressions and context-free grammars are language *generators*: they specify how to construct valid strings of characters or tokens. Scanners and parsers are language *recognizers*: they indicate whether a given string is valid. The principal job of the scanner is to reduce the quantity of information that must be processed by the parser, by grouping characters together into tokens, and by removing comments and white space. Scanner and parser generators automatically translate regular expressions and context-free grammars into scanners and parsers.

Practical parsers for programming languages (parsers that run in linear time) fall into two principal groups: top-down (also called LL or predictive) and bottom-up (also called LR or shift-reduce). A top-down parser constructs a parse tree starting from the root and proceeding in a left-to-right depth-first traversal. A bottom-up parser constructs a parse tree starting from the leaves, again working left-to-right, and combining partial trees together when it recognizes the children of an internal node. The stack of a top-down parser contains a prediction of what will be seen in the future; the stack of a bottom-up parser contains a record of what has been seen in the past.

Top-down parsers tend to be simple, both in the parsing of valid strings and in the recovery from errors in invalid strings. Bottom-up parsers are more powerful, and in some cases lend themselves to more intuitively structured grammars, though they suffer from the inability to embed action routines at arbitrary points in a right-hand side (we discuss this point in more detail in Section C-4.5.1). Both varieties of parser are used in real compilers, though bottom-up parsers are more common. Top-down parsers tend to be smaller in terms of code and data size, but modern machines provide ample memory for either.

Both scanners and parsers can be built by hand if an automatic tool is not available. Handbuilt scanners are simple enough to be relatively common. Handbuilt parsers are generally limited to top-down recursive descent, and are most commonly used for comparatively simple languages. Automatic generation of the scanner and parser has the advantage of increased reliability, reduced development time, and easy modification and enhancement.

Various features of language design can have a major impact on the complexity of syntax analysis. In many cases, features that make it difficult for a compiler to scan or parse also make it difficult for a human being to write correct, maintainable code. Examples include the lexical structure of Fortran and the `if`... `then` ... `else` statement of languages like Pascal. This interplay among language design, implementation, and use will be a recurring theme throughout the remainder of the book.

2.6 Exercises

2.1 Write regular expressions to capture the following.

- **(a)** Strings in C. These are delimited by double quotes (`"`), and may not contain newline characters. They may contain double-quote or backslash characters if and only if those characters are "escaped" by a preceding backslash. You may find it helpful to introduce shorthand notation to represent any character that is *not* a member of a small specified set.
- **(b)** Comments in Pascal. These are delimited by `(*` and `*)` or by `{` and `}`. They are not permitted to nest.
- **(c)** Numeric constants in C. These are octal, decimal, or hexadecimal integers, or decimal or hexadecimal floating-point values. An octal integer begins with `0`, and may contain only the digits `0`–`7`. A hexadecimal integer begins with `0x` or `0X`, and may contain the digits `0`–`9` and `a`/`A`–`f`/`F`. A decimal floating-point value has a fractional portion (beginning with a dot) or an exponent (beginning with `E` or `e`). Unlike a decimal integer, it is allowed to start with `0`. A hexadecimal floating-point value has an optional fractional portion and a mandatory exponent (beginning with `P` or `p`). In either decimal or hexadecimal, there may be digits

to the left of the dot, the right of the dot, or both, and the exponent itself is given in decimal, with an optional leading `+` or `-` sign. An integer may end with an optional `U` or `u` (indicating "unsigned"), and/or `L` or `l` (indicating "long") or `LL` or `ll` (indicating "long long"). A floating-point value may end with an optional `F` or `f` (indicating "float"—single precision) or `L` or `l` (indicating "long"—double precision).

(d) Floating-point constants in Ada. These match the definition of *real* in Example 2.3, except that (1) a digit is required on both sides of the decimal point, (2) an underscore is permitted between digits, and (3) an alternative numeric base may be specified by surrounding the nonexponent part of the number with pound signs, preceded by a base in decimal (e.g., `16#6.a7#e+2`). In this latter case, the letters `a..f` (both upper- and lowercase) are permitted as digits. Use of these letters in an inappropriate (e.g., decimal) number is an error, but need not be caught by the scanner.

(e) Inexact constants in Scheme. Scheme allows real numbers to be explicitly *inexact* (imprecise). A programmer who wants to express all constants using the same number of characters can use sharp signs (`#`) in place of any lower-significance digits whose values are not known. A base-10 constant without exponent consists of one or more digits followed by zero of more sharp signs. An optional decimal point can be placed at the beginning, the end, or anywhere in-between. (For the record, numbers in Scheme are actually a good bit more complicated than this. For the purposes of this exercise, please ignore anything you may know about sign, exponent, radix, exactness and length specifiers, and complex or rational values.)

(f) Financial quantities in American notation. These have a leading dollar sign (`$`), an optional string of asterisks (`*`—used on checks to discourage fraud), a string of decimal digits, and an optional fractional part consisting of a decimal point (`.`) and two decimal digits. The string of digits to the left of the decimal point may consist of a single zero (`0`). Otherwise it must not start with a zero. If there are more than three digits to the left of the decimal point, groups of three (counting from the right) must be separated by commas (`,`). Example: `$**2,345.67`. (Feel free to use "productions" to define abbreviations, so long as the language remains regular.)

2.2 Show (as "circles-and-arrows" diagrams) the finite automata for Exercise 2.1.

2.3 Build a regular expression that captures all nonempty sequences of letters other than `file`, `for`, and `from`. For notational convenience, you may assume the existence of a **not** operator that takes a set of letters as argument and matches any *other* letter. Comment on the practicality of constructing a regular expression for all sequences of letters other than the keywords of a large programming language.

2.4 (a) Show the NFA that results from applying the construction of Figure 2.7 to the regular expression *letter* (*letter* | *digit*)*.

(b) Apply the transformation illustrated by Example 2.14 to create an equivalent DFA.

(c) Apply the transformation illustrated by Example 2.15 to minimize the DFA.

2.5 Starting with the regular expressions for *integer* and *decimal* in Example 2.3, construct an equivalent NFA, the set-of-subsets DFA, and the minimal equivalent DFA. Be sure to keep separate the final states for the two different kinds of token (see Sidebar 2.4). You may find the exercise easier if you undertake it by modifying the machines in Examples 2.13 through 2.15.

2.6 Build an ad hoc scanner for the calculator language. As output, have it print a list, in order, of the input tokens. For simplicity, feel free to simply halt in the event of a lexical error.

2.7 Write a program in your favorite scripting language to remove comments from programs in the calculator language (Example 2.9).

2.8 Build a nested-`case`-statements finite automaton that converts all letters in its input to lower case, except within Pascal-style comments and strings. A Pascal comment is delimited by `{` and `}`, or by `(*` and `*)`. Comments do not nest. A Pascal string is delimited by single quotes (`' ... '`). A quote character can be placed in a string by doubling it (`'Madam, I''m Adam.'`). This upper-to-lower mapping can be useful if feeding a program written in standard Pascal (which ignores case) to a compiler that considers upper- and lowercase letters to be distinct.

2.9 (a) Describe in English the language defined by the regular expression `a* ( b a* b a* )*`. Your description should be a high-level characterization—one that would still make sense if we were using a different regular expression for the same language.

(b) Write an unambiguous context-free grammar that generates the same language.

(c) Using your grammar from part (b), give a canonical (right-most) derivation of the string `b a a b a a a b b`.

2.10 Give an example of a grammar that captures right associativity for an exponentiation operator (e.g., `**` in Fortran).

2.11 Prove that the following grammar is LL(1):

decl ⟶ `ID` *decl_tail*
decl_tail ⟶ `,` *decl*
⟶ `: ID ;`

(The final `ID` is meant to be a type name.)

2.12 Consider the following grammar:

$$
\begin{aligned}
G &\longrightarrow S\ \texttt{\$\$} \\
S &\longrightarrow A\ M \\
M &\longrightarrow S \mid \epsilon \\
A &\longrightarrow \texttt{a}\ E \mid \texttt{b}\ A\ A \\
E &\longrightarrow \texttt{a}\ B \mid \texttt{b}\ A \mid \epsilon \\
B &\longrightarrow \texttt{b}\ E \mid \texttt{a}\ B\ B
\end{aligned}
$$

(a) Describe in English the language that the grammar generates.

(b) Show a parse tree for the string `a b a a`.

(c) Is the grammar LL(1)? If so, show the parse table; if not, identify a prediction conflict.

2.13 Consider the following grammar:

$$
\begin{aligned}
\textit{stmt} &\longrightarrow \textit{assignment} \\
&\longrightarrow \textit{subr\_call} \\
\textit{assignment} &\longrightarrow \texttt{id}\ \texttt{:=}\ \textit{expr} \\
\textit{subr\_call} &\longrightarrow \texttt{id}\ \texttt{(}\ \textit{arg\_list}\ \texttt{)} \\
\textit{expr} &\longrightarrow \textit{primary}\ \textit{expr\_tail} \\
\textit{expr\_tail} &\longrightarrow \textit{op}\ \textit{expr} \\
&\longrightarrow \epsilon \\
\textit{primary} &\longrightarrow \texttt{id} \\
&\longrightarrow \textit{subr\_call} \\
&\longrightarrow \texttt{(}\ \textit{expr}\ \texttt{)} \\
\textit{op} &\longrightarrow \texttt{+} \mid \texttt{-} \mid \texttt{*} \mid \texttt{/} \\
\textit{arg\_list} &\longrightarrow \textit{expr}\ \textit{args\_tail} \\
\textit{args\_tail} &\longrightarrow \texttt{,}\ \textit{arg\_list} \\
&\longrightarrow \epsilon
\end{aligned}
$$

(a) Construct a parse tree for the input string
`foo(a, b)`.

(b) Give a canonical (right-most) derivation of this same string.

(c) Prove that the grammar is not LL(1).

(d) Modify the grammar so that it *is* LL(1).

2.14 Consider the language consisting of all strings of properly balanced parentheses and brackets.

(a) Give LL(1) and SLR(1) grammars for this language.

(b) Give the corresponding LL(1) and SLR(1) parsing tables.

(c) For each grammar, show the parse tree for `([]([]))[](())`.

(d) Give a trace of the actions of the parsers in constructing these trees.

2.15 Consider the following context-free grammar.

$$
\begin{array}{lcl}
G & \longrightarrow & G\ B \\
 & \longrightarrow & G\ N \\
 & \longrightarrow & \epsilon \\
B & \longrightarrow & \texttt{(}\ E\ \texttt{)} \\
E & \longrightarrow & E\ \texttt{(}\ E\ \texttt{)} \\
 & \longrightarrow & \epsilon \\
N & \longrightarrow & \texttt{(}\ L\ \texttt{]} \\
L & \longrightarrow & L\ E \\
 & \longrightarrow & L\ \texttt{(} \\
 & \longrightarrow & \epsilon
\end{array}
$$

(a) Describe, in English, the language generated by this grammar. (Hint: *B* stands for "balanced"; *N* stands for "nonbalanced".) (Your description should be a high-level characterization of the language—one that is independent of the particular grammar chosen.)

(b) Give a parse tree for the string `(( ]( )`.

(c) Give a canonical (right-most) derivation of this same string.

(d) What is FIRST(*E*) in our grammar? What is FOLLOW(*E*)? (Recall that FIRST and FOLLOW sets are defined for symbols in an arbitrary CFG, regardless of parsing algorithm.)

(e) Given its use of left recursion, our grammar is clearly not LL(1). Does this language have an LL(1) grammar? Explain.

2.16 Give a grammar that captures all levels of precedence for arithmetic expressions in C, as shown in Figure 6.1. (Hint: This exercise is somewhat tedious. You'll probably want to attack it with a text editor rather than a pencil.)

2.17 Extend the grammar of Figure 2.25 to include `if` statements and `while` loops, along the lines suggested by the following examples:

```
abs := n
if n < 0 then abs := 0 - abs fi

sum := 0
read count
while count > 0 do
    read n
    sum := sum + n
    count := count - 1
od
write sum
```

Your grammar should support the six standard comparison operations in conditions, with arbitrary expressions as operands. It should also allow an arbitrary number of statements in the body of an `if` or `while` statement.

2.18 Consider the following LL(1) grammar for a simplified subset of Lisp:

$$\begin{array}{lll} P & \longrightarrow & E\ \texttt{\$\$} \\ E & \longrightarrow & \texttt{atom} \\ & \longrightarrow & '\ E \\ & \longrightarrow & \texttt{(}\ E\ Es\ \texttt{)} \\ Es & \longrightarrow & E\ Es \\ & \longrightarrow & \end{array}$$

(a) What is FIRST(Es)? FOLLOW(E)? PREDICT($Es \longrightarrow \epsilon$)?

(b) Give a parse tree for the string `(cdr '(a b c)) $$`.

(c) Show the left-most derivation of `(cdr '(a b c)) $$`.

(d) Show a trace, in the style of Figure 2.21, of a table-driven top-down parse of this same input.

(e) Now consider a recursive descent parser running on the same input. At the point where the quote token (’) is matched, which recursive descent routines will be active (i.e., what routines will have a frame on the parser's run-time stack)?

2.19 Write top-down and bottom-up grammars for the language consisting of all well-formed regular expressions. Arrange for all operators to be left-associative. Give Kleene closure the highest precedence and alternation the lowest precedence.

2.20 Suppose that the expression grammar in Example 2.8 were to be used in conjunction with a scanner that did *not* remove comments from the input, but rather returned them as tokens. How would the grammar need to be modified to allow comments to appear at arbitrary places in the input?

2.21 Build a complete recursive descent parser for the calculator language. As output, have it print a trace of its matches and predictions.

2.22 Extend your solution to Exercise 2.21 to build an explicit parse tree.

2.23 Extend your solution to Exercise 2.21 to build an abstract syntax tree directly, without constructing a parse tree first.

2.24 The dangling `else` problem of Pascal was not shared by its predecessor Algol 60. To avoid ambiguity regarding which `then` is matched by an `else`, Algol 60 prohibited `if` statements immediately inside a `then` clause. The Pascal fragment

```
if C1 then if C2 then S1 else S2
```

had to be written as either

```
if C1 then begin if C2 then S1 end else S2
```

or

```
if C1 then begin if C2 then S1 else S2 end
```

in Algol 60. Show how to write a grammar for conditional statements that enforces this rule. (Hint: You will want to distinguish in your grammar between conditional statements and nonconditional statements; some contexts will accept either, some only the latter.)

2.25 Flesh out the details of an algorithm to eliminate left recursion and common prefixes in an arbitrary context-free grammar.

2.26 In some languages an assignment can appear in any context in which an expression is expected: the value of the expression is the right-hand side of the assignment, which is placed into the left-hand side as a side effect. Consider the following grammar fragment for such a language. Explain why it is not LL(1), and discuss what might be done to make it so.

expr ⟶ `id :=` *expr*
⟶ *term term_tail*
term_tail ⟶ `+` *term term_tail* | ϵ
term ⟶ *factor factor_tail*
factor_tail ⟶ `*` *factor factor_tail* | ϵ
factor ⟶ `(` *expr* `)` | `id`

2.27 Construct the CFSM for the *id_list* grammar in Example 2.20 and verify that it can be parsed bottom-up with *zero* tokens of look-ahead.

2.28 Modify the grammar in Exercise 2.27 to allow an *id_list* to be empty. Is the grammar still LR(0)?

2.29 Repeat Example 2.36 using the grammar of Figure 2.15.

2.30 Consider the following grammar for a declaration list:

decl_list ⟶ *decl_list decl* `;` | *decl* `;`
decl ⟶ `id :` *type*
type ⟶ `int` | `real` | `char`
⟶ `array const .. const of` *type*
⟶ `record` *decl_list* `end`

Construct the CFSM for this grammar. Use it to trace out a parse (as in Figure 2.30) for the following input program:

```
foo : record
        a : char;
        b : array 1 .. 2 of real;
    end;
```

2.31–2.37 In More Depth.

2.7 Explorations

2.38 Some languages (e.g., C) distinguish between upper- and lowercase letters in identifiers. Others (e.g., Ada) do not. Which convention do you prefer? Why?

2.39 The syntax for type casts in C and its descendants introduces potential ambiguity: is `(x)-y` a subtraction, or the unary negation of `y`, cast to type `x`? Find out how C, C++, Java, and C# answer this question. Discuss how you would implement the answer(s).

2.40 What do you think of Haskell, Occam, and Python's use of indentation to delimit control constructs (Section 2.1.1)? Would you expect this convention to make program construction and maintenance easier or harder? Why?

2.41 Skip ahead to Section 14.4.2 and learn about the "regular expressions" used in scripting languages, editors, search tools, and so on. Are these really regular? What can they express that cannot be expressed in the notation introduced in Section 2.1.1?

2.42 Rebuild the automaton of Exercise 2.8 using `lex/flex`.

2.43 Find a manual for `yacc/bison`, or consult a compiler textbook [ALSU07, Secs. 4.8.1 and 4.9.2] to learn about *operator precedence parsing*. Explain how it could be used to simplify the grammar of Exercise 2.16.

2.44 Use `lex/flex` and `yacc/bison` to construct a parser for the calculator language. Have it output a trace of its shifts and reductions.

2.45 Repeat the previous exercise using ANTLR.

2.46–2.47 In More Depth.

2.8 Bibliographic Notes

Our coverage of scanning and parsing in this chapter has of necessity been brief. Considerably more detail can be found in texts on parsing theory [AU72] and compiler construction [ALSU07, FCL10, App97, GBJ$^+$12, CT04]. Many compilers of the early 1960s employed recursive descent parsers. Lewis and Stearns [LS68] and Rosenkrantz and Stearns [RS70] published early formal studies of LL grammars and parsing. The original formulation of LR parsing is due to Knuth [Knu65]. Bottom-up parsing became practical with DeRemer's discovery of the SLR and LALR algorithms [DeR71]. W. L. Johnson et al. [JPAR68] describe an early scanner generator. The Unix `lex` tool is due to Lesk [Les75]. `Yacc` is due to S. C. Johnson [Joh75].

Further details on formal language theory can be found in a variety of textbooks, including those of Hopcroft, Motwani, and Ullman [HMU07] and

Sipser [Sip13]. Kleene [Kle56] and Rabin and Scott [RS59] proved the equivalence of regular expressions and finite automata.[15] The proof that finite automata are unable to recognize nested constructs is based on a theorem known as the *pumping lemma*, due to Bar-Hillel, Perles, and Shamir [BHPS61]. Context-free grammars were first explored by Chomsky [Cho56] in the context of natural language. Independently, Backus and Naur developed BNF for the syntactic description of Algol 60 [NBB$^+$63]. Ginsburg and Rice [GR62] recognized the equivalence of the two notations. Chomsky [Cho62] and Evey [Eve63] demonstrated the equivalence of context-free grammars and push-down automata.

Fischer et al.'s text [FCL10] contains an excellent survey of error recovery and repair techniques, with references to other work. The phrase-level recovery mechanism for recursive descent parsers described in Section C-2.3.5 is due to Wirth [Wir76, Sec. 5.9]. The locally least-cost recovery mechanism for table-driven LL parsers described in Section C-2.3.5 is due to Fischer, Milton, and Quiring [FMQ80]. Dion published a locally least-cost bottom-up repair algorithm in 1978 [Dio78]. It is quite complex, and requires very large precomputed tables. McKenzie, Yeatman, and De Vere subsequently showed how to effect the same repairs without the precomputed tables, at a higher but still acceptable cost in time [MYD95].

[15] Dana Scott (1932–), Professor Emeritus at Carnegie Mellon University, is known principally for inventing domain theory and launching the field of denotational semantics, which provides a mathematically rigorous way to formalize the meaning of programming languages. Michael Rabin (1931–), of Harvard University, has made seminal contributions to the concepts of nondeterminism and randomization in computer science. Scott and Rabin shared the ACM Turing Award in 1976.

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3 Names, Scopes, and Bindings

Early languages such as Fortran, Algol, and Lisp were termed "high level" because their syntax and semantics were significantly more *abstract*—farther from the hardware—than those of the assembly languages they were intended to supplant. Abstraction made it possible to write programs that would run well on a wide variety of machines. It also made programs significantly easier for human beings to understand. While machine independence remains important, it is primarily ease of programming that continues to drive the design of modern languages. This chapter is the first of six to address core issues in language design. (The others are Chapters 6 through 10.) Much of the current discussion will revolve around the notion of *names*.

A name is a mnemonic character string used to represent something else. Names in most languages are identifiers (alphanumeric tokens), though certain other symbols, such as `+` or `:=`, can also be names. Names allow us to refer to variables, constants, operations, types, and so on using symbolic identifiers rather than low-level concepts like addresses. Names are also essential in the context of a second meaning of the word *abstraction*. In this second meaning, abstraction is a process by which the programmer associates a name with a potentially complicated program fragment, which can then be thought of in terms of its purpose or function, rather than in terms of how that function is achieved. By hiding irrelevant details, abstraction reduces conceptual complexity, making it possible for the programmer to focus on a manageable subset of the program text at any particular time. Subroutines are *control abstractions*: they allow the programmer to hide arbitrarily complicated code behind a simple interface. Classes are *data abstractions*: they allow the programmer to hide data representation details behind a (comparatively) simple set of operations.

We will look at several major issues related to names. Section 3.1 introduces the notion of *binding time*, which refers not only to the binding of a name to the thing it represents, but also in general to the notion of resolving any design decision in a language implementation. Section 3.2 outlines the various mechanisms used to allocate and deallocate storage space for objects, and distinguishes between the lifetime of an object and the lifetime of a binding of a name to that object.[1] Most name-to-object bindings are usable only within a limited region of a given high-level program. Section 3.3 explores the *scope* rules that define this region; Section 3.4 (mostly on the companion site) considers their implementation.

The complete set of bindings in effect at a given point in a program is known as the current *referencing environment*. Section 3.5 discusses aliasing, in which more than one name may refer to a given object in a given scope, and overloading, in which a name may refer to more than one object in a given scope, depending on the context of the reference. Section 3.6 expands on the notion of scope rules by considering the ways in which a referencing environment may be bound to a subroutine that is passed as a parameter, returned from a function, or stored in a variable. Section 3.7 discusses macro expansion, which can introduce new names via textual substitution, sometimes in ways that are at odds with the rest of the language. Finally, Section 3.8 (mostly on the companion site) discusses separate compilation.

3.1 The Notion of Binding Time

A *binding* is an association between two things, such as a name and the thing it names. *Binding time* is the time at which a binding is created or, more generally, the time at which any implementation decision is made (we can think of this as binding an answer to a question). There are many different times at which decisions may be bound:

Language design time: In most languages, the control-flow constructs, the set of fundamental (primitive) types, the available *constructors* for creating complex types, and many other aspects of language semantics are chosen when the language is designed.

Language implementation time: Most language manuals leave a variety of issues to the discretion of the language implementor. Typical (though by no means universal) examples include the precision (number of bits) of the fundamental types, the coupling of I/O to the operating system's notion of files, and the organization and maximum sizes of the stack and heap.

Program writing time: Programmers, of course, choose algorithms, data structures, and names.

Compile time: Compilers choose the mapping of high-level constructs to machine code, including the layout of statically defined data in memory.

[1] For want of a better term, we will use the term "object" throughout Chapters 3–9 to refer to anything that might have a name: variables, constants, types, subroutines, modules, and others. In many modern languages "object" has a more formal meaning, which we will consider in Chapter 10.

Link time: Since most compilers support *separate compilation*—compiling different modules of a program at different times—and depend on the availability of a library of standard subroutines, a program is usually not complete until the various modules are joined together by a linker. The linker chooses the overall layout of the modules with respect to one another, and resolves intermodule references. When a name in one module refers to an object in another module, the binding between the two is not finalized until link time.

Load time: Load time refers to the point at which the operating system loads the program into memory so that it can run. In primitive operating systems, the choice of machine addresses for objects within the program was not finalized until load time. Most modern operating systems distinguish between virtual and physical addresses. Virtual addresses are chosen at link time; physical addresses can actually change at run time. The processor's memory management hardware translates virtual addresses into physical addresses during each individual instruction at run time.

Run time: Run time is actually a very broad term that covers the entire span from the beginning to the end of execution. Bindings of values to variables occur at run time, as do a host of other decisions that vary from language to language. Run time subsumes program start-up time, module entry time, elaboration time (the point at which a declaration is first "seen"), subroutine call time, block entry time, and expression evaluation time/statement execution.

The terms *static* and *dynamic* are generally used to refer to things bound before run time and at run time, respectively. Clearly "static" is a coarse term. So is "dynamic."

Compiler-based language implementations tend to be more efficient than interpreter-based implementations because they make earlier decisions. For example, a compiler analyzes the syntax and semantics of global variable declarations once, before the program ever runs. It decides on a layout for those variables in memory and generates efficient code to access them wherever they appear in the program. A pure interpreter, by contrast, must analyze the declarations every time the program begins execution. In the worst case, an interpreter may reanalyze the local declarations within a subroutine each time that subroutine is called. If a call appears in a deeply nested loop, the savings achieved by a compiler that is able to analyze the declarations only once may be very large. As we shall see in

DESIGN & IMPLEMENTATION

3.1 Binding time

It is difficult to overemphasize the importance of binding times in the design and implementation of programming languages. In general, early binding times are associated with greater efficiency, while later binding times are associated with greater flexibility. The tension between these goals provides a recurring theme for later chapters of this book.

the following section, a compiler will not usually be able to predict the address of a local variable at compile time, since space for the variable will be allocated dynamically on a stack, but it can arrange for the variable to appear at a fixed offset from the location pointed to by a certain register at run time.

Some languages are difficult to compile because their semantics require fundamental decisions to be postponed until run time, generally in order to increase the flexibility or expressiveness of the language. Most scripting languages, for example, delay all type checking until run time. References to objects of arbitrary types (classes) can be assigned into arbitrary named variables, as long as the program never ends up applying an operator to (invoking a method of) an object that is not prepared to handle it. This form of *polymorphism*—applicability to objects or expressions of multiple types—allows the programmer to write unusually flexible and general-purpose code. We will mention polymorphism again in several future sections, including 7.1.2, 7.3, 10.1.1, and 14.4.4.

3.2 Object Lifetime and Storage Management

In any discussion of names and bindings, it is important to distinguish between names and the objects to which they refer, and to identify several key events:

- Creation and destruction of objects
- Creation and destruction of bindings
- Deactivation and reactivation of bindings that may be temporarily unusable
- References to variables, subroutines, types, and so on, all of which use bindings

The period of time between the creation and the destruction of a name-to-object binding is called the binding's *lifetime*. Similarly, the time between the creation and destruction of an object is the object's lifetime. These lifetimes need not necessarily coincide. In particular, an object may retain its value and the potential to be accessed even when a given name can no longer be used to access it. When a variable is passed to a subroutine by *reference*, for example (as it typically is in Fortran or with '`&`' parameters in C++), the binding between the parameter name and the variable that was passed has a lifetime shorter than that of the variable itself. It is also possible, though generally a sign of a program bug, for a name-to-object binding to have a lifetime *longer* than that of the object. This can happen, for example, if an object created via the C++ `new` operator is passed as a `&` parameter and then deallocated (`delete`-ed) before the subroutine returns. A binding to an object that is no longer live is called a *dangling reference*. Dangling references will be discussed further in Sections 3.6 and 8.5.2.

Object lifetimes generally correspond to one of three principal *storage allocation* mechanisms, used to manage the object's space:

1. *Static* objects are given an absolute address that is retained throughout the program's execution.

2. *Stack* objects are allocated and deallocated in last-in, first-out order, usually in conjunction with subroutine calls and returns.
3. *Heap* objects may be allocated and deallocated at arbitrary times. They require a more general (and expensive) storage management algorithm.

3.2.1 Static Allocation

Global variables are the obvious example of static objects, but not the only one. The instructions that constitute a program's machine code can also be thought of as statically allocated objects. We shall see examples in Section 3.3.1 of variables that are local to a single subroutine, but retain their values from one invocation to the next; their space is statically allocated. Numeric and string-valued constant literals are also statically allocated, for statements such as `A = B/14.7` or `printf("hello, world\n")`. (Small constants are often stored within the instruction itself; larger ones are assigned a separate location.) Finally, most compilers produce a variety of tables that are used by run-time support routines for debugging, dynamic type checking, garbage collection, exception handling, and other purposes; these are also statically allocated. Statically allocated objects whose value should not change during program execution (e.g., instructions, constants, and certain run-time tables) are often allocated in protected, read-only memory, so that any inadvertent attempt to write to them will cause a processor interrupt, allowing the operating system to announce a run-time error.

Logically speaking, local variables are created when their subroutine is called, and destroyed when it returns. If the subroutine is called repeatedly, each invocation is said to create and destroy a separate *instance* of each local variable. It is not always the case, however, that a language implementation must perform work at run time corresponding to these create and destroy operations. Recursion was not originally supported in Fortran (it was added in Fortran 90). As a result, there can never be more than one invocation of a subroutine active in an older Fortran program at any given time, and a compiler may choose to use static allocation for local variables, effectively arranging for the variables of different invocations to share the same locations, and thereby avoiding any run-time overhead for creation and destruction. ■

EXAMPLE 3.1

Static allocation of local variables

DESIGN & IMPLEMENTATION

3.2 Recursion in Fortran

The lack of recursion in (pre-Fortran 90) Fortran is generally attributed to the expense of stack manipulation on the IBM 704, on which the language was first implemented. Many (perhaps most) Fortran implementations choose to use a stack for local variables, but because the language definition permits the use of static allocation instead, Fortran programmers were denied the benefits of language-supported recursion for over 30 years.

In many languages a named constant is required to have a value that can be determined at compile time. Usually the expression that specifies the constant's value is permitted to include only other known constants and built-in functions and arithmetic operators. Named constants of this sort, together with constant literals, are sometimes called *manifest constants* or *compile-time constants*. Manifest constants can always be allocated statically, even if they are local to a recursive subroutine: multiple instances can share the same location.

In other languages (e.g., C and Ada), constants are simply variables that cannot be changed after elaboration (initialization) time. Their values, though unchanging, can sometimes depend on other values that are not known until run time. Such *elaboration-time constants*, when local to a recursive subroutine, must be allocated on the stack. C# distinguishes between compile-time and elaboration-time constants using the `const` and `readonly` keywords, respectively.

3.2.2 Stack-Based Allocation

EXAMPLE 3.2

Layout of the run-time stack

If a language permits recursion, static allocation of local variables is no longer an option, since the number of instances of a variable that may need to exist at the same time is conceptually unbounded. Fortunately, the natural nesting of subroutine calls makes it easy to allocate space for locals on a stack. A simplified picture of a typical stack appears in Figure 3.1. Each instance of a subroutine at run time has its own *frame* (also called an *activation record*) on the stack, containing arguments and return values, local variables, temporaries, and bookkeeping information. Temporaries are typically intermediate values produced in complex calculations. Bookkeeping information typically includes the subroutine's return address, a reference to the stack frame of the caller (also called the *dynamic link*), saved values of registers needed by both the caller and the callee, and various other values that we will study later. Arguments to be passed to subsequent routines lie at the top of the frame, where the callee can easily find them. The organization of the remaining information is implementation-dependent: it varies from one language, machine, and compiler to another. ■

Maintenance of the stack is the responsibility of the subroutine *calling sequence*—the code executed by the caller immediately before and after the call—and of the *prologue* (code executed at the beginning) and *epilogue* (code executed at the end) of the subroutine itself. Sometimes the term "calling sequence" is used to refer to the combined operations of the caller, the prologue, and the epilogue. We will study calling sequences in more detail in Section 9.2.

While the location of a stack frame cannot be predicted at compile time (the compiler cannot in general tell what other frames may already be on the stack), the offsets of objects *within* a frame usually *can* be statically determined. Moreover, the compiler can arrange (in the calling sequence or prologue) for a particular register, known as the *frame pointer* to always point to a known location within the frame of the current subroutine. Code that needs to access a local variable within the current frame, or an argument near the top of the calling frame,

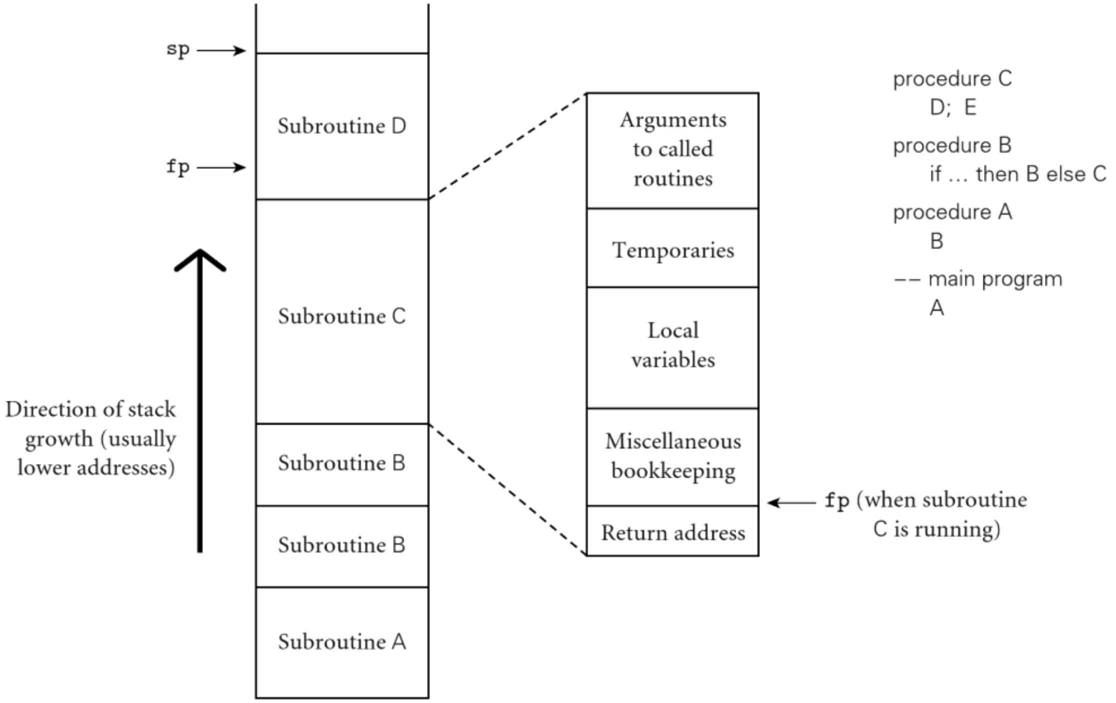


Figure 3.1 **Stack-based allocation of space for subroutines.** We assume here that subroutines have been called as shown in the upper right. In particular, B has called itself once, recursively, before calling C. If D returns and C calls E, E's frame (activation record) will occupy the same space previously used for D's frame. At any given time, the stack pointer (`sp`) register points to the first unused location on the stack (or the last used location on some machines), and the frame pointer (`fp`) register points to a known location within the frame of the current subroutine. The relative order of fields within a frame may vary from machine to machine and compiler to compiler.

can do so by adding a predetermined offset to the value in the frame pointer. As we discuss in Section C-5.3.1, almost every processor provides a *displacement addressing* mechanism that allows this addition to be specified implicitly as part of an ordinary `load` or `store` instruction. The stack grows "downward" toward lower addresses in most language implementations. Some machines provide special `push` and `pop` instructions that assume this direction of growth. Local variables, temporaries, and bookkeeping information typically have negative offsets from the frame pointer. Arguments and returns typically have positive offsets; they reside in the caller's frame.

Even in a language without recursion, it can be advantageous to use a stack for local variables, rather than allocating them statically. In most programs the pattern of potential calls among subroutines does not permit all of those subroutines to be active at the same time. As a result, the total space needed for local variables of currently active subroutines is seldom as large as the total space across *all*

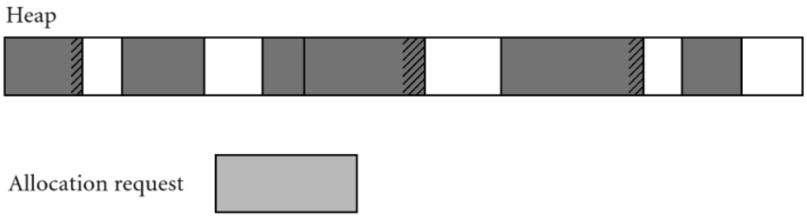


Figure 3.2 **Fragmentation.** The shaded blocks are in use; the clear blocks are free. Cross-hatched space at the ends of in-use blocks represents internal fragmentation. The discontiguous free blocks indicate external fragmentation. While there is more than enough total free space remaining to satisfy an allocation request of the illustrated size, no single remaining block is large enough.

subroutines, active or not. A stack may therefore require substantially less memory at run time than would be required for static allocation.

3.2.3 Heap-Based Allocation

A *heap* is a region of storage in which subblocks can be allocated and deallocated at arbitrary times.[2] Heaps are required for the dynamically allocated pieces of linked data structures, and for objects such as fully general character strings, lists, and sets, whose size may change as a result of an assignment statement or other update operation.

There are many possible strategies to manage space in a heap. We review the major alternatives here; details can be found in any data-structures textbook. The principal concerns are speed and space, and as usual there are tradeoffs between them. Space concerns can be further subdivided into issues of internal and external *fragmentation*. Internal fragmentation occurs when a storage-management algorithm allocates a block that is larger than required to hold a given object; the extra space is then unused. External fragmentation occurs when the blocks that have been assigned to active objects are scattered through the heap in such a way that the remaining, unused space is composed of multiple blocks: there may be quite a lot of free space, but no one piece of it may be large enough to satisfy some future request (see Figure 3.2). ■

EXAMPLE 3.3
External fragmentation in the heap

Many storage-management algorithms maintain a single linked list—the *free list*—of heap blocks not currently in use. Initially the list consists of a single block comprising the entire heap. At each allocation request the algorithm searches the list for a block of appropriate size. With a *first fit* algorithm we select the first block on the list that is large enough to satisfy the request. With a *best fit* algorithm we search the entire list to find the smallest block that is large enough to satisfy the

[2] Unfortunately, the term "heap" is also used for the common tree-based implementation of a priority queue. These two uses of the term have nothing to do with one another.

request. In either case, if the chosen block is significantly larger than required, then we divide it into two and return the unneeded portion to the free list as a smaller block. (If the unneeded portion is below some minimum threshold in size, we may leave it in the allocated block as internal fragmentation.) When a block is deallocated and returned to the free list, we check to see whether either or both of the physically adjacent blocks are free; if so, we coalesce them.

Intuitively, one would expect a best fit algorithm to do a better job of reserving large blocks for large requests. At the same time, it has higher allocation cost than a first fit algorithm, because it must always search the entire list, and it tends to result in a larger number of very small "left-over" blocks. Which approach—first fit or best fit—results in lower external fragmentation depends on the distribution of size requests.

In any algorithm that maintains a single free list, the cost of allocation is linear in the number of free blocks. To reduce this cost to a constant, some storage management algorithms maintain separate free lists for blocks of different sizes. Each request is rounded up to the next standard size (at the cost of internal fragmentation) and allocated from the appropriate list. In effect, the heap is divided into "pools," one for each standard size. The division may be static or dynamic. Two common mechanisms for dynamic pool adjustment are known as the *buddy system* and the *Fibonacci heap*. In the buddy system, the standard block sizes are powers of two. If a block of size 2^k is needed, but none is available, a block of size 2^{k+1} is split in two. One of the halves is used to satisfy the request; the other is placed on the kth free list. When a block is deallocated, it is coalesced with its "buddy"—the other half of the split that created it—if that buddy is free. Fibonacci heaps are similar, but use Fibonacci numbers for the standard sizes, instead of powers of two. The algorithm is slightly more complex, but leads to slightly lower internal fragmentation, because the Fibonacci sequence grows more slowly than 2^k.

The problem with external fragmentation is that the ability of the heap to satisfy requests may degrade over time. Multiple free lists may help, by clustering small blocks in relatively close physical proximity, but they do not eliminate the problem. It is always possible to devise a sequence of requests that cannot be satisfied, even though the total space required is less than the size of the heap. If memory is partitioned among size pools statically, one need only exceed the maximum number of requests of a given size. If pools are dynamically readjusted, one can "checkerboard" the heap by allocating a large number of small blocks and then deallocating every other one, in order of physical address, leaving an alternating pattern of small free and allocated blocks. To eliminate external fragmentation, we must be prepared to *compact* the heap, by moving already-allocated blocks. This task is complicated by the need to find and update all outstanding references to a block that is being moved. We will discuss compaction further in Section 8.5.3.

3.2.4 Garbage Collection

Allocation of heap-based objects is always triggered by some specific operation in a program: instantiating an object, appending to the end of a list, assigning a long value into a previously short string, and so on. Deallocation is also explicit in some languages (e.g., C, C++, and Rust). As we shall see in Section 8.5, however, many languages specify that objects are to be deallocated implicitly when it is no longer possible to reach them from any program variable. The run-time library for such a language must then provide a *garbage collection* mechanism to identify and reclaim unreachable objects. Most functional and scripting languages require garbage collection, as do many more recent imperative languages, including Java and C#.

The traditional arguments in favor of explicit deallocation are implementation simplicity and execution speed. Even naive implementations of automatic garbage collection add significant complexity to the implementation of a language with a rich type system, and even the most sophisticated garbage collector can consume nontrivial amounts of time in certain programs. If the programmer can correctly identify the end of an object's lifetime, without too much run-time bookkeeping, the result is likely to be faster execution.

The argument in favor of automatic garbage collection, however, is compelling: manual deallocation errors are among the most common and costly bugs in real-world programs. If an object is deallocated too soon, the program may follow a *dangling reference*, accessing memory now used by another object. If an object is *not* deallocated at the end of its lifetime, then the program may "leak memory," eventually running out of heap space. Deallocation errors are notoriously difficult to identify and fix. Over time, many language designers and programmers have come to consider automatic garbage collection an essential language feature. Garbage-collection algorithms have improved, reducing their run-time overhead; language implementations have become more complex in general, reducing the marginal complexity of automatic collection; and leading-edge applications have become larger and more complex, making the benefits of automatic collection ever more compelling.

☑ **CHECK YOUR UNDERSTANDING**

1. What is *binding time*?

2. Explain the distinction between decisions that are bound statically and those that are bound dynamically.

3. What is the advantage of binding things as early as possible? What is the advantage of delaying bindings?

4. Explain the distinction between the *lifetime* of a name-to-object binding and its *visibility*.

5. What determines whether an object is allocated statically, on the stack, or in the heap?
6. List the objects and information commonly found in a stack frame.
7. What is a *frame pointer*? What is it used for?
8. What is a *calling sequence*?
9. What are internal and external *fragmentation*?
10. What is *garbage collection*?
11. What is a *dangling reference*?

3.3 Scope Rules

The textual region of the program in which a binding is active is its *scope*. In most modern languages, the scope of a binding is determined statically, that is, at compile time. In C, for example, we introduce a new scope upon entry to a subroutine. We create bindings for local objects and deactivate bindings for global objects that are hidden (made invisible) by local objects of the same name. On subroutine exit, we destroy bindings for local variables and reactivate bindings for any global objects that were hidden. These manipulations of bindings may at first glance appear to be run-time operations, but they do not require the execution of any code: the portions of the program in which a binding is active are completely determined at compile time. We can look at a C program and know which names refer to which objects at which points in the program based on purely textual rules. For this reason, C is said to be *statically scoped* (some authors say *lexically scoped*[3]). Other languages, including APL, Snobol, Tcl, and early dialects of Lisp, are *dynamically scoped*: their bindings depend on the flow of execution at run time. We will examine static and dynamic scoping in more detail in Sections 3.3.1 and 3.3.6.

In addition to talking about the "scope of a binding," we sometimes use the word "scope" as a noun all by itself, without a specific binding in mind. Informally, a scope is a program region of maximal size in which no bindings change (or at least none are destroyed—more on this in Section 3.3.3). Typically, a scope is the body of a module, class, subroutine, or structured control-flow statement, sometimes called a *block*. In C family languages it would be delimited with `{...}` braces.

[3] *Lexical scope* is actually a better term than *static scope*, because scope rules based on nesting can be enforced at run time instead of compile time if desired. In fact, in Common Lisp and Scheme it is possible to pass the unevaluated text of a subroutine declaration into some other subroutine as a parameter, and then use the text to create a lexically nested declaration at run time.

Algol 68 and Ada use the term *elaboration* to refer to the process by which declarations become active when control first enters a scope. Elaboration entails the creation of bindings. In many languages, it also entails the allocation of stack space for local objects, and possibly the assignment of initial values. In Ada it can entail a host of other things, including the execution of error-checking or heap-space-allocating code, the propagation of exceptions, and the creation of concurrently executing *tasks* (to be discussed in Chapter 13).

At any given point in a program's execution, the set of active bindings is called the current *referencing environment*. The set is principally determined by static or dynamic *scope rules*. We shall see that a referencing environment generally corresponds to a sequence of scopes that can be examined (in order) to find the current binding for a given name.

In some cases, referencing environments also depend on what are (in a confusing use of terminology) called *binding rules*. Specifically, when a reference to a subroutine *S* is stored in a variable, passed as a parameter to another subroutine, or returned as a function value, one needs to determine when the referencing environment for *S* is chosen—that is, when the binding between the reference to *S* and the referencing environment of *S* is made. The two principal options are *deep binding*, in which the choice is made when the reference is first created, and *shallow binding*, in which the choice is made when the reference is finally used. We will examine these options in more detail in Section 3.6.

3.3.1 Static Scoping

In a language with static (lexical) scoping, the bindings between names and objects can be determined at compile time by examining the text of the program, without consideration of the flow of control at run time. Typically, the "current" binding for a given name is found in the matching declaration whose block most closely surrounds a given point in the program, though as we shall see there are many variants on this basic theme.

The simplest static scope rule is probably that of early versions of Basic, in which there was only a single, global scope. In fact, there were only a few hundred possible names, each of which consisted of a letter optionally followed by a digit. There were no explicit declarations; variables were declared implicitly by virtue of being used.

Scope rules are somewhat more complex in (pre-Fortran 90) Fortran, though not much more. Fortran distinguishes between global and local variables. The scope of a local variable is limited to the subroutine in which it appears; it is not visible elsewhere. Variable declarations are optional. If a variable is not declared, it is assumed to be local to the current subroutine and to be of type `integer` if its name begins with the letters I–N, or `real` otherwise. (Different conventions for implicit declarations can be specified by the programmer. In Fortran 90 and its successors, the programmer can also turn off implicit declarations, so that use of an undeclared variable becomes a compile-time error.)

```
/*
    Place into *s a new name beginning with the letter 'L' and
    continuing with the ASCII representation of a unique integer.
    Parameter s is assumed to point to space large enough to hold any
    such name; for the short ints used here, 7 characters suffice.
*/
void label_name (char *s) {
    static short int n;         /* C guarantees that static locals
                                   are initialized to zero */
    sprintf (s, "L%d\0", ++n);  /* "print" formatted output to s */
}
```

Figure 3.3 C code to illustrate the use of static variables.

Semantically, the lifetime of a local Fortran variable (both the object itself and the name-to-object binding) encompasses a single execution of the variable's subroutine. Programmers can override this rule by using an explicit save statement. (Similar mechanisms appear in many other languages: in C one declares the variable static; in Algol one declares it own.) A save-ed (static, own) variable has a lifetime that encompasses the entire execution of the program. Instead of a logically separate object for every invocation of the subroutine, the compiler creates a single object that retains its value from one invocation of the subroutine to the next. (The name-to-variable binding, of course, is inactive when the subroutine is not executing, because the name is out of scope.)

EXAMPLE 3.4
Static variables in C

As an example of the use of static variables, consider the code in Figure 3.3. The subroutine label_name can be used to generate a series of distinct character-string names: L1, L2, ... A compiler might use these names in its assembly language output.

3.3.2 Nested Subroutines

The ability to nest subroutines inside each other, introduced in Algol 60, is a feature of many subsequent languages, including Ada, ML, Common Lisp, Python, Scheme, Swift, and (to a limited extent) Fortran 90. Other languages, including C and its descendants, allow classes or other scopes to nest. Just as the local variables of a Fortran subroutine are not visible to other subroutines, any constants, types, variables, or subroutines declared within a scope are not visible outside that scope in Algol-family languages. More formally, Algol-style nesting gives rise to the *closest nested scope rule* for bindings from names to objects: a name that is introduced in a declaration is known in the scope in which it is declared, and in each internally nested scope, unless it is *hidden* by another declaration of the same name in one or more nested scopes. To find the object corresponding to a given use of a name, we look for a declaration with that name in the current, innermost scope. If there is one, it defines the active binding for the name. Otherwise, we look for a declaration in the immediately surrounding scope. We continue outward, examining successively surrounding scopes, until we reach the outer nesting level of the program, where global objects are declared. If no declaration is found at any level, then the program is in error.

Many languages provide a collection of *built-in*, or *predefined objects*, such as I/O routines, mathematical functions, and in some cases types such as `integer` and `char`. It is common to consider these to be declared in an extra, invisible, outermost scope, which surrounds the scope in which global objects are declared. The search for bindings described in the previous paragraph terminates at this extra, outermost scope, if it exists, rather than at the scope in which global objects are declared. This outermost scope convention makes it possible for a programmer to define a global object whose name is the same as that of some predefined object (whose "declaration" is thereby hidden, making it invisible).

EXAMPLE 3.5
Nested scopes

An example of nested scopes appears in Figure 3.4.[4] In this example, procedure `P2` is called only by `P1`, and need not be visible outside. It is therefore declared inside `P1`, limiting its scope (its region of visibility) to the portion of the program shown here. In a similar fashion, `P4` is visible only within `P1`, `P3` is visible only within `P2`, and `F1` is visible only within `P4`. Under the standard rules for nested scopes, `F1` could call `P2` and `P4` could call `F1`, but `P2` could not call `F1`.

Though they are hidden from the rest of the program, nested subroutines are able to access the parameters and local variables (and other local objects) of the surrounding scope(s). In our example, `P3` can name (and modify) `A1`, `X`, and `A2`, in addition to `A3`. Because `P1` and `F1` both declare local variables named `X`, the inner declaration hides the outer one within a portion of its scope. Uses of `X` in `F1` refer to the inner `X`; uses of `X` in other regions of the code refer to the outer `X`. ■

A name-to-object binding that is hidden by a nested declaration of the same name is said to have a *hole* in its scope. In some languages, the object whose name is hidden is simply inaccessible in the nested scope (unless it has more than one name). In others, the programmer can access the outer meaning of a name by applying a *qualifier* or *scope resolution operator*. In Ada, for example, a name may be prefixed by the name of the scope in which it is declared, using syntax that resembles the specification of fields in a record. `My_proc.X`, for example, refers to the declaration of `X` in subroutine `My_proc`, regardless of whether some other `X` has been declared in a lexically closer scope. In C++, which does not allow subroutines to nest, `::X` refers to a global declaration of `X`, regardless of whether the current subroutine also has an `X`.[5]

Access to Nonlocal Objects

We have already seen (Section 3.2.2) that the compiler can arrange for a frame pointer register to point to the frame of the currently executing subroutine at run

[4] This code is not contrived; it was extracted from an implementation (originally in Pascal) of the FMQ error repair algorithm described in Section C-2.3.5.

[5] The C++ `::` operator is also used to name members (fields or methods) of a base class that are hidden by members of a derived class; we will consider this use in Section 10.2.2.

```
procedure P1(A1)
    var X           -- local to P1
    ...
    procedure P2(A2)
        ...
        procedure P3(A3)
            ...
        begin
            ...     -- body of P3
        end
        ...
    begin
        ...         -- body of P2
    end
    ...
    procedure P4(A4)
        ...
        function F1(A5)
            var X   -- local to F1
            ...
        begin
            ...     -- body of F1
        end
        ...
    begin
        ...         -- body of P4
    end
    ...
begin
    ...             -- body of P1
end
```

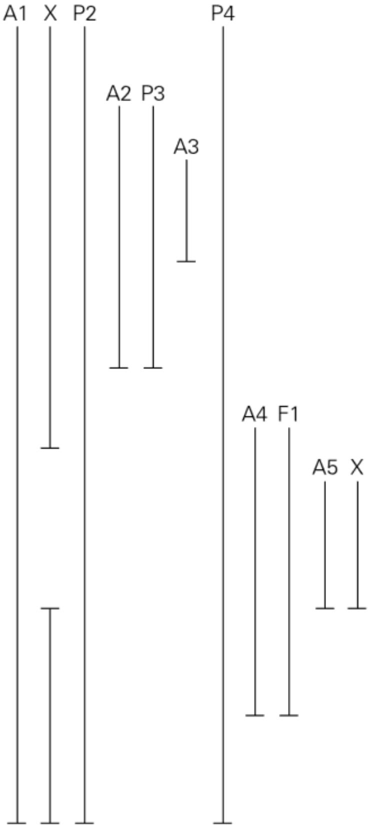


Figure 3.4 **Example of nested subroutines, shown in pseudocode.** Vertical bars indicate the scope of each name, for a language in which declarations are visible throughout their subroutine. Note the hole in the scope of the outer X.

time. Using this register as a base for *displacement* (register plus offset) addressing, target code can access objects within the current subroutine. But what about objects in lexically surrounding subroutines? To find these we need a way to find the frames corresponding to those scopes at run time. Since a nested subroutine may call a routine in an outer scope, the order of stack frames at run time may not necessarily correspond to the order of lexical nesting. Nonetheless, we can be sure that there *is* some frame for the surrounding scope already in the stack, since the current subroutine could not have been called unless it was visible, and it could not have been visible unless the surrounding scope was active. (It is actually possible in some languages to save a reference to a nested subroutine, and then call it when the surrounding scope is no longer active. We defer this possibility to Section 3.6.2.)

The simplest way in which to find the frames of surrounding scopes is to maintain a *static link* in each frame that points to the "parent" frame: the frame of the

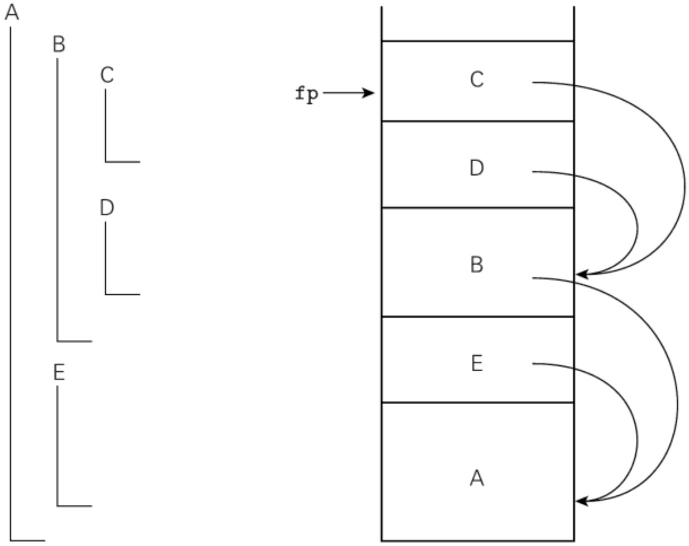


Figure 3.5 **Static chains.** Subroutines A, B, C, D, and E are nested as shown on the left. If the sequence of nested calls at run time is A, E, B, D, and C, then the static links in the stack will look as shown on the right. The code for subroutine C can find local objects at known offsets from the frame pointer. It can find local objects of the surrounding scope, B, by dereferencing its static chain once and then applying an offset. It can find local objects in B's surrounding scope, A, by dereferencing its static chain twice and then applying an offset.

most recent invocation of the lexically surrounding subroutine. If a subroutine is declared at the outermost nesting level of the program, then its frame will have a null static link at run time. If a subroutine is nested *k* levels deep, then its frame's static link, and those of its parent, grandparent, and so on, will form a *static chain* of length *k* at run time. To find a variable or parameter declared *j* subroutine scopes outward, target code at run time can dereference the static chain *j* times, and then add the appropriate offset. Static chains are illustrated in Figure 3.5. We will discuss the code required to maintain them in Section 9.2. ■

EXAMPLE 3.6
Static chains

3.3.3 Declaration Order

In our discussion so far we have glossed over an important subtlety: suppose an object `x` is declared somewhere within block `B`. Does the scope of `x` include the portion of `B` before the declaration, and if so can `x` actually be used in that portion of the code? Put another way, can an expression *E* refer to any name declared in the current scope, or only to names that are declared *before E* in the scope?

Several early languages, including Algol 60 and Lisp, required that all declarations appear at the beginning of their scope. One might at first think that this rule would avoid the questions in the preceding paragraph, but it does not, because declarations may refer to one another.[6]

EXAMPLE 3.7

A "gotcha" in declare-before-use

In an apparent attempt to simplify the implementation of the compiler, Pascal modified the requirement to say that names must be declared before they are used. There are special mechanisms to accommodate recursive types and subroutines, but in general, a *forward reference* (an attempt to use a name before its declaration) is a static semantic error. At the same time, however, Pascal retained the notion that the scope of a declaration is the entire surrounding block. Taken together, whole-block scope and declare-before-use rules can interact in surprising ways:

```
1.  const N = 10;
2.  ...
3.  procedure foo;
4.  const
5.      M = N;      (* static semantic error! *)
6.      ...
7.      N = 20;     (* local constant declaration; hides the outer N *)
```

Pascal says that the second declaration of N covers all of foo, so the semantic analyzer should complain on line 5 that N is being used before its declaration. The error has the potential to be highly confusing, particularly if the programmer meant to use the outer N:

```
const N = 10;
...
procedure foo;
const
    M = N;          (* static semantic error! *)
var
    A : array [1..M] of integer;
    N : real;       (* hiding declaration *)
```

Here the pair of messages "N used before declaration" and "N is not a constant" are almost certainly not helpful.

DESIGN & IMPLEMENTATION

3.3 Mutual recursion

Some Algol 60 compilers were known to process the declarations of a scope in program order. This strategy had the unfortunate effect of implicitly outlawing mutually recursive subroutines and types, something the language designers clearly did not intend [Atk73].

[6] We saw an example of mutually recursive subroutines in the recursive descent parsing of Section 2.3.1. Mutually recursive types frequently arise in linked data structures, where nodes of two types may need to point to each other.

In order to determine the validity of any declaration that appears to use a name from a surrounding scope, a Pascal compiler must scan the remainder of the scope's declarations to see if the name is hidden. To avoid this complication, most Pascal successors (and some dialects of Pascal itself) specify that the scope of an identifier is not the entire block in which it is declared (excluding holes), but rather the portion of that block from the declaration to the end (again excluding holes). If our program fragment had been written in Ada, for example, or in C, C++, or Java, no semantic errors would be reported. The declaration of `M` would refer to the first (outer) declaration of `N`.

EXAMPLE 3.8

Whole-block scope in C#

C++ and Java further relax the rules by dispensing with the define-before-use requirement in many cases. In both languages, members of a class (including those that are not defined until later in the program text) are visible inside all of the class's methods. In Java, classes themselves can be declared in any order. Interestingly, while C# echos Java in requiring declaration before use for local variables (but not for classes and members), it returns to the Pascal notion of whole-block scope. Thus the following is invalid in C#:

```
class A {
    const int N = 10;
    void foo() {
        const int M = N;    // uses inner N before it is declared
        const int N = 20;
```

EXAMPLE 3.9

"Local if written" in Python

Perhaps the simplest approach to declaration order, from a conceptual point of view, is that of Modula-3, which says that the scope of a declaration is the entire block in which it appears (minus any holes created by nested declarations), and that the order of declarations doesn't matter. The principal objection to this approach is that programmers may find it counterintuitive to use a local variable before it is declared. Python takes the "whole block" scope rule one step further by dispensing with variable declarations altogether. In their place it adopts the unusual convention that the local variables of subroutine `S` are precisely those variables that are written by some statement in the (static) body of `S`. If `S` is nested inside of `T`, and the name `x` appears on the left-hand side of assignment statements in both `S` and `T`, then the `x`'s are distinct: there is one in `S` and one in `T`. Non-local variables are read-only unless explicitly imported (using Python's `global` statement). We will consider these conventions in more detail in Section 14.4.1, as part of a general discussion of scoping in scripting languages.

EXAMPLE 3.10

Declaration order in Scheme

In the interest of flexibility, modern Lisp dialects tend to provide several options for declaration order. In Scheme, for example, the `letrec` and `let*` constructs define scopes with, respectively, whole-block and declaration-to-end-of-block semantics. The most frequently used construct, `let`, provides yet another option:

```
(let ((A 1))          ; outer scope, with A defined to be 1
  (let ((A 2)         ; inner scope, with A defined to be 2
        (B A))        ;                    and B defined to be A
    B))               ; return the value of B
```

Here the nested declarations of A and B don't take effect until after the end of the declaration list. Thus when B is defined, the redefinition of A has not yet taken effect. B is defined to be the *outer* A, and the code as a whole returns 1. ■

Declarations and Definitions

Recursive types and subroutines introduce a problem for languages that require names to be declared before they can be used: how can two declarations each appear before the other? C and C++ handle the problem by distinguishing between the *declaration* of an object and its *definition*. A declaration introduces a name and indicates its scope, but may omit certain implementation details. A definition describes the object in sufficient detail for the compiler to determine its implementation. If a declaration is not complete enough to be a definition, then a separate definition must appear somewhere else in the scope. In C we can write

EXAMPLE 3.11

Declarations vs definitions in C

```
struct manager;                     /* declaration only */
struct employee {
    struct manager *boss;
    struct employee *next_employee;
    ...
};
struct manager {                    /* definition */
    struct employee *first_employee;
    ...
};
```

and

```
void list_tail(follow_set fs);      /* declaration only */
void list(follow_set fs)
{
    switch (input_token) {
        case id : match(id); list_tail(fs);
    ...
}
void list_tail(follow_set fs)       /* definition */
{
    switch (input_token) {
        case comma : match(comma); list(fs);
    ...
}
```

The initial declaration of manager needed only to introduce a name: since pointers are generally all the same size, the compiler can determine the implementation of employee without knowing any manager details. The initial declaration of list_tail, however, must include the return type and parameter list, so the compiler can tell that the call in list is correct. ■

Nested Blocks

In many languages, including Algol 60, C89, and Ada, local variables can be declared not only at the beginning of any subroutine, but also at the top of any `begin...end` (`{...}`) block. Other languages, including Algol 68, C, and all of C's descendants, are even more flexible, allowing declarations wherever a statement may appear. In most languages a nested declaration hides any outer declaration with the same name (Java and C# make it a static semantic error if the outer declaration is local to the current subroutine).

DESIGN & IMPLEMENTATION

3.4 Redeclarations

Some languages, particularly those that are intended for interactive use, permit the programmer to redeclare an object: to create a new binding for a given name in a given scope. Interactive programmers commonly use redeclarations to experiment with alternative implementations or to fix bugs during early development. In most interactive languages, the new meaning of the name replaces the old in all contexts. In ML dialects, however, the old meaning of the name may remain accessible to functions that were elaborated before the name was redeclared. This design choice can sometimes be counterintuitive. Here's an example in OCaml (the lines beginning with # are user input; the others are printed by the interpreter):

```
# let x = 1;;
val x : int = 1
# let f y = x + y;;
val f : int -> int = <fun>
# let x = 2;;
val x : int = 2
# f 3;;
- : int = 4
```

The second line of user input defines `f` to be a function of one argument (`y`) that returns the sum of that argument and the previously defined value `x`. When we redefine `x` to be 2, however, the function does not notice: it still returns `y` plus 1. This behavior reflects the fact that OCaml is usually compiled, bit by bit on the fly, rather than interpreted. When `x` is redefined, `f` has already been compiled into a form (bytecode or machine code) that accesses the old meaning of `x` directly. By comparison, a language like Scheme, which is lexically scoped but usually interpreted, stores the bindings for names in known locations. Programs always access the meanings of names indirectly through those locations: if the meaning of a name changes, all accesses to the name will use the new meaning.

EXAMPLE 3.12
Inner declarations in C

Variables declared in nested blocks can be very useful, as for example in the following C code:

```
{
    int temp = a;
    a = b;
    b = temp;
}
```

Keeping the declaration of `temp` lexically adjacent to the code that uses it makes the program easier to read, and eliminates any possibility that this code will interfere with another variable named `temp`.

No run-time work is needed to allocate or deallocate space for variables declared in nested blocks; their space can be included in the total space for local variables allocated in the subroutine prologue and deallocated in the epilogue. Exercise 3.9 considers how to minimize the total space required.

✓ CHECK YOUR UNDERSTANDING

12. What do we mean by the *scope* of a name-to-object binding?
13. Describe the difference between static and dynamic scoping.
14. What is *elaboration*?
15. What is a *referencing environment*?
16. Explain the *closest nested scope rule*.
17. What is the purpose of a *scope resolution operator*?
18. What is a *static chain*? What is it used for?
19. What are *forward references*? Why are they prohibited or restricted in many programming languages?
20. Explain the difference between a *declaration* and a *definition*. Why is the distinction important?

3.3.4 Modules

An important challenge in the construction of any large body of software is to divide the effort among programmers in such a way that work can proceed on multiple fronts simultaneously. This modularization of effort depends critically on the notion of *information hiding*, which makes objects and algorithms invisible, whenever possible, to portions of the system that do not need them. Properly modularized code reduces the “cognitive load” on the programmer by minimizing the amount of information required to understand any given portion of the system. In a well-designed program the interfaces among modules are as "narrow" (i.e., simple) as possible, and any design decision that is likely to change is hidden inside a single module.

Information hiding is crucial for software maintenance (bug fixes and enhancement), which tends to significantly outweigh the cost of initial development for most commercial software. In addition to reducing cognitive load, hiding reduces the risk of name conflicts: with fewer visible names, there is less chance that a newly introduced name will be the same as one already in use. It also safeguards the integrity of data abstractions: any attempt to access an object outside of the module to which it belongs will cause the compiler to issue an "undefined symbol" error message. Finally, it helps to compartmentalize run-time errors: if a variable takes on an unexpected value, we can generally be sure that the code that modified it is in the variable's scope.

Encapsulating Data and Subroutines

Unfortunately, the information hiding provided by nested subroutines is limited to objects whose lifetime is the same as that of the subroutine in which they are hidden. When control returns from a subroutine, its local variables will no longer be live: their values will be discarded. We have seen a partial solution to this problem in the form of the `save` statement in Fortran and the `static` and `own` variables of C and Algol.

EXAMPLE 3.13
Pseudorandom numbers as a motivation for modules

Static variables allow a subroutine to have "memory"—to retain information from one invocation to the next—while protecting that memory from accidental access or modification by other parts of the program. Put another way, static variables allow programmers to build single-subroutine abstractions. Unfortunately, they do not allow the construction of abstractions whose interface needs to consist of more than one subroutine. Consider, for example, a simple pseudorandom number generator. In addition to the main `rand_int` routine, we might want a `set_seed` routine that primes the generator for a specific pseudorandom sequence (e.g., for deterministic testing). We should like to make the state of the generator, which determines the next pseudorandom number, visible to both `rand_int` and `set_seed`, but hide it from the rest of the program. We can achieve this goal in many languages through use of a *module* construct. ■

Modules as Abstractions

A module allows a collection of objects—subroutines, variables, types, and so on—to be encapsulated in such a way that (1) objects inside are visible to each other, but (2) objects on the inside may not be visible on the outside unless they are *exported*, and (3) objects on the outside may not be visible on the inside unless they are *imported*. Import and export conventions vary significantly from one language to another, but in all cases, only the *visibility* of objects is affected; modules do not affect the lifetime of the objects they contain.

```
#include <time.h>
namespace rand_mod {
    unsigned int seed = time(0);    // initialize from current time of day
    const unsigned int a = 48271;
    const unsigned int m = 0x7fffffff;

    void set_seed(unsigned int s) {
        seed = s;
    }
    unsigned int rand_int() {
        return seed = (a * seed) % m;
    }
}
```

Figure 3.6 **Pseudorandom number generator module in C++.** Uses the linear congruential method, with a default seed taken from the current time of day. While there exist much better (more random) generators, this one is simple, and acceptable for many purposes.

Modules were one of the principal language innovations of the late 1970s and early 1980s; they appeared in Clu[7] (which called them *clusters*), Modula (1, 2, and 3), Turing, and Ada 83, among others. In more modern form, they also appear in Haskell, C++, Java, C#, and all the major scripting languages. Several languages, including Ada, Java, and Perl, use the term *package* instead of module. Others, including C++, C#, and PHP, use *namespace*. Modules can be emulated to some degree through use of the separate compilation facilities of C; we discuss this possibility in Section C-3.8.

EXAMPLE 3.14

Pseudorandom number generator in C++

As an example of the use of modules, consider the pseudorandom number generator shown in Figure 3.6. As discussed in Sidebar 3.5, this module (namespace) would typically be placed in its own file, and then imported wherever it is needed in a C++ program.

Bindings of names made inside the namespace may be partially or totally hidden (inactive) on the outside—but not destroyed. In C++, where namespaces can appear only at the outermost level of lexical nesting, integer `seed` would retain its value throughout the execution of the program, even though it is visible only to `set_seed` and `rand_int`.

Outside the `rand_mod` namespace, C++ allows `set_seed` and `rand_int` to be accessed as `rand_mod::set_seed` and `rand_mod::rand_int`. The `seed` variable could also be accessed as `rand_mod::seed`, but this is probably not a good idea, and the need for the `rand_mod` prefix means it's unlikely to happen by accident.

[7] Barbara Liskov (1939–), the principal designer of Clu, is one of the leading figures in the history of abstraction mechanisms. A faculty member at MIT since 1971, she was also the principal designer of the Argus programming language, which combined language and database technology to improve the reliability and programmability of distributed systems. She received the ACM Turing Award in 2008.

The need for the prefix can be eliminated, on a name-by-name basis, with a `using` directive:

```
using rand_mod::rand_int;
...
int r = rand_int();
```

Alternatively, the full set of names declared in a namespace can be made available at once:

```
using namespace rand_mod;
...
set_seed(12345);
int r = rand_int();
```

Unfortunately, such wholesale exposure of a module's names increases both the likelihood of conflict with names in the importing context and the likelihood that objects like `seed`, which are logically private to the module, will be accessed accidentally. ■

Imports and Exports

Some languages allow the programmer to specify that names exported from modules be usable only in restricted ways. Variables may be exported read-only, for example, or types may be exported *opaquely*, meaning that variables of that type may be declared, passed as arguments to the module's subroutines, and possibly compared or assigned to one another, but not manipulated in any other way.

Modules into which names must be explicitly imported are said to be *closed scopes*. By extension, modules that do not require imports are said to be *open scopes*. Imports serve to document the program: they increase modularity by requiring a module to specify the ways in which it depends on the rest of the program. They also reduce name conflicts by refraining from importing anything that isn't needed. Modules are closed in Modula (1, 2, and 3) and Haskell. C++ is representative of an increasingly common option, in which names are automatically exported, but are available on the outside only when *qualified* with the module name—unless they are explicitly "imported" by another scope (e.g., with the C++ `using` directive), at which point they are available unqualified. This option, which we might call *selectively open* modules, also appears in Ada, Java, C#, and Python, among others.

Modules as Managers

EXAMPLE 3.15

Module as "manager" for a type

Modules facilitate the construction of abstractions by allowing data to be made private to the subroutines that use them. When used as in Figure 3.6, however, each module defines a single abstraction. Continuing our previous example, there are times when it may be desirable to have more than one pseudorandom number generator. When debugging a game, for example, we might want to obtain deterministic (repeatable) behavior in one particular game module (a particular

```
#include <time.h>
namespace rand_mgr {
    const unsigned int a = 48271;
    const unsigned int m = 0x7fffffff;

    typedef struct {
        unsigned int seed;
    } generator;

    generator* create() {
        generator* g = new generator;
        g->seed = time(0);
        return g;
    }
    void set_seed(generator* g, unsigned int s) {
        g->seed = s;
    }
    unsigned int rand_int(generator* g) {
        return g->seed = (a * g->seed) % m;
    }
}
```

Figure 3.7 Manager module for pseudorandom numbers in C++.

character, perhaps), regardless of uses of pseudorandom numbers elsewhere in the program. If we want to have several generators, we can make our namespace a "manager" for instances of a generator *type*, which is then exported from the module, as shown in Figure 3.7. The manager idiom requires additional subroutines to create/initialize and possibly destroy generator instances, and it requires that every subroutine (`set_seed`, `rand_int`, `create`) take an extra parameter, to specify the generator in question.

Given the declarations in Figure 3.7, we could create and use an arbitrary number of generators:

```
using rand_mgr::generator;
generator *g1 = rand_mgr::create();
generator *g2 = rand_mgr::create();
...
using rand_mgr::rand_int;
int r1 = rand_int(g1);
int r2 = rand_int(g2);
```

In more complex programs, it may make sense for a module to export several related types, instances of which can then be passed to its subroutines.

3.3.5 Module Types and Classes

An alternative solution to the multiple instance problem appeared in Euclid, which treated each module as a *type*, rather than a simple encapsulation construct. Given a module type, the programmer could declare an arbitrary number of similar module objects. As it turns out, the classes of modern object-oriented languages are an extension of module types. Access to a module instance typically looks like access to an object, and we can illustrate the ideas in any object-oriented language. For our C++ pseudorandom number example, the syntax

EXAMPLE 3.16

A pseudorandom number generator type

```
generator *g = rand_mgr::create();
...
int r = rand_int(g);
```

might be replaced by

```
rand_gen *g = new rand_gen();
...
int r = g->rand_int();
```

where the rand_gen class is declared as in Figure 3.8. Module types or classes allow the programmer to think of the rand_int routine as "belonging to" the generator, rather than as a separate entity to which the generator must be passed

DESIGN & IMPLEMENTATION

3.5 Modules and separate compilation

One of the hallmarks of a good abstraction is that it tends to be useful in multiple contexts. To facilitate code reuse, many languages make modules the basis of separate compilation. Modula-2 actually provided two different kinds of modules: one (external modules) for separate compilation, the other (internal modules) for textual nesting within a larger scope. Experience with these options eventually led Niklaus Wirth, the designer of Modula-2, to conclude that external modules were by far the more useful variety; he omitted the internal version from his subsequent language, Oberon. Many would argue, however, that internal modules find their real utility only when extended with instantiation and inheritance. Indeed, as noted near the end of this section, many object-oriented languages provide both modules *and* classes. The former support separate compilation and serve to minimize name conflicts; the latter are for data abstraction.

To facilitate separate compilation, modules in many languages (Modula-2 and Oberon among them) can be divided into a declaration part (*header*) and an implementation part (*body*), each of which occupies a separate file. Code that uses the exports of a given module can be compiled as soon as the header exists; it is not dependent on the body. In particular, work on the bodies of cooperating modules can proceed concurrently once the headers exist. We will return to the subjects of separate compilation and code reuse in Sections C-3.8 and 10.1, respectively.

```
class rand_gen {
    unsigned int seed = time(0);
    const unsigned int a = 48271;
    const unsigned int m = 0x7fffffff;

public:
    void set_seed(unsigned int s) {
        seed = s;
    }
    unsigned int rand_int() {
        return seed = (a * seed) % m;
    }
};
```

Figure 3.8 Pseudorandom number generator class in C++.

as an argument. Conceptually, there is a dedicated `rand_int` routine for every generator (`rand_gen` object). In practice, of course, it would be highly wasteful to create multiple copies of the code. As we shall see in Chapter 10, `rand_gen` instances really share a single pair of `set_seed` and `rand_int` routines, and the compiler arranges for a pointer to the relevant instance to be passed to the routine as an extra, hidden parameter. The implementation turns out to be very similar to that of Figure 3.7, but the programmer need not think of it that way.

Object Orientation

The difference between module types and classes is a powerful pair of features found together in the latter but not the former—namely, *inheritance* and *dynamic method dispatch*.[8] Inheritance allows new classes to be defined as extensions or refinements of existing classes. Dynamic method dispatch allows a refined class to *override* the definition of an operation in its parent class, and for the choice among definitions to be made at run time, on the basis of whether a particular object belongs to the child class or merely to the parent.

Inheritance facilitates a programming style in which all or most operations are thought of as belonging to objects, and in which new objects can inherit many of their operations from existing objects, without the need to rewrite code. Classes have their roots in Simula-67, and were further developed in Smalltalk. They appear in many modern languages, including Eiffel, OCaml, C++, Java, C#, and several scripting languages, notably Python and Ruby. Inheritance mechanisms can also be found in certain languages that are not usually considered object-oriented, including Modula-3, Ada 95, and Oberon. We will examine inheritance, dynamic dispatch, and their impact on scope rules in Chapter 10 and in Section 14.4.4.

[8] A few languages—notably members of the ML family—have module types with inheritance—but still without dynamic method dispatch. Modules in most languages are missing both features.

Module types and classes (ignoring issues related to inheritance) require only simple changes to the scope rules defined for modules in Section 3.3.4. Every instance A of a module type or class (e.g., every `rand_gen`) has a separate copy of the module or class's variables. These variables are then visible when executing one of A's operations. They may also be indirectly visible to the operations of some other instance B if A is passed as a parameter to one of those operations. This rule makes it possible in most object-oriented languages to construct binary (or more-ary) operations that can manipulate the variables (fields) of more than one instance of a class.

Modules Containing Classes

EXAMPLE 3.17

Modules and classes in a large application

While there is a clear progression from modules to module types to classes, it is not necessarily the case that classes are an adequate replacement for modules in all cases. Suppose we are developing an interactive "first person" game. Class hierarchies may be just what we need to represent characters, possessions, buildings, goals, and a host of other data abstractions. At the same time, especially on a project with a large team of programmers, we will probably want to divide the functionality of the game into large-scale subsystems such as graphics and rendering, physics, and strategy. These subsystems are really not data abstractions, and we probably don't *want* the option to create multiple instances of them. They are naturally captured with traditional modules, particularly if those modules are designed for separate compilation (Section 3.8). Recognizing the need for both multi-instance abstractions and functional subdivision, many languages, including C++, Java, C#, Python, and Ruby, provide separate class and module mechanisms.

3.3.6 Dynamic Scoping

In a language with dynamic scoping, the bindings between names and objects depend on the flow of control at run time, and in particular on the order in which subroutines are called. In comparison to the static scope rules discussed in the previous section, dynamic scope rules are generally quite simple: the "current" binding for a given name is the one encountered most recently *during execution*, and not yet destroyed by returning from its scope.

Languages with dynamic scoping include APL, Snobol, Tcl, TeX (the typesetting language with which this book was created), and early dialects of Lisp [MAE$^+$65, Moo78, TM81] and Perl.[9] Because the flow of control cannot in general be predicted in advance, the bindings between names and objects in a language with dynamic scoping cannot in general be determined by a compiler. As a

[9] Scheme and Common Lisp are statically scoped, though the latter allows the programmer to specify dynamic scoping for individual variables. Static scoping was added to Perl in version 5; the programmer now chooses static or dynamic scoping explicitly in each variable declaration. (We consider this choice in more detail in Section 14.4.1.)

```
 1.  n : integer            –– global declaration

 2.  procedure first( )
 3.      n := 1

 4.  procedure second( )
 5.      n : integer        –– local declaration
 6.      first( )

 7.  n := 2
 8.  if read_integer( ) > 0
 9.      second( )
10.  else
11.      first( )
12.  write_integer(n)
```

Figure 3.9 **Static versus dynamic scoping.** Program output depends on both scope rules and, in the case of dynamic scoping, a value read at run time.

result, many semantic rules in a language with dynamic scoping become a matter of dynamic semantics rather than static semantics. Type checking in expressions and argument checking in subroutine calls, for example, must in general be deferred until run time. To accommodate all these checks, languages with dynamic scoping tend to be interpreted, rather than compiled.

EXAMPLE 3.18

Static vs dynamic scoping

Consider the program in Figure 3.9. If static scoping is in effect, this program prints a 1. If dynamic scoping is in effect, the output depends on the value read at line 8 at run time: if the input is positive, the program prints a 2; otherwise it prints a 1. Why the difference? At issue is whether the assignment to the variable n at line 3 refers to the global variable declared at line 1 or to the local variable declared at line 5. Static scope rules require that the reference resolve to the closest lexically enclosing declaration, namely the global n. Procedure first changes n to 1, and line 12 prints this value. Dynamic scope rules, on the other hand, require that we choose the most recent, active binding for n at run time.

DESIGN & IMPLEMENTATION

3.6 Dynamic scoping

It is not entirely clear whether the use of dynamic scoping in Lisp and other early interpreted languages was deliberate or accidental. One reason to think that it may have been deliberate is that it makes it very easy for an interpreter to look up the meaning of a name: all that is required is a stack of declarations (we examine this stack more closely in Section C-3.4.2). Unfortunately, this simple implementation has a very high run-time cost, and experience indicates that dynamic scoping makes programs harder to understand. The modern consensus seems to be that dynamic scoping is usually a bad idea (see Exercise 3.17 and Exploration 3.36 for two exceptions).

We create a binding for n when we enter the main program. We create another when and if we enter procedure second. When we execute the assignment statement at line 3, the n to which we are referring will depend on whether we entered first through second or directly from the main program. If we entered through second, we will assign the value 1 to second's local n. If we entered from the main program, we will assign the value 1 to the global n. In either case, the write at line 12 will refer to the global n, since second's local n will be destroyed, along with its binding, when control returns to the main program. ■

EXAMPLE 3.19

Run-time errors with dynamic scoping

With dynamic scoping, errors associated with the referencing environment may not be detected until run time. In Figure 3.10, for example, the declaration of local variable max_score in procedure foo accidentally redefines a global variable used by function scaled_score, which is then called from foo. Since the global max_score is an integer, while the local max_score is a floating-point number, dynamic semantic checks in at least some languages will result in a type clash message at run time. If the local max_score had been an integer, no error would have been detected, but the program would almost certainly have produced incorrect results. This sort of error can be very hard to find. ■

3.4 Implementing Scope

To keep track of the names in a statically scoped program, a compiler relies on a data abstraction called a *symbol table*. In essence, the symbol table is a dictionary: it maps names to the information the compiler knows about them. The most basic operations are to insert a new mapping (a name-to-object binding) or to look up the information that is already present for a given name. Static scope rules add complexity by allowing a given name to correspond to different objects—and thus to different information—in different parts of the program. Most variations on static scoping can be handled by augmenting a basic dictionary-style symbol table with enter_scope and leave_scope operations to keep track of visibility. Nothing is ever deleted from the table; the entire structure is retained throughout compilation, and then saved for use by debuggers or run-time reflection (type lookup) mechanisms.

In a language with dynamic scoping, an interpreter (or the output of a compiler) must perform operations analogous to symbol table insert and lookup at run time. In principle, any organization used for a symbol table in a compiler could be used to track name-to-object bindings in an interpreter, and vice versa. In practice, implementations of dynamic scoping tend to adopt one of two specific organizations: an *association list* or a *central reference table*.

IN MORE DEPTH

A symbol table with visibility support can be implemented in several different ways. One appealing approach, due to LeBlanc and Cook [CL83], is described on the companion site, along with both association lists and central reference tables.

```
max_score : integer        –– maximum possible score

function scaled_score(raw_score : integer) : real
    return raw_score / max_score * 100
. . .
procedure foo( )
    max_score : real := 0        –– highest percentage seen so far
    . . .
    foreach student in class
        student.percent := scaled_score(student.points)
        if student.percent > max_score
            max_score := student.percent
```

Figure 3.10 **The problem with dynamic scoping.** Procedure scaled_score probably does not do what the programmer intended when dynamic scope rules allow procedure foo to change the meaning of max_score.

An association list (or *A-list* for short) is simply a list of name/value pairs. When used to implement dynamic scoping it functions as a stack: new declarations are pushed as they are encountered, and popped at the end of the scope in which they appeared. Bindings are found by searching down the list from the top. A central reference table avoids the need for linear-time search by maintaining an explicit mapping from names to their current meanings. Lookup is faster, but scope entry and exit are somewhat more complex, and it becomes substantially more difficult to save a referencing environment for future use (we discuss this issue further in Section 3.6.1).

3.5 The Meaning of Names within a Scope

So far in our discussion of naming and scopes we have assumed that there is a one-to-one mapping between names and visible objects at any given point in a program. This need not be the case. Two or more names that refer to the same object at the same point in the program are said to be *aliases*. A name that can refer to more than one object at a given point in the program is said to be *overloaded*. Overloading is in turn related to the more general subject of *polymorphism*, which allows a subroutine or other program fragment to behave in different ways depending on the types of its arguments.

3.5.1 Aliases

Simple examples of aliases occur in the variant records and unions of many programming languages (we will discuss these features detail in Section C-8.1.3).

They also arise naturally in programs that make use of pointer-based data structures. A more subtle way to create aliases in many languages is to pass a variable by reference to a subroutine that also accesses that variable directly. Consider the following code in C++:

EXAMPLE 3.20
Aliasing with parameters

```
double sum, sum_of_squares;
...
void accumulate(double& x) {      // x is passed by reference
    sum += x;
    sum_of_squares += x * x;
}
```

If we pass `sum` as an argument to `accumulate`, then `sum` and `x` will be aliases for one another inside the called routine, and the program will probably not do what the programmer intended. ■

As a general rule, aliases tend to make programs more confusing than they otherwise would be. They also make it much more difficult for a compiler to perform certain important code improvements. Consider the following C code:

EXAMPLE 3.21
Aliases and code improvement

```
int a, b, *p, *q;
...
a = *p;     /* read from the variable referred to by p */
*q = 3;     /* assign to the variable referred to by q */
b = *p;     /* read from the variable referred to by p */
```

DESIGN & IMPLEMENTATION

3.7 Pointers in C and Fortran

The tendency of pointers to introduce aliases is one of the reasons why Fortran compilers tended, historically, to produce faster code than C compilers: pointers are heavily used in C, but missing from Fortran 77 and its predecessors. It is only in recent years that sophisticated alias analysis algorithms have allowed C compilers to rival their Fortran counterparts in speed of generated code. Pointer analysis is sufficiently important that the designers of the C99 standard decided to add a new keyword to the language. The `restrict` qualifier, when attached to a pointer declaration, is an assertion on the part of the programmer that the object to which the pointer refers has no alias in the current scope. It is the programmer's responsibility to ensure that the assertion is correct; the compiler need not attempt to check it. C99 also introduced *strict aliasing*. This allows the compiler to assume that pointers of different types will never refer to the same location in memory. Most compilers provide a command-line option to disable optimizations that exploit this rule; otherwise (poorly written) legacy programs may behave incorrectly when compiled at higher optimization levels.

```
declare
    type month is (jan, feb, mar, apr, may, jun,
                   jul, aug, sep, oct, nov, dec);
    type print_base is (dec, bin, oct, hex);
    mo : month;
    pb : print_base;
begin
    mo := dec;      -- the month dec (since mo has type month)
    pb := oct;      -- the print_base oct (since pb has type print_base)
    print(oct);     -- error!  insufficient context
                    --         to decide which oct is intended
```

Figure 3.11 Overloading of enumeration constants in Ada.

The initial assignment to a will, on most machines, require that *p be loaded into a register. Since accessing memory is expensive, the compiler will want to hang on to the loaded value and reuse it in the assignment to b. It will be unable to do so, however, unless it can verify that p and q cannot refer to the same object—that is, that *p and *q are not aliases. While compile-time verification of this sort is possible in many common cases, in general it's undecidable. ■

3.5.2 Overloading

EXAMPLE 3.22
Overloaded enumeration constants in Ada

Most programming languages provide at least a limited form of overloading. In C, for example, the plus sign (+) is used to name several different functions, including signed and unsigned integer and floating-point addition. Most programmers don't worry about the distinction between these two functions—both are based on the same mathematical concept, after all—but they take arguments of different types and perform very different operations on the underlying bits. A slightly more sophisticated form of overloading appears in the enumeration constants of Ada. In Figure 3.11, the constants oct and dec refer either to months or to numeric bases, depending on the context in which they appear. ■

EXAMPLE 3.23
Resolving ambiguous overloads

Within the symbol table of a compiler, overloading must be handled (*resolved*) by arranging for the lookup routine to return a *list* of possible meanings for the requested name. The semantic analyzer must then choose from among the elements of the list based on context. When the context is not sufficient to decide, as in the call to print in Figure 3.11, then the semantic analyzer must announce an error. Most languages that allow overloaded enumeration constants allow the programmer to provide appropriate context explicitly. In Ada, for example, one can say

```
print(month'(oct));
```

In Modula-3 and C#, *every* use of an enumeration constant must be prefixed with a type name, even when there is no chance of ambiguity:

```
struct complex {
    double real, imaginary;
};
enum base {dec, bin, oct, hex};

int i;
complex x;

void print_num(int n) { ...
void print_num(int n, base b) { ...
void print_num(complex c) { ...

print_num(i);       // uses the first function above
print_num(i, hex);  // uses the second function above
print_num(x);       // uses the third function above
```

Figure 3.12 **Simple example of overloading in C++.** In each case the compiler can tell which function is intended by the number and types of arguments.

```
mo := month.dec;            (* Modula-3 *)

pb = print_base.oct;        // C#
```

In C, one cannot overload enumeration constants at all; every constant visible in a given scope must be distinct. C++11 introduced new syntax to give the programmer control over this behavior: `enum` constants must be distinct; `enum class` constants must be qualified with the class name (e.g., month::oct). ■

EXAMPLE 3.24
Overloading in C++

Both Ada and C++ have elaborate facilities for overloading subroutine names. Many of the C++ facilities carry over to Java and C#. A given name may refer to an arbitrary number of subroutines in the same scope, so long as the subroutines differ in the number or types of their arguments. C++ examples appear in Figure 3.12. ■

Redefining Built-in Operators

EXAMPLE 3.25
Operator overloading in Ada

Many languages also allow the built-in arithmetic operators (`+`, `-`, `*`, etc.) to be overloaded with user-defined functions. Ada, C++, and C# do this by defining alternative *prefix* forms of each operator, and defining the usual infix forms to be abbreviations (or "syntactic sugar") for the prefix forms. In Ada, `A + B` is short for `"+"(A, B)`. If `"+"` (the prefix form) is overloaded, then `+` (the infix form) will work for the new types as well. It must be possible to resolve the overloading (determine which `+` is intended) from the types of `A` and `B`. ■

EXAMPLE 3.26
Operator overloading in C++

Fortran 90 provides a special `interface` construct that can be used to associate an operator with some named binary function. In C++ and C#, which are object-oriented, `A + B` may be short for either `operator+(A, B)` or `A.operator+(B)`. In the latter case, `A` is an instance of a class (module type) that defines an `operator+` function. In C++ one might say

```
class complex {
    double real, imaginary;
    ...
public:
    complex operator+(complex other) {
        return complex(real + other.real, imaginary + other.imaginary);
    }
    ...
};
...
complex A, B, C;
...
C = A + B;              // uses user-defined operator+
```

C# syntax is similar.

EXAMPLE 3.27

Infix operators in Haskell

In Haskell, user-defined infix operators are simply functions whose names consist of non-alphanumeric characters:

```
let a @@ b = a * 2 + b
```

Here we have defined a 2-argument operator named `@@`. We could also have declared it with the usual prefix notation, in which case we would have needed to enclose the name in parentheses:

```
let (@@) a b = a * 2 + b
```

Either way, both `3 @@ 4` and `(@@) 3 4` will evaluate to `10`. (An arbitrary function can also be used as infix operator in Haskell by enclosing its name in backquotes. With an appropriate definition, `gcd 8 12` and ``8 `gcd` 12`` will both evaluate to `4`.)

Unlike most languages, Haskell allows the programmer to specify both the associativity and the precedence of user-defined operators. We will return to this subject in Section 6.1.1.

EXAMPLE 3.28

Overloading with type classes

Both operators and ordinary functions can be overloaded in Haskell, using a mechanism known as *type classes*. Among the simplest of these is the class `Eq`, declared in the standard library as

DESIGN & IMPLEMENTATION

3.8 User-defined operators in OCaml

OCaml does not support overloading, but it does allow the user to create new operators, whose names—as in Haskell—consist of non-alphanumeric characters. Each such name must begin with the name of one of the built-in operators, from which the new operator inherits its syntactic role (prefix, infix, or postfix) and precedence. So, for example, `+.` is used for floating-point addition; `+/` is used for "bignum" (arbitrary precision) integer addition.

```
class Eq a, where
  (==) :: a -> a -> Bool
```

This declaration establishes Eq as the set of types that provide an == operator. Any instance of ==, for some particular type a, must take two arguments (each of type a) and return a Boolean result. In other words, == is an overloaded operator, supported by all types of class Eq; each such type must provide its own equality definition. The definition for integers, again from the standard library, looks like this:

```
instance Eq Integer where
  x == y = x `integerEq` y
```

Here integerEq is the built-in, non-overloaded integer equality operator.

Type classes can build upon themselves. The Haskell Ord class, for example, encompasses all Eq types that also support the operators <, >, <=, and >=. The Num class (simplifying a bit) encompasses all Eq types that also support addition, subtraction, and multiplication. In addition to making overloading a bit more explicit than it is in most languages, type classes make it possible to specify that certain polymorphic functions can be used only when their arguments are of a type that supports some particular overloaded function (for more on this subject, see Sidebar 7.7).

Related Concepts

When considering function and subroutine calls, it is important to distinguish overloading from the related concepts of *coercion* and *polymorphism*. All three can be used, in certain circumstances, to pass arguments of multiple types to (or return values of multiple types from) what appears to be a single named routine. The syntactic similarity, however, hides significant differences in semantics and pragmatics.

Coercion, which we will cover in more detail in Section 7.2.2, is the process by which a compiler automatically converts a value of one type into a value of another type when that second type is required by the surrounding context. Polymorphism, which we will consider in Sections 7.1.2, 7.3, 10.1.1, and 14.4.4, allows a single subroutine to accept arguments of multiple types.

EXAMPLE 3.29

Printing objects of multiple types

Consider a print routine designed to display its argument on the standard output stream, and suppose that we wish to be able to display objects of multiple types. With overloading, we might write a separate print routine for each type of interest. Then when it sees a call to print(my_object), the compiler would choose the appropriate routine based on the type of my_object.

Now suppose we already have a print routine that accepts a floating-point argument. With coercion, we might be able to print integers by passing them to this existing routine, rather than writing a new one. When it sees a call to print(my_integer), the compiler would coerce (convert) the argument automatically to floating-point type prior to the call.

Finally, suppose we have a language in which many types support a to_string operation that will generate a character-string representation of an object of that type. We might then be able to write a polymorphic print routine that accepts an argument of any type for which to_string is defined. The to_string operation might itself be polymorphic, built in, or simply overloaded; in any of these cases, print could call it and output the result. ■

In short, overloading allows the programmer to give the same name to multiple objects, and to disambiguate (*resolve*) them based on context—for subroutines, on the number or types of arguments. Coercion allows the compiler to perform an automatic type conversion to make an argument conform to the expected type of some existing routine. Polymorphism allows a single routine to accept arguments of multiple types, provided that it attempts to use them only in ways that their types support.

☑ CHECK YOUR UNDERSTANDING

21. Explain the importance of information hiding.
22. What is an *opaque* export?
23. Why might it be useful to distinguish between the *header* and the *body* of a module?
24. What does it mean for a scope to be *closed*?
25. Explain the distinction between "modules as managers" and "modules as types."
26. How do classes differ from modules?
27. Why might it be useful to have modules and classes in the same language?
28. Why does the use of dynamic scoping imply the need for run-time type checking?
29. Explain the purpose of a compiler's symbol table.
30. What are *aliases*? Why are they considered a problem in language design and implementation?
31. Explain the value of the `restrict` qualifier in C.
32. What is *overloading*? How does it differ from *coercion* and *polymorphism*?
33. What are *type classes* in Haskell? What purpose do they serve?

3.6 The Binding of Referencing Environments

We have seen in Section 3.3 how scope rules determine the referencing environment of a given statement in a program. Static scope rules specify that the referencing environment depends on the lexical nesting of program blocks in which names are declared. Dynamic scope rules specify that the referencing environment depends on the order in which declarations are encountered at run time. An additional issue that we have not yet considered arises in languages that allow one to create a *reference* to a subroutine—for example, by passing it as a parameter. When should scope rules be applied to such a subroutine: when the reference is first created, or when the routine is finally called? The answer is particularly important for languages with dynamic scoping, though we shall see that it matters even in languages with static scoping.

EXAMPLE 3.30
Deep and shallow binding

A dynamic scoping example appears as pseudocode in Figure 3.13. Procedure print_selected_records is assumed to be a general-purpose routine that knows how to traverse the records in a database, regardless of whether they represent people, sprockets, or salads. It takes as parameters a database, a predicate to make print/don't print decisions, and a subroutine that knows how to format the data in the records of this particular database. We have hypothesized that procedure print_person uses the value of nonlocal variable line_length to calculate the number and width of columns in its output. In a language with dynamic scoping, it is natural for procedure print_selected_records to declare and initialize this variable locally, knowing that code inside print_routine will pick it up if needed. For this coding technique to work, the referencing environment of print_routine must not be created until the routine is actually called by print_selected_records. This late binding of the referencing environment of a subroutine that has been passed as a parameter is known as *shallow binding*. It is usually the default in languages with dynamic scoping.

For function older_than_threshold, by contrast, shallow binding may not work well. If, for example, procedure print_selected_records happens to have a local variable named threshold, then the variable set by the main program to influence the behavior of older_than_threshold will not be visible when the function is finally called, and the predicate will be unlikely to work correctly. In such a situation, the code that originally passes the function as a parameter has a particular referencing environment (the current one) in mind; it does not want the routine to be called in any other environment. It therefore makes sense to bind the environment at the time the routine is first passed as a parameter, and then restore that environment when the routine is finally called. That is, we arrange for older_than_threshold to see, when it is eventually called, the same referencing environment it would have seen if it had been called at the point where the reference was created. This early binding of the referencing environment is known as *deep binding*. It is almost always the default in languages with static scoping, and is sometimes available as an option with dynamic scoping as well. ■

```
type person = record
    . . .
    age : integer
    . . .
threshold : integer
people : database

function older_than_threshold(p : person) : boolean
    return p.age $\geq$ threshold

procedure print_person(p : person)
    –– Call appropriate I/O routines to print record on standard output.
    –– Make use of nonlocal variable line_length to format data in columns.
    . . .

procedure print_selected_records(db : database;
        predicate, print_routine : procedure)
    line_length : integer

    if device_type(stdout) = terminal
        line_length := 80
    else        –– Standard output is a file or printer.
        line_length := 132
    foreach record r in db
        –– Iterating over these may actually be
        –– a lot more complicated than a ‘for’ loop.
        if predicate(r)
            print_routine(r)

–– main program
. . .
threshold := 35
print_selected_records(people, older_than_threshold, print_person)
```

Figure 3.13 Program (in pseudocode) to illustrate the importance of binding rules. One might argue that deep binding is appropriate for the environment of function older_than_threshold (for access to threshold), while shallow binding is appropriate for the environment of procedure print_person (for access to line_length).

3.6.1 Subroutine Closures

Deep binding is implemented by creating an explicit representation of a referencing environment (generally the one in which the subroutine would execute if called at the present time) and bundling it together with a reference to the subroutine. The bundle as a whole is referred to as a *closure*. Usually the subroutine itself can be represented in the closure by a pointer to its code. In a language with dynamic scoping, the representation of the referencing environment depends on whether the language implementation uses an association list or a

```
def A(I, P):

    def B():
        print(I)

    # body of A:
    if I > 1:
        P()
    else:
        A(2, B)

def C():
    pass     # do nothing

A(1, C)      # main program
```

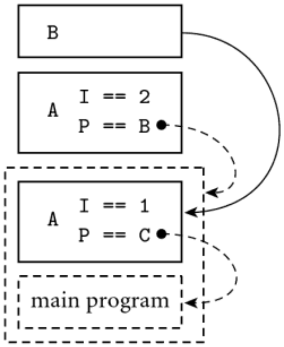


Figure 3.14 Deep binding in Python. At right is a conceptual view of the run-time stack. Referencing environments captured in closures are shown as dashed boxes and arrows. When `B` is called via formal parameter `P`, two instances of `I` exist. Because the closure for `P` was created in the initial invocation of `A`, `B`'s static link (solid arrow) points to the frame of that earlier invocation. `B` uses that invocation's instance of `I` in its `print` statement, and the output is a `1`.

central reference table for run-time lookup of names; we consider these alternatives at the end of Section C-3.4.2.

In early dialects of Lisp, which used dynamic scoping, deep binding was available via the built-in primitive `function`, which took a function as its argument and returned a closure whose referencing environment was the one in which the function would have executed if called at that moment in time. The closure could then be passed as a parameter to another function. If and when it was eventually called, it would execute in the saved environment. (Closures work slightly differently from "bare" functions in most Lisp dialects: they must be called by passing them to the built-in primitives `funcall` or `apply`.)

At first glance, one might be tempted to think that the binding time of referencing environments would not matter in a language with static scoping. After all, the meaning of a statically scoped name depends on its lexical nesting, not on the flow of execution, and this nesting is the same whether it is captured at the time a subroutine is passed as a parameter or at the time the subroutine is called. The catch is that a running program may have more than one *instance* of an object that is declared within a recursive subroutine. A closure in a language with static scoping captures the current instance of every object, at the time the closure is created. When the closure's subroutine is called, it will find these captured instances, even if newer instances have subsequently been created by recursive calls.

EXAMPLE 3.31
Binding rules with static scoping

One could imagine combining static scoping with shallow binding [VF82], but the combination does not seem to make much sense, and does not appear to have been adopted in any language. Figure 3.14 contains a Python program that illustrates the impact of binding rules in the presence of static scoping. This program prints a 1. With shallow binding it would print a 2. ■

It should be noted that binding rules matter with static scoping only when accessing objects that are neither local nor global, but are defined at some intermediate level of nesting. If an object is local to the currently executing subroutine, then it does not matter whether the subroutine was called directly or through a closure; in either case local objects will have been created when the subroutine started running. If an object is global, there will never be more than one instance, since the main body of the program is not recursive. Binding rules are therefore irrelevant in languages like C, which has no nested subroutines, or Modula-2, which allows only outermost subroutines to be passed as parameters, thus ensuring that any variable defined outside the subroutine is global. (Binding rules are also irrelevant in languages like PL/I and Ada 83, which do not permit subroutines to be passed as parameters at all.)

Suppose then that we have a language with static scoping in which nested subroutines can be passed as parameters, with deep binding. To represent a closure for subroutine *S*, we can simply save a pointer to *S*'s code together with the static link that *S* would use if it were called right now, in the current environment. When *S* is finally called, we temporarily restore the saved static link, rather than creating a new one. When *S* follows its static chain to access a nonlocal object, it will find the object instance that was current at the time the closure was created. This instance may not have the *value* it had at the time the closure was created, but its identity, at least, will reflect the intent of the closure's creator.

3.6.2 First-Class Values and Unlimited Extent

In general, a value in a programming language is said to have *first-class* status if it can be passed as a parameter, returned from a subroutine, or assigned into a variable. Simple types such as integers and characters are first-class values in most programming languages. By contrast, a "second-class" value can be passed as a parameter, but not returned from a subroutine or assigned into a variable, and a "third-class" value cannot even be passed as a parameter. As we shall see in Section 9.3.2, labels (in languages that have them) are usually third-class values, but they are second-class values in Algol. Subroutines display the most variation. They are first-class values in all functional programming languages and most scripting languages. They are also first-class values in C# and, with some restrictions, in several other imperative languages, including Fortran, Modula-2 and -3, Ada 95, C, and C++.[10] They are second-class values in most other imperative languages, and third-class values in Ada 83.

Our discussion of binding so far has considered only second-class subroutines. First-class subroutines in a language with nested scopes introduce an additional level of complexity: they raise the possibility that a reference to a subroutine may

[10] Some authors would say that first-class status requires anonymous function definitions—lambda expressions—that can be embedded in other expressions. C#, several scripting languages, and all functional languages meet this requirement, but many imperative languages do not.

EXAMPLE 3.32

Returning a first-class subroutine in Scheme

outlive the execution of the scope in which that routine was declared. Consider the following example in Scheme:

```
1.  (define plus-x
2.    (lambda (x)
3.      (lambda (y) (+ x y))))
4.  ...
5.  (let ((f (plus-x 2)))
6.    (f 3))               ; returns 5
```

Here the `let` construct on line 5 declares a new function, `f`, which is the result of calling `plus-x` with argument `2`. Function `plus-x` is defined at line 1. It returns the (unnamed) function declared at line 3. But that function refers to parameter `x` of `plus-x`. When `f` is called at line 6, its referencing environment will include the `x` in `plus-x`, despite the fact that `plus-x` has already returned (see Figure 3.15). Somehow we must ensure that `x` remains available.

If local objects were destroyed (and their space reclaimed) at the end of each scope's execution, then the referencing environment captured in a long-lived closure might become full of dangling references. To avoid this problem, most functional languages specify that local objects have *unlimited extent*: their lifetimes continue indefinitely. Their space can be reclaimed only when the garbage collection system is able to prove that they will never be used again. Local objects (other than `own`/`static` variables) in most imperative languages have *limited extent*: they are destroyed at the end of their scope's execution. (C# and Smalltalk are exceptions to the rule, as are most scripting languages.) Space for local objects with limited extent can be allocated on a stack. Space for local objects with unlimited extent must generally be allocated on a heap.

Given the desire to maintain stack-based allocation for the local variables of subroutines, imperative languages with first-class subroutines must generally adopt alternative mechanisms to avoid the dangling reference problem for closures. C and (pre-Fortran 90) Fortran, of course, do not have nested subroutines. Modula-2 allows references to be created only to outermost subroutines (outermost routines are first-class values; nested routines are third-class values). Modula-3 allows nested subroutines to be passed as parameters, but only outer-

DESIGN & IMPLEMENTATION

3.9 Binding rules and extent

Binding mechanisms and the notion of extent are closely tied to implementation issues. A-lists make it easy to build closures (Section C-3.4.2), but so do the non-nested subroutines of C and the rule against passing nonglobal subroutines as parameters in Modula-2. In a similar vein, the lack of first-class subroutines in many imperative languages reflects in large part the desire to avoid heap allocation, which would be needed for local variables with unlimited extent.

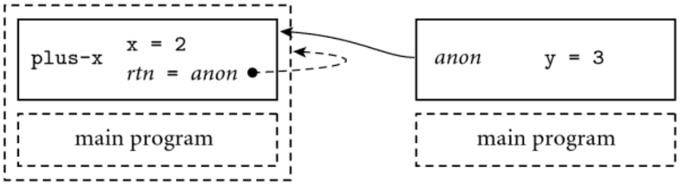


Figure 3.15 **The need for unlimited extent.** When function `plus-x` is called in Example 3.32, it returns (left side of the figure) a closure containing an anonymous function. The referencing environment of that function encompasses both `plus-x` and `main`—including the local variables of `plus-x` itself. When the anonymous function is subsequently called (right side of the figure), it must be able to access variables in the closure's environment—in particular, the `x` inside `plus-x`—despite the fact that `plus-x` is no longer active.

most routines to be returned or stored in variables (outermost routines are first-class values; nested routines are second-class values). Ada 95 allows a nested routine to be returned, but only if the scope in which it was declared is the same as, or larger than, the scope of the declared return type. This containment rule, while more conservative than strictly necessary (it forbids the Ada equivalent of Figure 3.14), makes it impossible to propagate a subroutine reference to a portion of the program in which the routine's referencing environment is not active.

3.6.3 Object Closures

As noted in Section 3.6.1, the referencing environment in a closure will be nontrivial only when passing a nested subroutine. This means that the implementation of first-class subroutines is trivial in a language without nested subroutines. At the same time, it means that a programmer working in such a language is missing a useful feature: the ability to pass a subroutine *with context*. In object-oriented languages, there is an alternative way to achieve a similar effect: we can encapsulate our subroutine as a method of a simple object, and let the object's fields hold context for the method. In Java we might write the equivalent of Example 3.32 as follows:

EXAMPLE 3.33
An object closure in Java

```
interface IntFunc {
    public int call(int i);
}
class PlusX implements IntFunc {
    final int x;
    PlusX(int n) { x = n; }
    public int call(int i) { return i + x; }
}
...
IntFunc f = new PlusX(2);
System.out.println(f.call(3));      // prints 5
```

Here the *interface* `IntFunc` defines a static type for objects enclosing a function from integers to integers. Class `PlusX` is a concrete implementation of this type, and can be instantiated for any integer constant `x`. Where the Scheme code in Example 3.32 captured `x` in the subroutine closure returned by `(plus-x 2)`, the Java code here captures `x` in the object closure returned by `new PlusX(2)`. ■

EXAMPLE 3.34
Delegates in C#

An object that plays the role of a function and its referencing environment may variously be called an *object closure*, a *function object*, or a *functor*. (This is unrelated to use of the term *functor* in Prolog, ML, or Haskell.) In C#, a first-class subroutine is an instance of a *delegate* type:

```
delegate int IntFunc(int i);
```

This type can be instantiated for any subroutine that matches the specified argument and return types. That subroutine may be static, or it may be a method of some object:

```
static int Plus2(int i)  return i + 2;
...
IntFunc f = new IntFunc(Plus2);
Console.WriteLine(f(3));           // prints 5

class PlusX
    int x;
    public PlusX(int n)  x = n;
    public int call(int i)  return i + x;
...
IntFunc g = new IntFunc(new PlusX(2).call);
Console.WriteLine(g(3));           // prints 5
```

■

EXAMPLE 3.35
Delegates and unlimited extent

Remarkably, though C# does not permit subroutines to nest in the general case, it does allow delegates to be instantiated in-line from *anonymous* (unnamed) methods. These allow us to mimic the code of Example 3.32:

```
static IntFunc PlusY(int y) {
    return delegate(int i) { return i + y; };
}
...
IntFunc h = PlusY(2);
```

Here `y` has unlimited extent! The compiler arranges to allocate it in the heap, and to refer to it indirectly through a hidden pointer, included in the closure. This implementation incurs the cost of dynamic storage allocation (and eventual garbage collection) only when it is needed; local variables remain in the stack in the common case. ■

EXAMPLE 3.36
Function objects in C++

Object closures are sufficiently important that some languages support them with special syntax. In C++, an object of a class that overrides `operator()` can be called as if it were a function:

```
class int_func {
public:
    virtual int operator()(int i) = 0;
};
class plus_x : public int_func {
    const int x;
public:
    plus_x(int n) : x(n) { }
    virtual int operator()(int i) { return i + x; }
};
...
plus_x f(2);
cout << f(3) << "\n";              // prints 5
```

Object `f` could also be passed to any function that expected a parameter of class `int_func`. ■

3.6.4 Lambda Expressions

In most of our examples so far, closures have corresponded to subroutines that were declared—and named—in the usual way. In the Scheme code of Example 3.32, however, we saw an anonymous function—a *lambda expression*. Similarly, in Example 3.35, we saw an anonymous delegate in C#. That example can be made even simpler using C#'s lambda syntax:

EXAMPLE 3.37
A lambda expression in C#

```
static IntFunc PlusY(int y) {
    return i => i + y;
}
```

Here the keyword `delegate` of Example 3.35 has been replaced by an `=>` sign that separates the anonymous function's parameter list (in this case, just `i`) from its body (the expression `i + y`). In a function with more than one parameter, the parameter list would be parenthesized; in a longer, more complicated function, the body could be a code block, with one or more explicit `return` statements. ■

The term "lambda expression" comes from the *lambda calculus*, a formal notation for functional programming that we will consider in more detail in Chapter 11. As one might expect, lambda syntax varies quite a bit from one language to another:

EXAMPLE 3.38
Variety of lambda syntax

```
(lambda (i j) (> i j) i j)          ; Scheme

(int i, int j) => i > j ? i : j     // C#

fun i j -> if i > j then i else j   (* OCaml *)

->(i, j){ i > j ? i : j }           # Ruby
```

Each of these expressions evaluates to the larger of two parameters.

In Scheme and OCaml, which are predominately functional languages, a lambda expression simply *is* a function, and can be called in the same way as any other function:

```
; Scheme:
((lambda (i j) (> i j) i j) 5 8)          ; evaluates to 8

(* OCaml: *)
(fun i j -> if i > j then i else j) 5 8    (* likewise *)
```

In Ruby, which is predominately imperative, a lambda expression must be called explicitly:

```
print ->(i, j){ i > j ? i : j }.call(5, 8)
```

In C#, the expression must be assigned into a variable (or passed into a parameter) before it can be invoked:

```
Func<int, int, int> m = (i, j) => i > j ? i : j;
Console.WriteLine(m.Invoke(5, 8));
```

Here `Func<int, int, int>` is how one names the type of a function taking two integer parameters and returning an integer result.

In functional programming languages, lambda expressions make it easy to manipulate functions as values—to combine them in various ways to create new functions on the fly. This sort of manipulation is less common in imperative languages, but even there, lambda expressions can help encourage code reuse and generality. One particularly common idiom is the *callback*—a subroutine, passed into a library, that allows the library to "call back" into the main program when appropriate. Examples of callbacks include a comparison operator passed into a sorting routine, a predicate used to filter elements of a collection, or a handler to be called in response to some future event (see Section 9.6.2).

With the increasing popularity of first-class subroutines, lambda expressions have even made their way into C++, where the lack of garbage collection and the emphasis on stack-based allocation make it particularly difficult to solve the problem of variable capture. The adopted solution, in keeping with the nature of the language, stresses efficiency and expressiveness more than run-time safety.

EXAMPLE 3.39
A simple lambda expression in C++11

In the simple case, no capture of nonlocal variables is required. If `V` is a vector of integers, the following will print all elements less than 50:

```
for_each(V.begin(), V.end(),
    [](int e){ if (e < 50) cout << e << " "; }
);
```

Here `for_each` is a standard library routine that applies its third parameter—a function—to every element of a collection in the range specified by its first two parameters. In our example, the function is denoted by a lambda expression, introduced by the empty square brackets. The compiler turns the lambda expression into an anonymous function, which is then passed to `for_each` via C++'s usual mechanism—a simple pointer to the code. ■

EXAMPLE 3.40

Variable capture in C++ lambda expressions

Suppose, however, that we wanted to print all elements less than `k`, where `k` is a variable outside the scope of the lambda expression. We now have two options in C++:

```
[=](int e){ if (e < k) cout << e << " "; }

[&](int e){ if (e < k) cout << e << " "; }
```

Both of these cause the compiler to create an object closure (a *function object* in C++), which could be passed to (and called from) `for_each` in the same way as an ordinary function. The difference between the two options is that `[=]` arranges for a copy of each captured variable to be placed in the object closure; `[&]` arranges for a reference to be placed there instead. The programmer must choose between these options. Copying can be expensive for large objects, and any changes to the object made after the closure is created will not be seen by the code of the lambda expression when it finally executes. References allow changes to be seen, but will lead to undefined (and presumably incorrect) behavior if the closure's lifetime exceeds that of the captured object: C++ does *not* have unlimited extent. In particularly complex situations, the programmer can specify capture on an object-by-object basis:

```
[j, &k](int e){ ...  // capture j's value and a reference to k,
                     // so they can be used in here
```

■

DESIGN & IMPLEMENTATION

3.10 Functions and function objects

The astute reader may be wondering: In Example 3.40, how does `for_each` manage to "do the right thing" with two different implementations of its third parameter? After all, sometimes that parameter is implemented as a simple pointer; other times it is a pointer to an object with an `operator()`, which requires a different kind of call. The answer is that `for_each` is a *generic* routine (a *template* in C++). The compiler generates customized implementations of `for_each` on demand. We will discuss generics in more detail in Section 7.3.1.

In some situations, it may be difficult to use generics to distinguish among "function-like" parameters. As an alternative, C++ provides a standard `function` *class*, with constructors that allow it to be instantiated from a function, a function pointer, a function object, or a manually created object closure. Something like `for_each` could then be written as an ordinary (nongeneric) subroutine whose third parameter was a object of class `function`. In any given call, the compiler would coerce the provided argument to be a function object.

EXAMPLE 3.41

Lambda expressions in Java 8

Lambda expressions appear in Java 8 as well, but in a restricted form. In situations where they might be useful, Java has traditionally relied on an idiom known as a *functional interface*. The `Arrays.sort` routine, for example, expects a parameter of type `Comparator`. To sort an array of personnel records by age, we would (traditionally) have written

```
class AgeComparator implements Comparator<Person> {
    public int compare(Person p1, Person p2) {
        return Integer.compare(p1.age, p2.age);
    }
}
Person[] People = ...
...
Arrays.sort(People, new AgeComparator());
```

Significantly, `Comparator` has only a single abstract method: the `compare` routine provided by our `AgeComparator` class. With lambda expressions in Java 8, we can omit the declaration of `AgeComparator` and simply write

```
Arrays.sort(People, (p1, p2) -> Integer.compare(p1.age, p2.age));
```

The key to the simpler syntax is that `Comparator` is a functional interface, and thus has only a single abstract method. When a variable or formal parameter is declared to be of some functional interface type, Java 8 allows a lambda expression whose parameter and return types match those of the interface's single method to be assigned into the variable or passed as the parameter. In effect, the compiler uses the lambda expression to create an instance of an anonymous class that implements the interface. ■

As it turns out, coercion to functional interface types is the *only* use of lambda expressions in Java. In particular, lambda expressions have no types of their own: they are not really objects, and cannot be directly manipulated. Their behavior with respect to variable capture is entirely determined by the usual rules for nested classes. We will consider these rules in more detail in Section 10.2.3; for now, suffice it to note that Java, like C++, does not support unlimited extent.

3.7 Macro Expansion

Prior to the development of high-level programming languages, assembly language programmers could find themselves writing highly repetitive code. To ease the burden, many assemblers provided sophisticated *macro expansion* facilities.

EXAMPLE 3.42

A simple assembly macro

Consider the task of loading an element of a two-dimensional array from memory into a register. As we shall see in Section 8.2.3, this operation can easily require half a dozen instructions, with details depending on the hardware instruction set; the size of the array elements; and whether the indices are constants, values in memory, or values in registers. In many early assemblers, one could define a macro that would replace an expression like ld2d(target_reg, array_name, row, column, row_size, element_size) with the appropriate multi-instruction sequence. In a numeric program containing hundreds or thousands of array access operations, this macro could prove extremely useful. ■

EXAMPLE 3.43
Preprocessor macros in C

When C was created in the early 1970s, it was natural to include a macro preprocessing facility:

```
#define LINE_LEN 80
#define DIVIDES(a,n) (!((n) % (a)))
    /* true iff n has zero remainder modulo a */
#define SWAP(a,b) {int t = (a); (a) = (b); (b) = t;}
#define MAX(a,b) ((a) > (b) ? (a) : (b))
```

Macros like LINE_LEN avoided the need (in early versions of C) to support named constants in the language itself. Perhaps more important, parameterized macros like DIVIDES, MAX, and SWAP were much more efficient than equivalent C functions. They avoided the overhead of the subroutine call mechanism (including register saves and restores), and the code they generated could be integrated into any code improvements that the compiler was able to effect in the code surrounding the call. ■

EXAMPLE 3.44
"Gotchas" in C macros

Unfortunately, C macros suffer from several limitations, all of which stem from the fact that they are implemented by textual substitution, and are not understood by the rest of the compiler. Put another way, they provide a naming and binding mechanism that is separate from—and often at odds with—the rest of the programming language.

In the definition of DIVIDES, the parentheses around the occurrences of a and n are essential. Without them, DIVIDES(y + z, x) would be replaced by (!(x % y + z)), which is the same as (!((x % y) + z)), according to the rules of precedence. In a similar vein, SWAP may behave unexpectedly if the programmer writes SWAP(x, t): textual substitution of arguments allows the macro's declaration of t to *capture* the t that was passed. MAX(x++, y++) may also behave unexpectedly, since the increment side effects will happen more than once. Unfortunately,

DESIGN & IMPLEMENTATION

3.11 Generics as macros

In some sense, the ability to import names into an ordinary module provides a primitive sort of generic facility. A stack module that imports its element type, for example, can be inserted (with a text editor) into any context in which the appropriate type name has been declared, and will produce a "customized" stack for that context when compiled. Early versions of C++ formalized this mechanism by using macros to implement templates. Later versions of C++ have made templates (generics) a fully supported language feature, giving them much of the flavor of hygienic macros. (More on templates and on *template metaprogramming* can be found in Section C-7.3.2.)

in standard C we cannot avoid the extra side effects by assigning the parameters into temporary variables: a C macro that "returns" a value must be an expression, and declarations are one of many language constructs that cannot appear inside (see also Exercise 3.23). ■

Modern languages and compilers have, for the most part, abandoned macros as an anachronism. Named constants are type-safe and easy to implement, and *in-line* subroutines (to be discussed in Section 9.2.4) provide almost all the performance of parameterized macros without their limitations. A few languages (notably Scheme and Common Lisp) take an alternative approach, and integrate macros into the language in a safe and consistent way. So-called *hygienic* macros implicitly encapsulate their arguments, avoiding unexpected interactions with associativity and precedence. They rename variables when necessary to avoid the capture problem, and they can be used in any expression context. Unlike subroutines, however, they are expanded during semantic analysis, making them generally unsuitable for unbounded recursion. Their appeal is that, like all macros, they take *unevaluated* arguments, which they evaluate lazily on demand. Among other things, this means that they preserve the multiple side effect "gotcha" of our `MAX` example. Delayed evaluation was a bug in this context, but can sometimes be a feature. We will return to it in Sections 6.1.5 (short-circuit Boolean evaluation), 9.3.2 (call-by-name parameters), and 11.5 (normal-order evaluation in functional programming languages).

✓ CHECK YOUR UNDERSTANDING

34. Describe the difference between deep and shallow *binding* of referencing environments.

35. Why are binding rules particularly important for languages with dynamic scoping?

36. What are *first-class* subroutines? What languages support them?

37. What is a *subroutine closure*? What is it used for? How is it implemented?

38. What is an *object closure*? How is it related to a subroutine closure?

39. Describe how the *delegates* of C# extend and unify both subroutine and object closures.

40. Explain the distinction between limited and unlimited *extent* of objects in a local scope.

41. What is a *lambda expression*? How does the support for lambda expressions in functional languages compare to that of C# or Ruby? To that of C++ or Java?

42. What are *macros*? What was the motivation for including them in C? What problems may they cause?

3.8 Separate Compilation

Since most large programs are constructed and tested incrementally, and since the compilation of a very large program can be a multihour operation, any language designed to support large programs must provide for separate compilation.

IN MORE DEPTH

On the companion site we consider the relationship between modules and separate compilation. Because they are designed for encapsulation and provide a narrow interface, modules are the natural choice for the "compilation units" of many programming languages. The separate module headers and bodies of Modula-3 and Ada, for example, are explicitly intended for separate compilation, and reflect experience gained with more primitive facilities in other languages. C and C++, by contrast, must maintain backward compatibility with mechanisms designed in the early 1970s. Modern versions of C and C++ include a *namespace* mechanism that provides module-like data hiding, but names must still be declared before they are used in every compilation unit, and the mechanisms used to accommodate this rule are purely a matter of convention. Java and C# break with the C tradition by requiring the compiler to infer header information automatically from separately compiled class definitions; no header files are required.

3.9 Summary and Concluding Remarks

This chapter has addressed the subject of names, and the *binding* of names to objects (in a broad sense of the word). We began with a general discussion of the notion of *binding time*—the time at which a name is associated with a particular object or, more generally, the time at which an answer is associated with any open question in language or program design or implementation. We defined the notion of *lifetime* for both objects and name-to-object bindings, and noted that they need not be the same. We then introduced the three principal storage allocation mechanisms—static, stack, and heap—used to manage space for objects.

In Section 3.3 we described how the binding of names to objects is governed by *scope rules*. In some languages, scope rules are dynamic: the meaning of a name is found in the most recently entered scope that contains a declaration and that has not yet been exited. In most modern languages, however, scope rules are static, or *lexical*: the meaning of a name is found in the closest lexically surrounding scope that contains a declaration. We found that lexical scope rules vary in important but sometimes subtle ways from one language to another. We considered what sorts of scopes are allowed to nest, whether scopes are *open* or *closed*, whether the scope of a name encompasses the entire block in which it is declared, and whether a name must be declared before it is used. We explored the implementation of scope rules in Section 3.4.

In Section 3.5 we examined several ways in which bindings relate to one another. Aliases arise when two or more names in a given scope are bound to the same object. Overloading arises when one name is bound to multiple objects. We noted that while behavior reminiscent of overloading can sometimes be achieved through coercion or polymorphism, the underlying mechanisms are really very different. In Section 3.6 we considered the question of when to bind a referencing environment to a subroutine that is passed as a parameter, returned from a function, or stored in a variable. Our discussion touched on the notions of *closures* and *lambda expressions*, both of which will appear repeatedly in later chapters. In Sections 3.7 and 3.8 we considered macros and separate compilation.

Some of the more complicated aspects of lexical scoping illustrate the evolution of language support for data abstraction, a subject to which we will return in Chapter 10. We began by describing the `own` or `static` variables of languages like Fortran, Algol 60, and C, which allow a variable that is local to a subroutine to retain its value from one invocation to the next. We then noted that simple modules can be seen as a way to make long-lived objects local to a group of subroutines, in such a way that they are not visible to other parts of the program. By selectively exporting names, a module may serve as the "manager" for one or more abstract data types. At the next level of complexity, we noted that some languages treat modules *as* types, allowing the programmer to create an arbitrary number of instances of the abstraction defined by a module. Finally, we noted that object-oriented languages extend the module-as-type approach (as well as the notion of lexical scope) by providing an inheritance mechanism that allows new abstractions (classes) to be defined as extensions or refinements of existing classes.

Among the topics considered in this chapter, we saw several examples of useful features (recursion, static scoping, forward references, first-class subroutines, unlimited extent) that have been omitted from certain languages because of concern for their implementation complexity or run-time cost. We also saw an example of a feature (the private part of a module specification) introduced expressly to facilitate a language's implementation, and another (separate compilation in C) whose design was clearly intended to mirror a particular implementation. In several additional aspects of language design (late vs early binding, static vs dynamic scoping, support for coercions and conversions, toleration of pointers and other aliases), we saw that implementation issues play a major role.

In a similar vein, apparently simple language rules can have surprising implications. In Section 3.3.3, for example, we considered the interaction of whole-block scope with the requirement that names be declared before they can be used. Like the `do` loop syntax and white space rules of Fortran (Section 2.2.2) or the `if`... `then`... `else` syntax of Pascal (Section 2.3.2), poorly chosen scoping rules can make program analysis difficult not only for the compiler, but for human beings as well. In future chapters we shall see several additional examples of features that are both confusing and hard to compile. Of course, semantic utility and ease of implementation do not always go together. Many easy-to-compile features (e.g., `goto` statements) are of questionable value at best. We will also see several examples of highly useful and (conceptually) simple features, such as garbage collection (Section 8.5.3) and unification (Sections 7.2.4, C-7.3.2, and 12.2.1), whose implementations are quite complex.

3.10 Exercises

3.1 Indicate the binding time (when the language is designed, when the program is linked, when the program begins execution, etc.) for each of the following decisions in your favorite programming language and implementation. Explain any answers you think are open to interpretation.

- The number of built-in functions (math, type queries, etc.)
- The variable declaration that corresponds to a particular variable reference (use)
- The maximum length allowed for a constant (literal) character string
- The referencing environment for a subroutine that is passed as a parameter
- The address of a particular library routine
- The total amount of space occupied by program code and data

3.2 In Fortran 77, local variables were typically allocated statically. In Algol and its descendants (e.g., Ada and C), they are typically allocated in the stack. In Lisp they are typically allocated at least partially in the heap. What accounts for these differences? Give an example of a program in Ada or C that would not work correctly if local variables were allocated statically. Give an example of a program in Scheme or Common Lisp that would not work correctly if local variables were allocated on the stack.

3.3 Give two examples in which it might make sense to delay the binding of an implementation decision, even though sufficient information exists to bind it early.

3.4 Give three concrete examples drawn from programming languages with which you are familiar in which a variable is live but not in scope.

3.5 Consider the following pseudocode:

```
procedure main()
    a : integer := 1
    b : integer := 2

    procedure middle()
        b : integer := a

        procedure inner()
            print a, b
        a : integer := 3

        -- body of middle
        inner()
        print a, b

    -- body of main
    middle()
    print a, b
```

Suppose this was code for a language with the declaration-order rules of C (but with nested subroutines)—that is, names must be declared before use, and the scope of a name extends from its declaration through the end of the block. At each print statement, indicate which declarations of a and b are in the referencing environment. What does the program print (or will the compiler identify static semantic errors)? Repeat the exercise for the declaration-order rules of C# (names must be declared before use, but the scope of a name is the entire block in which it is declared) and of Modula-3 (names can be declared in any order, and their scope is the entire block in which they are declared).

3.6 Consider the following pseudocode, assuming nested subroutines and static scope:

```
procedure main()
    g : integer

    procedure B(a : integer)
        x : integer

        procedure A(n : integer)
            g := n

        procedure R(m : integer)
            write_integer(x)
            x /:= 2 -- integer division
            if x > 1
                R(m + 1)
            else
                A(m)

        -- body of B
        x := a × a
        R(1)

    -- body of main
    B(3)
    write_integer(g)
```

(a) What does this program print?

```
typedef struct list_node {
    void* data;
    struct list_node* next;
} list_node;

list_node* insert(void* d, list_node* L) {
    list_node* t = (list_node*) malloc(sizeof(list_node));
    t->data = d;
    t->next = L;
    return t;
}

list_node* reverse(list_node* L) {
    list_node* rtn = 0;
    while (L) {
        rtn = insert(L->data, rtn);
        L = L->next;
    }
    return rtn;
}

void delete_list(list_node* L) {
    while (L) {
        list_node* t = L;
        L = L->next;
        free(t->data);
        free(t);
    }
}
```

Figure 3.16 List management routines for Exercise 3.7.

(b) Show the frames on the stack when A has just been called. For each frame, show the static and dynamic links.

(c) Explain how A finds g.

3.7 As part of the development team at MumbleTech.com, Janet has written a list manipulation library for C that contains, among other things, the code in Figure 3.16.

(a) Accustomed to Java, new team member Brad includes the following code in the main loop of his program:

```
list_node* L = 0;
while (more_widgets()) {
    L = insert(next_widget(), L);
}
L = reverse(L);
```

Sadly, after running for a while, Brad's program always runs out of memory and crashes. Explain what's going wrong.

(b) After Janet patiently explains the problem to him, Brad gives it another try:

```
list_node* L = 0;
while (more_widgets()) {
    L = insert(next_widget(), L);
}
list_node* T = reverse(L);
delete_list(L);
L = T;
```

This seems to solve the insufficient memory problem, but where the program used to produce correct results (before running out of memory), now its output is strangely corrupted, and Brad goes back to Janet for advice. What will she tell him this time?

3.8 Rewrite Figures 3.6 and 3.7 in C. You will need to use separate compilation for name hiding.

3.9 Consider the following fragment of code in C:

```
{   int a, b, c;
    ...
    {   int d, e;
        ...
        {   int f;
            ...
        }
        ...
    }
    ...
    {   int g, h, i;
        ...
    }
    ...
}
```

(a) Assume that each integer variable occupies four bytes. How much total space is required for the variables in this code?

(b) Describe an algorithm that a compiler could use to assign stack frame offsets to the variables of arbitrary nested blocks, in a way that minimizes the total space required.

3.10 Consider the design of a Fortran 77 compiler that uses static allocation for the local variables of subroutines. Expanding on the solution to the previous question, describe an algorithm to minimize the total space required for these variables. You may find it helpful to construct a *call graph* data structure in which each node represents a subroutine, and each directed arc indicates that the subroutine at the tail may sometimes call the subroutine at the head.

3.11 Consider the following pseudocode:

```
procedure P(A, B : real)
    X : real

    procedure Q(B, C : real)
        Y : real
        . . .

    procedure R(A, C : real)
        Z : real
        . . .                  -- (*)
    . . .
```

Assuming static scope, what is the referencing environment at the location marked by (*)?

3.12 Write a simple program in Scheme that displays three different behaviors, depending on whether we use `let`, `let*`, or `letrec` to declare a given set of names. (Hint: To make good use of `letrec`, you will probably want your names to be functions [`lambda` expressions].)

3.13 Consider the following program in Scheme:

```
(define A
  (lambda()
    (let* ((x 2)
           (C (lambda (P)
                (let ((x 4))
                  (P))))
           (D (lambda ()
                x))
           (B (lambda ()
                (let ((x 3))
                  (C D)))))
      (B))))
```

What does this program print? What would it print if Scheme used dynamic scoping and shallow binding? Dynamic scoping and deep binding? Explain your answers.

3.14 Consider the following pseudocode:

```
x : integer      -- global

procedure set_x(n : integer)
    x := n
```

```
procedure print_x()
    write_integer(x)

procedure first()
    set_x(1)
    print_x()

procedure second()
    x : integer
    set_x(2)
    print_x()

set_x(0)
first()
print_x()
second()
print_x()
```

What does this program print if the language uses static scoping? What does it print with dynamic scoping? Why?

3.15 The principal argument in *favor* of dynamic scoping is that it facilitates the customization of subroutines. Suppose, for example, that we have a library routine print_integer that is capable of printing its argument in any of several bases (decimal, binary, hexadecimal, etc.). Suppose further that we want the routine to use decimal notation most of the time, and to use other bases only in a few special cases: we do not want to have to specify a base explicitly on each individual call. We can achieve this result with dynamic scoping by having print_integer obtain its base from a nonlocal variable print_base. We can establish the default behavior by declaring a variable print_base and setting its value to 10 in a scope encountered early in execution. Then, any time we want to change the base temporarily, we can write

```
begin      -- nested block
    print_base : integer := 16      -- use hexadecimal
    print_integer(n)
```

The problem with this argument is that there are usually other ways to achieve the same effect, without dynamic scoping. Describe at least two for the print_integer example.

3.16 As noted in Section 3.6.3, C# has unusually sophisticated support for first-class subroutines. Among other things, it allows *delegates* to be instantiated from anonymous nested methods, and gives local variables and parameters unlimited extent when they may be needed by such a delegate. Consider the implications of these features in the following C# program:

```
using System;
public delegate int UnaryOp(int n);
   // type declaration: UnaryOp is a function from ints to ints

public class Foo {
    static int a = 2;
    static UnaryOp b(int c) {
        int d = a + c;
        Console.WriteLine(d);
        return delegate(int n) { return c + n; };
    }
    public static void Main(string[] args) {
        Console.WriteLine(b(3)(4));
    }
}
```

What does this program print? Which of a, b, c, and d, if any, is likely to be statically allocated? Which could be allocated on the stack? Which would need to be allocated in the heap? Explain.

3.17 If you are familiar with structured exception handling, as provided in Ada, C++, Java, C#, ML, Python, or Ruby, consider how this mechanism relates to the issue of scoping. Conventionally, a raise or throw statement is thought of as referring to an exception, which it passes as a parameter to a handler-finding library routine. In each of the languages mentioned, the exception itself must be declared in some surrounding scope, and is subject to the usual static scope rules. Describe an alternative point of view, in which the raise or throw is actually a reference to a *handler*, to which it transfers control directly. Assuming this point of view, what are the scope rules for handlers? Are these rules consistent with the rest of the language? Explain. (For further information on exceptions, see Section 9.4.)

3.18 Consider the following pseudocode:

```
x : integer      –– global

procedure set_x(n : integer)
    x := n

procedure print_x()
    write_integer(x)

procedure foo(S, P : function; n : integer)
    x : integer := 5
    if n in {1, 3}
        set_x(n)
    else
        S(n)
    if n in {1, 2}
        print_x()
    else
        P

set_x(0); foo(set_x, print_x, 1); print_x()
set_x(0); foo(set_x, print_x, 2); print_x()
set_x(0); foo(set_x, print_x, 3); print_x()
set_x(0); foo(set_x, print_x, 4); print_x()
```

Assume that the language uses dynamic scoping. What does the program print if the language uses shallow binding? What does it print with deep binding? Why?

3.19 Consider the following pseudocode:

```
x : integer := 1
y : integer := 2

procedure add()
    x := x + y

procedure second(P : procedure)
    x : integer := 2
    P()

procedure first
    y : integer := 3
    second(add)

first()
write_integer(x)
```

(a) What does this program print if the language uses static scoping?

(b) What does it print if the language uses dynamic scoping with deep binding?

(c) What does it print if the language uses dynamic scoping with shallow binding?

3.20 Consider mathematical operations in a language like C++, which supports both overloading and coercion. In many cases, it may make sense to provide multiple, overloaded versions of a function, one for each numeric type or combination of types. In other cases, we might use a single version—probably defined for double-precision floating point arguments—and rely on coercion to allow that function to be used for other numeric types (e.g., integers). Give an example in which overloading is clearly the preferable approach. Give another in which coercion is almost certainly better.

3.21 In a language that supports operator overloading, build support for rational numbers. Each number should be represented internally as a (numerator, denominator) pair in simplest form, with a positive denominator. Your code should support unary negation and the four standard arithmetic operators. For extra credit, create a conversion routine that accepts two floating-point parameters—a value and a error bound—and returns the simplest (smallest denominator) rational number within the given error bound of the given value.

3.22 In an imperative language with lambda expressions (e.g., C#, Ruby, C++, or Java), write the following higher-level functions. (A higher-level function, as we shall see in Chapter 11, takes other functions as argument and/or returns a function as a result.)

- `compose(g, f)`—returns a function `h` such that `h(x) == g(f(x))`.
- `map(f, L)`—given a function `f` and a list `L` returns a list `M` such that the *i*th element of `M` is `f(`*e*`)`, where *e* is the *i*th element of `L`.
- `filter(L, P)`—given a list `L` and a predicate (Boolean-returning function) `P`, returns a list containing all and only those elements of `L` for which `P` is true.

Ideally, your code should work for any argument or list element type.

3.23 Can you write a macro in standard C that "returns" the greatest common divisor of a pair of arguments, without calling a subroutine? Why or why not?

3.24–3.31 In More Depth.

3.11 Explorations

3.32 Experiment with naming rules in your favorite programming language. Read the manual, and write and compile some test programs. Does the language use lexical or dynamic scoping? Can scopes nest? Are they open or closed? Does the scope of a name encompass the entire block in which it is declared, or only the portion after the declaration? How does one declare mutually recursive types or subroutines? Can subroutines be passed as parameters, returned from functions, or stored in variables? If so, when are referencing environments bound?

3.33 List the keywords (reserved words) of one or more programming languages. List the predefined identifiers. (Recall that every keyword is a separate token. An identifier cannot have the same spelling as a keyword.) What criteria do you think were used to decide which names should be keywords and which should be predefined identifiers? Do you agree with the choices? Why or why not?

3.34 If you have experience with a language like C, C++, or Rust, in which dynamically allocated space must be manually reclaimed, describe your experience with dangling references or memory leaks. How often do these bugs arise? How do you find them? How much effort does it take? Learn about open-source or commercial tools for finding storage bugs (*Valgrind* is a popular open-source example). Do such tools weaken the argument for automatic garbage collection?

3.35 A few languages—notably Euclid and Turing, make every subroutine a closed scope, and require it to explicitly import any nonlocal names it uses. The import lists can be thought of as explicit, mandatory documentation of a part of the subroutine interface that is usually implicit. The use of import lists also makes it easy for Euclid and Turing to prohibit passing a variable, by reference, to a subroutine that also accesses that variable directly, thereby avoiding the errors alluded to in Example 3.20.

In programs you have written, how hard would it have been to document every use of a nonlocal variable? Would the effort be worth the improvement in the quality of documentation and error rates?

3.36 We learned in Section 3.3.6 that modern languages have generally abandoned dynamic scoping. One place it can still be found is in the so-called *environment variables* of the Unix programming environment. If you are not familiar with these, read the manual page for your favorite shell (command interpreter—`ksh/bash`, `csh/tcsh`, etc.) to learn how these behave. Explain why the usual alternatives to dynamic scoping (default parameters and static variables) are not appropriate in this case.

3.37 Compare the mechanisms for overloading of enumeration names in Ada and in Modula-3 or C# (Section 3.5.2). One might argue that the (historically more recent) Modula-3/C# approach moves responsibility from the compiler to the programmer: it requires even an unambiguous use of an enumeration constant to be annotated with its type. Why do you think this approach was chosen by the language designers? Do you agree with the choice? Why or why not?

3.38 Learn about *tied variables* in Perl. These allow the programmer to associate an ordinary variable with an (object-oriented) object in such a way that operations on the variable are automatically interpreted as method invocations on the object. As an example, suppose we write `tie $my_var, "my_class";`. The interpreter will create a new object of class `my_class`, which it will associate with scalar variable `$my_var`. For purposes of discussion, call that object *O*. Now, any attempt to read the value of `$my_var` will be interpreted as a call to method *O*`->FETCH()`. Similarly, the assignment `$my_var =` *value* will be interpreted as a call to *O*`->STORE(`*value*`)`. Array, hash, and filehandle variables, which support a larger set of built-in operations, provide access to a larger set of methods when tied.

Compare Perl's tying mechanism to the operator overloading of C++. Which features of each language can be conveniently emulated by the other?

3.39 Do you think coercion is a good idea? Why or why not?

3.40 The syntax for lambda expressions in Ruby evolved over time, with the result that there are now four ways to pass a *block* into a method as a closure:

by placing it after the end of the argument list (in which case it become an extra, final parameter); by passing it to `Proc.new`; or, within the argument list, by prefixing it with the keyword `lambda` or by writing it in `->` lambda notation. Investigate these options. Which came first? Which came later? What are their comparative advantages? Are their any minor differences in their behavior?

3.41 Lambda expressions were a late addition to the Java programming language: they were strongly resisted for many years. Research the controversy surrounding them. Where do your sympathies lie? What alternative proposals were rejected? Do you find any of them appealing?

3.42 Give three examples of features that are *not* provided in some language with which you are familiar, but that are common in other languages. Why do you think these features are missing? Would they complicate the implementation of the language? If so, would the complication (in your judgment) be justified?

3.43–3.47 In More Depth.

3.12 Bibliographic Notes

This chapter has traced the evolution of naming and scoping mechanisms through a very large number of languages, including Fortran (several versions), Basic, Algol 60 and 68, Pascal, Simula, C and C++, Euclid, Turing, Modula (1, 2, and 3), Ada (83 and 95), Oberon, Eiffel, Perl, Tcl, Python, Ruby, Rust, Java, and C#. Bibliographic references for all of these can be found in Appendix A.

Both modules and objects trace their roots to Simula, which was developed by Dahl, Nygaard, Myhrhaug, and others at the Norwegian Computing Center in the mid-1960s. (Simula I was implemented in 1964; descriptions in this book pertain to Simula 67.) The encapsulation mechanisms of Simula were refined in the 1970s by the developers of Clu, Modula, Euclid, and related languages. Other Simula innovations—inheritance and dynamic method binding in particular—provided the inspiration for Smalltalk, the original and arguably purest of the object-oriented languages. Modern object-oriented languages, including Eiffel, C++, Java, C#, Python, and Ruby, represent to a large extent a reintegration of the evolutionary lines of encapsulation on the one hand and inheritance and dynamic method binding on the other.

The notion of information hiding originates in Parnas's classic paper, "On the Criteria to be Used in Decomposing Systems into Modules" [Par72]. Comparative discussions of naming, scoping, and abstraction mechanisms can be found, among other places, in Liskov et al.'s discussion of Clu [LSAS77], Liskov and Guttag's text [LG86, Chap. 4], the Ada Rationale [IBFW91, Chaps. 9–12], Harbison's text on Modula-3 [Har92, Chaps. 8–9], Wirth's early work on modules [Wir80], and his later discussion of Modula and Oberon [Wir88a, Wir07]. Further information on object-oriented languages can be found in Chapter 10.

For a detailed discussion of overloading and polymorphism, see the survey by Cardelli and Wegner [CW85]. Cailliau [Cai82] provides a lighthearted discussion of many of the scoping pitfalls noted in Section 3.3.3. Abelson and Sussman [AS96, p. 11n] attribute the term “syntactic sugar” to Peter Landin.

Lambda expressions for C++ are described in the paper of Järvi and Freeman [JF10]. Lambda expressions for Java were developed under JSR 335 of the Java Community Process (documentation at *jcp.org*).

4 Semantic Analysis

In Chapter 2 we considered the topic of programming language syntax. In the current chapter we turn to the topic of semantics. Informally, syntax concerns the *form* of a valid program, while semantics concerns its *meaning*. Meaning is important for at least two reasons: it allows us to enforce rules (e.g., type consistency) that go beyond mere form, and it provides the information we need in order to generate an equivalent output program.

It is conventional to say that the syntax of a language is precisely that portion of the language definition that can be described conveniently by a context-free grammar, while the semantics is that portion of the definition that cannot. This convention is useful in practice, though it does not always agree with intuition. When we require, for example, that the number of arguments contained in a call to a subroutine match the number of formal parameters in the subroutine definition, it is tempting to say that this requirement is a matter of syntax. After all, we can count arguments without knowing what they mean. Unfortunately, we cannot count them with context-free rules. Similarly, while it is possible to write a context-free grammar in which every function must contain at least one `return` statement, the required complexity makes this strategy very unattractive. In general, any rule that requires the compiler to compare things that are separated by long distances, or to count things that are not properly nested, ends up being a matter of semantics.

Semantic rules are further divided into *static* and *dynamic* semantics, though again the line between the two is somewhat fuzzy. The compiler enforces static semantic rules at compile time. It generates code to enforce dynamic semantic rules at run time (or to call library routines that do so). Certain errors, such as division by zero, or attempting to index into an array with an out-of-bounds subscript, cannot in general be caught at compile time, since they may occur only for certain input values, or certain behaviors of arbitrarily complex code. In special cases, a compiler may be able to tell that a certain error will always or never occur, regardless of run-time input. In these cases, the compiler can generate an error message at compile time, or refrain from generating code to perform the check at run time, as appropriate. Basic results from computability theory, however, tell us that no algorithm can make these predictions correctly for arbitrary programs:

there will inevitably be cases in which an error will always occur, but the compiler cannot tell, and must delay the error message until run time; there will also be cases in which an error can never occur, but the compiler cannot tell, and must incur the cost of unnecessary run-time checks.

Both semantic analysis and intermediate code generation can be described in terms of annotation, or *decoration* of a parse tree or syntax tree. The annotations themselves are known as *attributes*. Numerous examples of static and dynamic semantic rules will appear in subsequent chapters. In this current chapter we focus primarily on the mechanisms a compiler uses to enforce the static rules. We will consider intermediate code generation (including the generation of code for dynamic semantic checks) in Chapter 15.

In Section 4.1 we consider the role of the semantic analyzer in more detail, considering both the rules it needs to enforce and its relationship to other phases of compilation. Most of the rest of the chapter is then devoted to the subject of *attribute grammars*. Attribute grammars provide a formal framework for the decoration of a tree. This framework is a useful conceptual tool even in compilers that do not build a parse tree or syntax tree as an explicit data structure. We introduce the notion of an attribute grammar in Section 4.2. We then consider various ways in which such grammars can be applied in practice. Section 4.3 discusses the issue of *attribute flow*, which constrains the order(s) in which nodes of a tree can be decorated. In practice, most compilers require decoration of the parse tree (or the evaluation of attributes that would reside in a parse tree if there were one) to occur in the process of an LL or LR parse. Section 4.4 presents *action routines* as an ad hoc mechanism for such "on-the-fly" evaluation. In Section 4.5 (mostly on the companion site) we consider the management of space for parse tree attributes.

Because they have to reflect the structure of the CFG, parse trees tend to be very complicated (recall the example in Figure 1.5). Once parsing is complete, we typically want to replace the parse tree with a syntax tree that reflects the input program in a more straightforward way (Figure 1.6). One particularly common compiler organization uses action routines during parsing solely for the purpose of constructing the syntax tree. The syntax tree is then decorated during a separate traversal, which can be formalized, if desired, with a separate attribute grammar. We consider the decoration of syntax trees in Section 4.6.

4.1 The Role of the Semantic Analyzer

Programming languages vary dramatically in their choice of semantic rules. Lisp dialects, for example, allow "mixed-mode" arithmetic on arbitrary numeric types, which they will automatically promote from integer to rational to floating-point or "bignum" (extended) precision, as required to maintain precision. Ada, by contract, assigns a specific type to every numeric variable, and requires the programmer to convert among these explicitly when combining them in expressions.

Languages also vary in the extent to which they require their implementations to perform dynamic checks. At one extreme, C requires no checks at all, beyond those that come "free" with the hardware (e.g., division by zero, or attempted access to memory outside the bounds of the program). At the other extreme, Java takes great pains to check as many rules as possible, in part to ensure that an untrusted program cannot do anything to damage the memory or files of the machine on which it runs. The role of the semantic analyzer is to enforce all static semantic rules and to annotate the program with information needed by the intermediate code generator. This information includes both clarifications (this is floating-point addition, not integer; this is a reference to the global variable x) and requirements for dynamic semantic checks.

In the typical compiler, analysis and intermediate code generation mark the end of *front end* computation. The exact division of labor between the front end and the back end, however, may vary from compiler to compiler: it can be hard to say exactly where analysis (figuring out what the program means) ends and synthesis (expressing that meaning in some new form) begins (and as noted in Section 1.6 there may be a "middle end" in between). Many compilers also carry a program through more than one intermediate form. In one common organization, described in more detail in Chapter 15, the semantic analyzer creates an annotated syntax tree, which the intermediate code generator then translates into a linear form reminiscent of the assembly language for some idealized machine. After machine-independent code improvement, this linear form is then translated into yet another form, patterned more closely on the assembly language of the target machine. That form may undergo machine-specific code improvement.

Compilers also vary in the extent to which semantic analysis and intermediate code generation are interleaved with parsing. With fully separated phases, the parser passes a full parse tree on to the semantic analyzer, which converts it to a syntax tree, fills in the symbol table, performs semantic checks, and passes it on to the code generator. With fully interleaved phases, there may be no need to build either the parse tree or the syntax tree in its entirety: the parser can call semantic check and code generation routines on the fly as it parses each expression, statement, or subroutine of the source. We will focus on an organization in which construction of the syntax tree is interleaved with parsing (and the parse tree is not built), but semantic analysis occurs during a separate traversal of the syntax tree.

Dynamic Checks

Many compilers that generate code for dynamic checks provide the option of disabling them if desired. It is customary in some organizations to enable dynamic checks during program development and testing, and then disable them for production use, to increase execution speed. The wisdom of this practice is questionable: Tony Hoare, one of the key figures in programming language design,[1] has likened the programmer who disables semantic checks to a sailing enthusiast who wears a life jacket when training on dry land, but removes it when going to sea [Hoa89, p. 198]. Errors may be less likely in production use than they are in testing, but the consequences of an undetected error are significantly worse. Moreover, on modern processors it is often possible for dynamic checks to execute in pipeline slots that would otherwise go unused, making them virtually free. On the other hand, some dynamic checks (e.g., ensuring that pointer arithmetic in C remains within the bounds of an array) are sufficiently expensive that they are rarely implemented.

Assertions

EXAMPLE 4.1
Assertions in Java

When reasoning about the correctness of their algorithms (or when formally proving properties of programs via axiomatic semantics) programmers frequently write logical *assertions* regarding the values of program data. Some programming languages make these assertions a part of the language syntax. The compiler then generates code to check the assertions at run time. An assertion is a statement that a specified condition is expected to be true when execution reaches a certain point in the code. In Java one can write

DESIGN & IMPLEMENTATION

4.1 Dynamic semantic checks

In the past, language theorists and researchers in programming methodology and software engineering tended to argue for more extensive semantic checks, while “real-world” programmers “voted with their feet” for languages like C and Fortran, which omitted those checks in the interest of execution speed. As computers have become more powerful, and as companies have come to appreciate the enormous costs of software maintenance, the “real-world” camp has become much more sympathetic to checking. Languages like Ada and Java have been designed from the outset with safety in mind, and languages like C and C++ have evolved (to the extent possible) toward increasingly strict definitions. In scripting languages, where many semantic checks are deferred until run time in order to avoid the need for explicit types and variable declarations, there has been a similar trend toward stricter rules. Perl, for example (one of the older scripting languages), will typically attempt to infer a possible meaning for expressions (e.g., `3 + "four"`) that newer languages (e.g., Python or Ruby) will flag as run-time errors.

[1] Among other things, C. A. R. Hoare (1934–) invented the quicksort algorithm and the `case` statement, contributed to the design of Algol W, and was one of the leaders in the development of axiomatic semantics. In the area of concurrent programming, he refined and formalized the *monitor* construct (to be described in Section 13.4.1), and designed the CSP programming model and notation. He received the ACM Turing Award in 1980.

```
assert denominator != 0;
```

An `AssertionError` exception will be thrown if the semantic check fails at run time. ■

Some languages (e.g., Euclid, Eiffel, and Ada 2012) also provide explicit support for *invariants*, *preconditions*, and *postconditions*. These are essentially structured assertions. An invariant is expected to be true at all "clean points" of a given body of code. In Eiffel, the programmer can specify an invariant on the data inside a class: the invariant will be checked, automatically, at the beginning and end of each of the class's methods (subroutines). Similar invariants for loops are expected to be true before and after every iteration. Pre- and postconditions are expected to be true at the beginning and end of subroutines, respectively. In Euclid, a postcondition, specified once in the header of a subroutine, will be checked not only at the end of the subroutine's text, but at every `return` statement as well.

EXAMPLE 4.2
Assertions in C

Many languages support assertions via standard library routines or macros. In C, for example, one can write

```
assert(denominator != 0);
```

If the assertion fails, the program will terminate abruptly with the message

```
myprog.c:42: failed assertion `denominator != 0'
```

The C manual requires `assert` to be implemented as a macro (or built into the compiler) so that it has access to the textual representation of its argument, and to the file name and line number on which the call appears. ■

Assertions, of course, could be used to cover the other three sorts of checks, but not as clearly or succinctly. Invariants, preconditions, and postconditions are a prominent part of the header of the code to which they apply, and can cover a potentially large number of places where an assertion would otherwise be required. Euclid and Eiffel implementations allow the programmer to disable assertions and related constructs when desired, to eliminate their run-time cost.

Static Analysis

In general, compile-time algorithms that predict run-time behavior are known as *static analysis*. Such analysis is said to be *precise* if it allows the compiler to determine whether a given program will always follow the rules. Type checking, for example, is static and precise in languages like Ada and ML: the compiler ensures that no variable will ever be used at run time in a way that is inappropriate for its type. By contrast, languages like Lisp, Smalltalk, Python, and Ruby obtain greater flexibility, while remaining completely type-safe, by accepting the run-time overhead of dynamic type checks. (We will cover type checking in more detail in Chapter 7.)

Static analysis can also be useful when it isn't precise. Compilers will often check what they can at compile time and then generate code to check the rest dynamically. In Java, for example, type checking is mostly static, but dynamically loaded classes and type casts may require run-time checks. In a similar vein, many compilers perform extensive static analysis in an attempt to eliminate the need for dynamic checks on array subscripts, variant record tags, or potentially dangling pointers (to be discussed in Chapter 8).

If we think of the omission of unnecessary dynamic checks as a performance optimization, it is natural to look for other ways in which static analysis may enable code improvement. We will consider this topic in more detail in Chapter 17. Examples include *alias analysis*, which determines when values can be safely cached in registers, computed "out of order," or accessed by concurrent threads; *escape analysis*, which determines when all references to a value will be confined to a given context, allowing the value to be allocated on the stack instead of the heap, or to be accessed without locks; and *subtype analysis*, which determines when a variable in an object-oriented language is guaranteed to have a certain subtype, so that its methods can be called without dynamic dispatch.

An optimization is said to be *unsafe* if it may lead to incorrect code in certain programs. It is said to be *speculative* if it usually improves performance, but may degrade it in certain cases. A compiler is said to be *conservative* if it applies optimizations only when it can guarantee that they will be both safe and effective. By contrast, an *optimistic* compiler may make liberal use of speculative optimizations. It may also pursue unsafe optimizations by generating two versions of the code, with a dynamic check that chooses between them based on information not available at compile time. Examples of speculative optimization include *nonbinding prefetches*, which try to bring data into the cache before they are needed, and *trace scheduling*, which rearranges code in hopes of improving the performance of the processor pipeline and the instruction cache.

To eliminate dynamic checks, language designers may choose to tighten semantic rules, banning programs for which conservative analysis fails. The ML type system, for example (Section 7.2.4), avoids the dynamic type checks of Lisp, but disallows certain useful programming idioms that Lisp supports. Similarly, the *definite assignment* rules of Java and C# (Section 6.1.3) allow the compiler to ensure that a variable is always given a value before it is used in an expression, but disallow certain programs that are legal (and correct) in C.

4.2 Attribute Grammars

EXAMPLE 4.3

Bottom-up CFG for constant expressions

In Chapter 2 we learned how to use a context-free grammar to specify the syntax of a programming language. Here, for example, is an LR (bottom-up) grammar for arithmetic expressions composed of constants, with precedence and associativity:[2]

[2] The addition of semantic rules tends to make attribute grammars quite a bit more verbose than context-free grammars. For the sake of brevity, many of the examples in this chapter use very short symbol names: *E* instead of *expr*, *TT* instead of *term_tail*.

$$
\begin{array}{lcl}
E & \longrightarrow & E \texttt{ + } T \\
E & \longrightarrow & E \texttt{ - } T \\
E & \longrightarrow & T \\
T & \longrightarrow & T \texttt{ * } F \\
T & \longrightarrow & T \texttt{ / } F \\
T & \longrightarrow & F \\
F & \longrightarrow & \texttt{- } F \\
F & \longrightarrow & \texttt{(} E \texttt{)} \\
F & \longrightarrow & \texttt{const}
\end{array}
$$

EXAMPLE 4.4

Bottom-up AG for constant expressions

This grammar will generate all properly formed constant expressions over the basic arithmetic operators, but it says nothing about their meaning. To tie these expressions to mathematical concepts (as opposed to, say, floor tile patterns or dance steps), we need additional notation. The most common is based on *attributes*. In our expression grammar, we can associate a val attribute with each E, T, F, and `const` in the grammar. The intent is that for any symbol S, S.val will be the meaning, as an arithmetic value, of the token string derived from S. We assume that the val of a `const` is provided to us by the scanner. We must then invent a set of rules for each production, to specify how the vals of different symbols are related. The resulting *attribute grammar* (AG) is shown in Figure 4.1.

In this simple grammar, every production has a single rule. We shall see more complicated grammars later, in which productions can have several rules. The rules come in two forms. Those in productions 3, 6, 8, and 9 are known as *copy rules*; they specify that one attribute should be a copy of another. The other rules invoke *semantic functions* (sum, quotient, additive_inverse, etc.). In this example, the semantic functions are all familiar arithmetic operations. In general, they can be arbitrarily complex functions specified by the language designer. Each semantic function takes an arbitrary number of arguments (each of which must be an attribute of a symbol in the current production—no global variables are allowed), and each computes a single result, which must likewise be assigned into an attribute of a symbol in the current production. When more than one symbol of a production has the same name, subscripts are used to distinguish them. These subscripts are solely for the benefit of the semantic functions; they are not part of the context-free grammar itself.

EXAMPLE 4.5

Top-down AG to count the elements of a list

In a strict definition of attribute grammars, copy rules and semantic function calls are the only two kinds of permissible rules. In our examples we use a ▷ symbol to introduce each code fragment corresponding to a single rule. In practice, it is common to allow rules to consist of small fragments of code in some well-defined notation (e.g., the language in which a compiler is being written), so that simple semantic functions can be written out "in-line." In this relaxed notation, the rule for the first production in Figure 4.1 might be simply E_1.val := E_2.val + T.val. As another example, suppose we wanted to count the elements of a comma-separated list:

1. $E_1 \longrightarrow E_2$ `+` T	▷ E_1.val := sum(E_2.val, T.val)
2. $E_1 \longrightarrow E_2$ `-` T	▷ E_1.val := difference(E_2.val, T.val)
3. $E \longrightarrow T$	▷ E.val := T.val
4. $T_1 \longrightarrow T_2$ `*` F	▷ T_1.val := product(T_2.val, F.val)
5. $T_1 \longrightarrow T_2$ `/` F	▷ T_1.val := quotient(T_2.val, F.val)
6. $T \longrightarrow F$	▷ T.val := F.val
7. $F_1 \longrightarrow$ `-` F_2	▷ F_1.val := additive_inverse(F_2.val)
8. $F \longrightarrow$ `(` E `)`	▷ F.val := E.val
9. $F \longrightarrow$ `const`	▷ F.val := const.val

Figure 4.1 A simple attribute grammar for constant expressions, using the standard arithmetic operations. Each semantic rule is introduced by a ▷ sign.

$L \longrightarrow$ `id` LT	▷ L.c := 1 + LT.c
$LT \longrightarrow$ `,` L	▷ LT.c := L.c
$LT \longrightarrow \epsilon$	▷ LT.c := 0

Here the rule on the first production sets the c (count) attribute of the left-hand side to one more than the count of the tail of the right-hand side. Like explicit semantic functions, in-line rules are not allowed to refer to any variables or attributes outside the current production. We will relax this restriction when we introduce action routines in Section 4.4.

Neither the notation for semantic functions (whether in-line or explicit) nor the types of the attributes themselves is intrinsic to the notion of an attribute grammar. The purpose of the grammar is simply to associate meaning with the nodes of a parse tree or syntax tree. Toward that end, we can use any notation and types whose meanings are already well defined. In Examples 4.4 and 4.5, we associated numeric values with the symbols in a CFG—and thus with parse tree nodes—using semantic functions drawn from ordinary arithmetic. In a compiler or interpreter for a full programming language, the attributes of tree nodes might include

- for an identifier, a reference to information about it in the symbol table
- for an expression, its type
- for a statement or expression, a reference to corresponding code in the compiler's intermediate form
- for almost any construct, an indication of the file name, line, and column where the corresponding source code begins
- for any internal node, a list of semantic errors found in the subtree below

For purposes other than translation—e.g., in a theorem prover or machine-independent language definition—attributes might be drawn from the disciplines of *denotational*, *operational*, or *axiomatic* semantics. Interested readers can find references in the Bibliographic Notes at the end of the chapter.

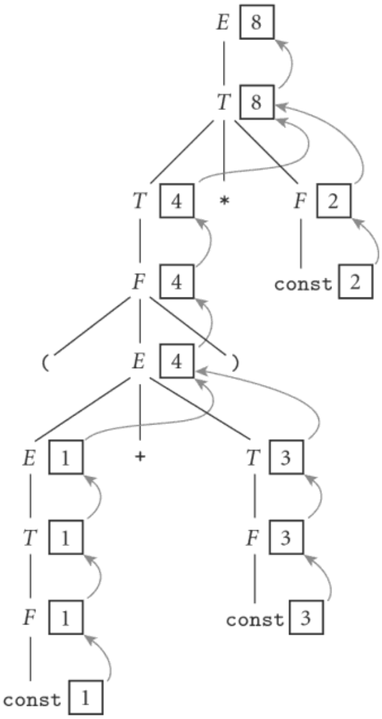


Figure 4.2 Decoration of a parse tree for `(1 + 3) * 2`, using the attribute grammar of Figure 4.1. The val attributes of symbols are shown in boxes. Curving arrows show the attribute flow, which is strictly upward in this case. Each box holds the output of a single semantic rule; the arrow(s) entering the box indicate the input(s) to the rule. At the second level of the tree, for example, the two arrows pointing into the box with the 8 represent application of the rule T_1.val := product(T_2.val, F.val).

4.3 Evaluating Attributes

EXAMPLE 4.6

Decoration of a parse tree

The process of evaluating attributes is called *annotation* or *decoration* of the parse tree. Figure 4.2 shows how to decorate the parse tree for the expression `(1 + 3) * 2`, using the AG of Figure 4.1. Once decoration is complete, the value of the overall expression can be found in the val attribute of the root of the tree. ■

Synthesized Attributes

The attribute grammar of Figure 4.1 is very simple. Each symbol has at most one attribute (the punctuation marks have none). Moreover, they are all so-called *synthesized attributes*: their values are calculated (synthesized) only in productions in which their symbol appears on the left-hand side. For annotated parse trees like the one in Figure 4.2, this means that the *attribute flow*—the pattern in which information moves from node to node—is entirely bottom-up.

An attribute grammar in which all attributes are synthesized is said to be *S-attributed*. The arguments to semantic functions in an S-attributed grammar are always attributes of symbols on the right-hand side of the current production, and the return value is always placed into an attribute of the left-hand side of the production. Tokens (terminals) often have intrinsic properties (e.g., the character-string representation of an identifier or the value of a numeric constant); in a compiler these are synthesized attributes initialized by the scanner.

Inherited Attributes

In general, we can imagine (and will in fact have need of) attributes whose values are calculated when their symbol is on the right-hand side of the current production. Such attributes are said to be *inherited*. They allow contextual information to flow into a symbol from above or from the side, so that the rules of that production can be enforced in different ways (or generate different values) depending on surrounding context. Symbol table information is commonly passed from symbol to symbol by means of inherited attributes. Inherited attributes of the root of the parse tree can also be used to represent the external environment (characteristics of the target machine, command-line arguments to the compiler, etc.).

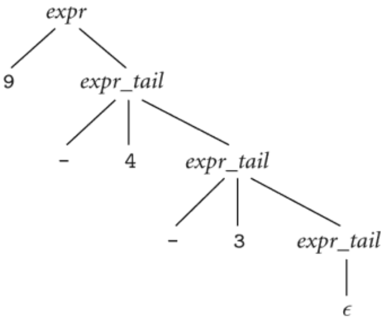
EXAMPLE 4.7

Top-down CFG and parse tree for subtraction

As a simple example of inherited attributes, consider the following fragment of an LL(1) expression grammar (here covering only subtraction):

expr ⟶ `const` *expr_tail*
expr_tail ⟶ `- const` *expr_tail* | ϵ

For the expression `9 - 4 - 3`, we obtain the following parse tree:

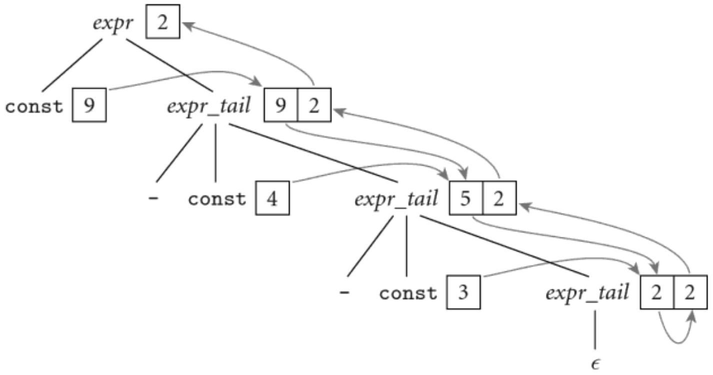


If we want to create an attribute grammar that accumulates the value of the overall expression into the root of the tree, we have a problem: because subtraction is left associative, we cannot summarize the right subtree of the root with a single numeric value. If we want to decorate the tree bottom-up, with an S-attributed grammar, we must be prepared to describe an arbitrary number of right operands in the attributes of the top-most *expr_tail* node (see Exercise 4.4). This is indeed possible, but it defeats the purpose of the formalism: in effect, it requires us to embed the entire tree into the attributes of a single node, and do all the real work inside a single semantic function.

EXAMPLE 4.8

Decoration with left-to-right attribute flow

If, however, we are allowed to pass attribute values not only bottom-up but also left-to-right in the tree, then we can pass the 9 into the top-most *expr_tail* node, where it can be combined (in proper left-associative fashion) with the 4. The resulting 5 can then be passed into the middle *expr_tail* node, combined with the 3 to make 2, and then passed upward to the root:



EXAMPLE 4.9

Top-down AG for subtraction

To effect this style of decoration, we need the following attribute rules:

expr ⟶ `const` *expr_tail*

▷ expr_tail.st := const.val

▷ expr.val := expr_tail.val

$expr\_tail_1$ ⟶ `- const` $expr\_tail_2$

▷ $\text{expr\_tail}_2\text{.st := expr\_tail}_1\text{.st} - \text{const.val}$

▷ $\text{expr\_tail}_1\text{.val := expr\_tail}_2\text{.val}$

expr_tail ⟶ ε

▷ expr_tail.val := expr_tail.st

In each of the first two productions, the first rule serves to copy the left context (value of the expression so far) into a "subtotal" (st) attribute; the second rule copies the final value from the right-most leaf back up to the root. In the *expr_tail* nodes of the picture in Example 4.8, the left box holds the st attribute; the right holds val.

EXAMPLE 4.10

Top-down AG for constant expressions

We can flesh out the grammar fragment of Example 4.7 to produce a more complete expression grammar, as shown (with shorter symbol names) in Figure 4.3. The underlying CFG for this grammar accepts the same language as the one in Figure 4.1, but where that one was SLR(1), this one is LL(1). Attribute flow for a parse of `(1 + 3) * 2`, using the LL(1) grammar, appears in Figure 4.4. As in the grammar fragment of Example 4.9, the value of the left operand of each operator is carried into the *TT* and *FT* productions by the st (subtotal) attribute. The relative complexity of the attribute flow arises from the fact that operators are left associative, but the grammar cannot be left recursive: the left and right operands of a given operator are thus found in separate productions. Grammars to perform

1. $E \longrightarrow T\ TT$
   $\triangleright$ TT.st := T.val $\triangleright$ E.val := TT.val
2. $TT_1 \longrightarrow$ `+` $T\ TT_2$
   $\triangleright$ TT_2.st := TT_1.st + T.val $\triangleright$ TT_1.val := TT_2.val
3. $TT_1 \longrightarrow$ `-` $T\ TT_2$
   $\triangleright$ TT_2.st := TT_1.st − T.val $\triangleright$ TT_1.val := TT_2.val
4. $TT \longrightarrow \epsilon$
   $\triangleright$ TT.val := TT.st
5. $T \longrightarrow F\ FT$
   $\triangleright$ FT.st := F.val $\triangleright$ T.val := FT.val
6. $FT_1 \longrightarrow$ `*` $F\ FT_2$
   $\triangleright$ FT_2.st := FT_1.st × F.val $\triangleright$ FT_1.val := FT_2.val
7. $FT_1 \longrightarrow$ `/` $F\ FT_2$
   $\triangleright$ FT_2.st := FT_1.st ÷ F.val $\triangleright$ FT_1.val := FT_2.val
8. $FT \longrightarrow \epsilon$
   $\triangleright$ FT.val := FT.st
9. $F_1 \longrightarrow$ `-` F_2
   $\triangleright$ F_1.val := − F_2.val
10. $F \longrightarrow$ `(` E `)`
    $\triangleright$ F.val := E.val
11. $F \longrightarrow$ `const`
    $\triangleright$ F.val := const.val

Figure 4.3 An attribute grammar for constant expressions based on an LL(1) CFG. In this grammar several productions have two semantic rules.

semantic analysis for practical languages generally require some non-S-attributed flow.

Attribute Flow

Just as a context-free grammar does not specify how it should be parsed, an attribute grammar does not specify the order in which attribute rules should be invoked. Put another way, both notations are *declarative*: they define a set of valid trees, but they don't say how to build or decorate them. Among other things, this means that the order in which attribute rules are listed for a given production is immaterial; attribute flow may require them to execute in any order. If, in Figure 4.3, we were to reverse the order in which the rules appear in productions 1, 2, 3, 5, 6, and/or 7 (listing the rule for symbol.val first), it would be a purely cosmetic change; the grammar would not be altered.

We say an attribute grammar is *well defined* if its rules determine a unique set of values for the attributes of every possible parse tree. An attribute grammar is *noncircular* if it never leads to a parse tree in which there are cycles in the attribute flow graph—that is, if no attribute, in any parse tree, ever depends (transitively)

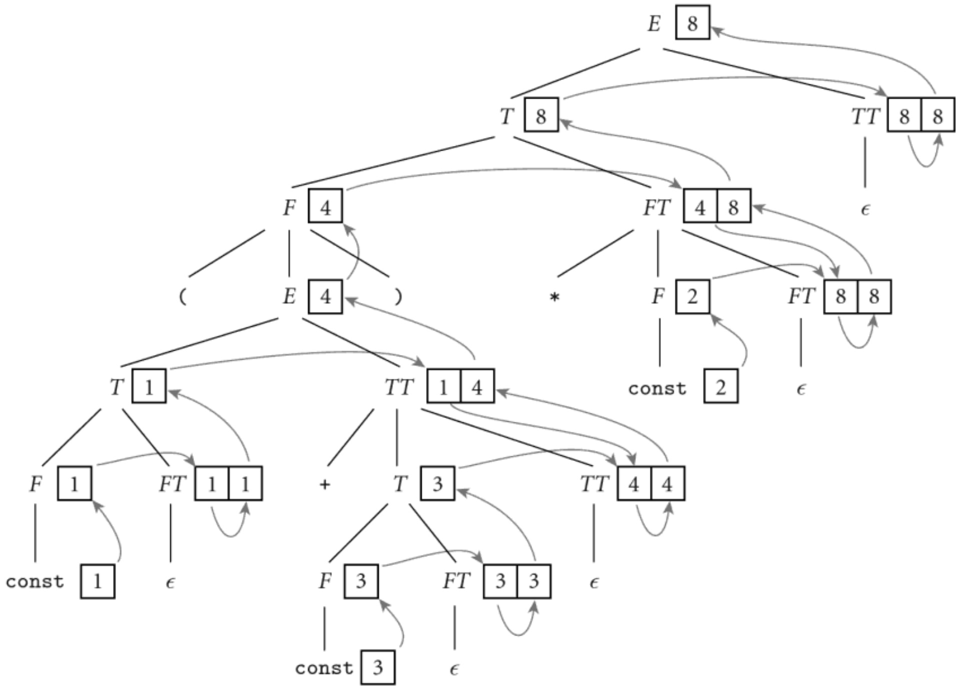


Figure 4.4 **Decoration of a top-down parse tree for `(1 + 3) * 2`, using the AG of Figure 4.3.** Curving arrows again indicate attribute flow; the arrow(s) entering a given box represent the application of a single semantic rule. Flow in this case is no longer strictly bottom-up, but it is still left-to-right. At *FT* and *TT* nodes, the left box holds the st attribute; the right holds `val`.

on itself. (A grammar can be circular and still be well defined if attributes are guaranteed to converge to a unique value.) As a general rule, practical attribute grammars tend to be noncircular.

An algorithm that decorates parse trees by invoking the rules of an attribute grammar in an order consistent with the tree's attribute flow is called a *translation scheme*. Perhaps the simplest scheme is one that makes repeated passes over a tree, invoking any semantic function whose arguments have all been defined, and stopping when it completes a pass in which no values change. Such a scheme is said to be *oblivious*, in the sense that it exploits no special knowledge of either the parse tree or the grammar. It will halt only if the grammar is well defined. Better performance, at least for noncircular grammars, may be achieved by a *dynamic* scheme that tailors the evaluation order to the structure of a given parse tree—for example, by constructing a topological sort of the attribute flow graph and then invoking rules in an order consistent with the sort.

The fastest translation schemes, however, tend to be *static*—based on an analysis of the structure of the attribute grammar itself, and then applied mechanically to any tree arising from the grammar. Like LL and LR parsers, linear-time static translation schemes can be devised only for certain restricted classes of grammars. S-attributed grammars, such as the one in Figure 4.1, form the simplest such class. Because attribute flow in an S-attributed grammar is strictly bottom-up, attributes can be evaluated by visiting the nodes of the parse tree in exactly the same order that those nodes are generated by an LR-family parser. In fact, the attributes can be evaluated on the fly during a bottom-up parse, thereby interleaving parsing and semantic analysis (attribute evaluation).

The attribute grammar of Figure 4.3 is a good bit messier than that of Figure 4.1, but it is still *L-attributed*: its attributes can be evaluated by visiting the nodes of the parse tree in a single left-to-right, depth-first traversal (the same order in which they are visited during a top-down parse—see Figure 4.4). If we say that an attribute A.s *depends on* an attribute B.t if B.t is ever passed to a semantic function that returns a value for A.s, then we can define L-attributed grammars more formally with the following two rules: (1) each synthesized attribute of a left-hand-side symbol depends only on that symbol's own inherited attributes or on attributes (synthesized or inherited) of the production's right-hand-side symbols, and (2) each inherited attribute of a right-hand-side symbol depends only on inherited attributes of the left-hand-side symbol or on attributes (synthesized or inherited) of symbols to its left in the right-hand side.

Because L-attributed grammars permit rules that initialize attributes of the left-hand side of a production using attributes of symbols on the right-hand side, every S-attributed grammar is also an L-attributed grammar. The reverse is not the case: S-attributed grammars do not permit the initialization of attributes on the right-hand side, so there are L-attributed grammars that are not S-attributed.

S-attributed attribute grammars are the most general class of attribute grammars for which evaluation can be implemented on the fly during an LR parse. L-attributed grammars are the most general class for which evaluation can be implemented on the fly during an LL parse. If we interleave semantic analysis (and possibly intermediate code generation) with parsing, then a bottom-up parser must in general be paired with an S-attributed translation scheme; a top-down parser must be paired with an L-attributed translation scheme. (Depending on the structure of the grammar, it is often possible for a bottom-up parser to accommodate some non-S-attributed attribute flow; we consider this possibility in Section C-4.5.1.) If we choose to separate parsing and semantic analysis into separate passes, then the code that builds the parse tree or syntax tree must still use an S-attributed or L-attributed translation scheme (as appropriate), but the semantic analyzer can use a more powerful scheme if desired. There are certain tasks, such as the generation of code for "short-circuit" Boolean expressions (to be discussed in Sections 6.1.5 and 6.4.1), that are easiest to accomplish with a non-L-attributed scheme.

One-Pass Compilers

A compiler that interleaves semantic analysis and code generation with parsing is said to be a *one-pass compiler*.[3] It is unclear whether interleaving semantic analysis with parsing makes a compiler simpler or more complex; it's mainly a matter of taste. If intermediate code generation is interleaved with parsing, one need not build a syntax tree at all (unless of course the syntax tree *is* the intermediate code). Moreover, it is often possible to write the intermediate code to an output file on the fly, rather than accumulating it in the attributes of the root of the parse tree. The resulting space savings were important for previous generations of computers, which had very small main memories. On the other hand, semantic analysis is easier to perform during a separate traversal of a syntax tree, because that tree reflects the program's semantic structure better than the parse tree does, especially with a top-down parser, and because one has the option of traversing the tree in an order other than that chosen by the parser.

Building a Syntax Tree

EXAMPLE 4.11

Bottom-up and top-down AGs to build a syntax tree

If we choose not to interleave parsing and semantic analysis, we still need to add attribute rules to the context-free grammar, but they serve only to create the syntax tree—not to enforce semantic rules or generate code. Figures 4.5 and 4.6 contain bottom-up and top-down attribute grammars, respectively, to build a syntax tree for constant expressions. The attributes in these grammars hold neither numeric values nor target code fragments; instead they point to nodes of the syntax tree. Function make_leaf returns a pointer to a newly allocated syntax tree node containing the value of a constant. Functions make_un_op and make_bin_op return pointers to newly allocated syntax tree nodes containing a unary or

DESIGN & IMPLEMENTATION

4.2 Forward references

In Sections 3.3.3 and C-3.4.1 we noted that the scope rules of many languages require names to be declared before they are used, and provide special mechanisms to introduce the forward references needed for recursive definitions. While these rules may help promote the creation of clear, maintainable code, an equally important motivation, at least historically, was to facilitate the construction of one-pass compilers. With increases in memory size, processing speed, and programmer expectations regarding the quality of code improvement, multipass compilers have become ubiquitous, and language designers have felt free (as, for example, in the class declarations of C++, Java, and C#) to abandon the requirement that declarations precede uses.

[3] Most authors use the term *one-pass* only for compilers that translate all the way from source to target code in a single pass. Some authors insist only that intermediate code be generated in a single pass, and permit additional pass(es) to translate intermediate code to target code.

$E_1 \longrightarrow E_2$ `+` T
▷ E_1.ptr := make_bin_op("+", E_2.ptr, T.ptr)

$E_1 \longrightarrow E_2$ `-` T
▷ E_1.ptr := make_bin_op("−", E_2.ptr, T.ptr)

$E \longrightarrow T$
▷ E.ptr := T.ptr

$T_1 \longrightarrow T_2$ `*` F
▷ T_1.ptr := make_bin_op("×", T_2.ptr, F.ptr)

$T_1 \longrightarrow T_2$ `/` F
▷ T_1.ptr := make_bin_op("÷", T_2.ptr, F.ptr)

$T \longrightarrow F$
▷ T.ptr := F.ptr

$F_1 \longrightarrow$ `-` F_2
▷ F_1.ptr := make_un_op("+/_", F_2.ptr)

$F \longrightarrow$ `(` E `)`
▷ F.ptr := E.ptr

$F \longrightarrow$ `const`
▷ F.ptr := make_leaf(const.val)

Figure 4.5 **Bottom-up (S-attributed) attribute grammar to construct a syntax tree.** The symbol $^{+}/_{-}$ is used (as it is on calculators) to indicate change of sign.

binary operator, respectively, and pointers to the supplied operand(s). Figures 4.7 and 4.8 show stages in the decoration of parse trees for `(1 + 3) * 2`, using the grammars of Figures 4.5 and 4.6, respectively. Note that the final syntax tree is the same in each case. ■

✓ **CHECK YOUR UNDERSTANDING**

1. What determines whether a language rule is a matter of syntax or of static semantics?
2. Why is it impossible to detect certain program errors at compile time, even though they can be detected at run time?
3. What is an *attribute grammar*?
4. What are programming *assertions*? What is their purpose?
5. What is the difference between *synthesized* and *inherited* attributes?
6. Give two examples of information that is typically passed through inherited attributes.
7. What is *attribute flow*?
8. What is a *one-pass* compiler?

$E \longrightarrow T\ TT$

▷ TT.st := T.ptr
▷ E.ptr := TT.ptr

$TT_1 \longrightarrow$ `+` $T\ TT_2$

▷ TT_2.st := make_bin_op(“+”, TT_1.st, T.ptr)
▷ TT_1.ptr := TT_2.ptr

$TT_1 \longrightarrow$ `-` $T\ TT_2$

▷ TT_2.st := make_bin_op(“−”, TT_1.st, T.ptr)
▷ TT_1.ptr := TT_2.ptr

$TT \longrightarrow \epsilon$

▷ TT.ptr := TT.st

$T \longrightarrow F\ FT$

▷ FT.st := F.ptr
▷ T.ptr := FT.ptr

$FT_1 \longrightarrow$ `*` $F\ FT_2$

▷ FT_2.st := make_bin_op(“×”, FT_1.st, F.ptr)
▷ FT_1.ptr := FT_2.ptr

$FT_1 \longrightarrow$ `/` $F\ FT_2$

▷ FT_2.st := make_bin_op(“÷”, FT_1.st, F.ptr)
▷ FT_1.ptr := FT_2.ptr

$FT \longrightarrow \epsilon$

▷ FT.ptr := FT.st

$F_1 \longrightarrow$ `-` F_2

▷ F_1.ptr := make_un_op(“+/_”, F_2.ptr)

$F \longrightarrow$ `(` E `)`

▷ F.ptr := E.ptr

$F \longrightarrow$ `const`

▷ F.ptr := make_leaf(const.val)

Figure 4.6 Top-down (L-attributed) attribute grammar to construct a syntax tree. Here the st attribute, like the ptr attribute (and unlike the st attribute of Figure 4.3), is a pointer to a syntax tree node.

9. What does it mean for an attribute grammar to be *S-attributed*? *L-attributed*? *Noncircular*? What is the significance of these grammar classes?

4.4 Action Routines

Just as there are automatic tools that will construct a parser for a given context-free grammar, there are automatic tools that will construct a semantic analyzer (attribute evaluator) for a given attribute grammar. Attribute evaluator gen-

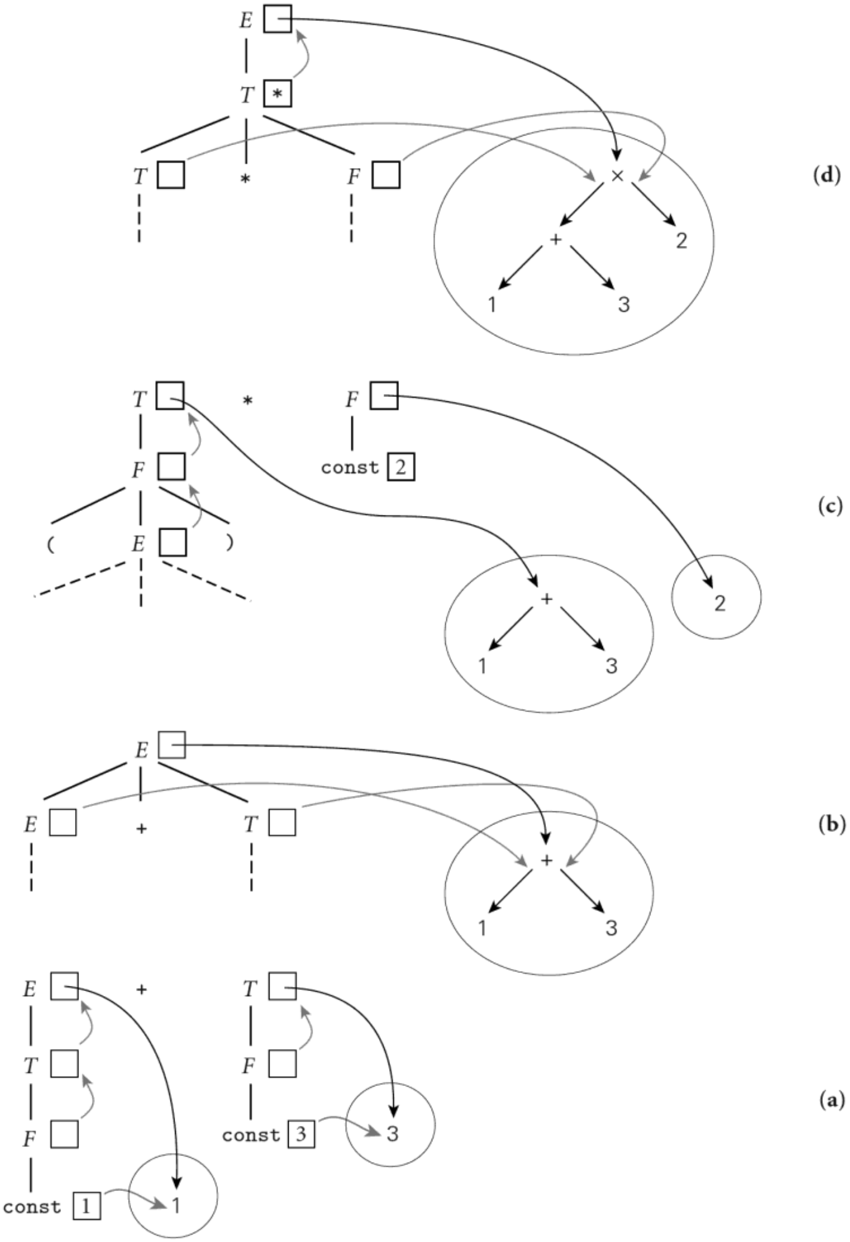


Figure 4.7 Construction of a syntax tree for `(1 + 3) * 2` via decoration of a bottom-up parse tree, using the grammar of Figure 4.5. This figure reads from bottom to top. In diagram (a), the values of the constants 1 and 3 have been placed in new syntax tree leaves. Pointers to these leaves propagate up into the attributes of E and T. In (b), the pointers to these leaves become child pointers of a new internal + node. In (c) the pointer to this node propagates up into the attributes of T, and a new leaf is created for 2. Finally, in (d), the pointers from T and F become child pointers of a new internal × node, and a pointer to this node propagates up into the attributes of E.

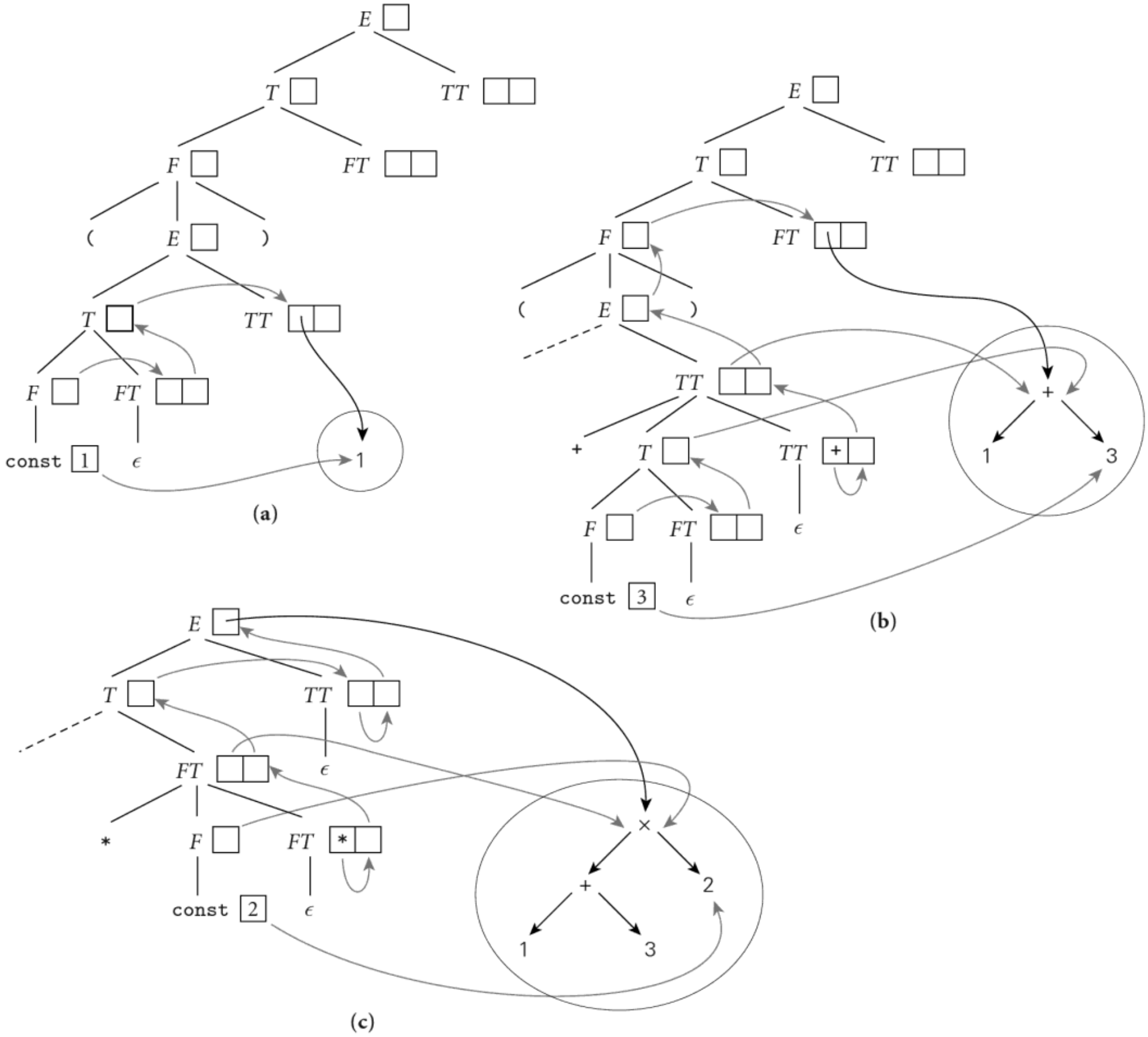


Figure 4.8 **Construction of a syntax tree via decoration of a top-down parse tree, using the grammar of Figure 4.6.** In the top diagram, (a), the value of the constant 1 has been placed in a new syntax tree leaf. A pointer to this leaf then propagates to the st attribute of *TT*. In (b), a second leaf has been created to hold the constant 3. Pointers to the two leaves then become child pointers of a new internal + node, a pointer to which propagates from the st attribute of the bottom-most *TT*, where it was created, all the way up and over to the st attribute of the top-most *FT*. In (c), a third leaf has been created for the constant 2. Pointers to this leaf and to the + node then become the children of a new × node, a pointer to which propagates from the st of the lower *FT*, where it was created, all the way to the root of the tree.

erators have been used in syntax-based editors [RT88], incremental compilers [SDB84], web-page layout [MTAB13], and various aspects of programming language research. Most production compilers, however, use an ad hoc, handwritten translation scheme, interleaving parsing with the construction of a syntax tree and, in some cases, other aspects of semantic analysis or intermediate code generation. Because they evaluate the attributes of each production as it is parsed, they do not need to build the full parse tree.

An ad hoc translation scheme that is interleaved with parsing takes the form of a set of *action routines*. An action routine is a semantic function that the programmer (grammar writer) instructs the compiler to execute at a particular point in the parse. Most parser generators allow the programmer to specify action routines. In an LL parser generator, an action routine can appear anywhere within a right-hand side. A routine at the beginning of a right-hand side will be called as soon as the parser predicts the production. A routine embedded in the middle of a right-hand side will be called as soon as the parser has matched (the yield of) the symbol to the left. The implementation mechanism is simple: when it predicts a production, the parser pushes *all* of the right-hand side onto the stack, including terminals (to be matched), nonterminals (to drive future predictions), and pointers to action routines. When it finds a pointer to an action routine at the top of the parse stack, the parser simply calls it, passing (pointers to) the appropriate attributes as arguments.

EXAMPLE 4.12

Top-down action routines to build a syntax tree

To make this process more concrete, consider again our LL(1) grammar for constant expressions. Action routines to build a syntax tree while parsing this grammar appear in Figure 4.9. The only difference between this grammar and the one in Figure 4.6 is that the action routines (delimited here with curly braces) are embedded among the symbols of the right-hand sides; the work performed is the same. The ease with which the attribute grammar can be transformed into the grammar with action routines is due to the fact that the attribute grammar is L-attributed. If it required more complicated flow, we would not be able to cast it as action routines. ■

DESIGN & IMPLEMENTATION

4.3 Attribute evaluators

Automatic evaluators based on formal attribute grammars are popular in language research projects because they save developer time when the language definition changes. They are popular in syntax-based editors and incremental compilers because they save execution time: when a small change is made to a program, the evaluator may be able to “patch up” tree decorations significantly faster than it could rebuild them from scratch. For the typical compiler, however, semantic analysis based on a formal attribute grammar is overkill: it has higher overhead than action routines, and doesn’t really save the compiler writer that much work.