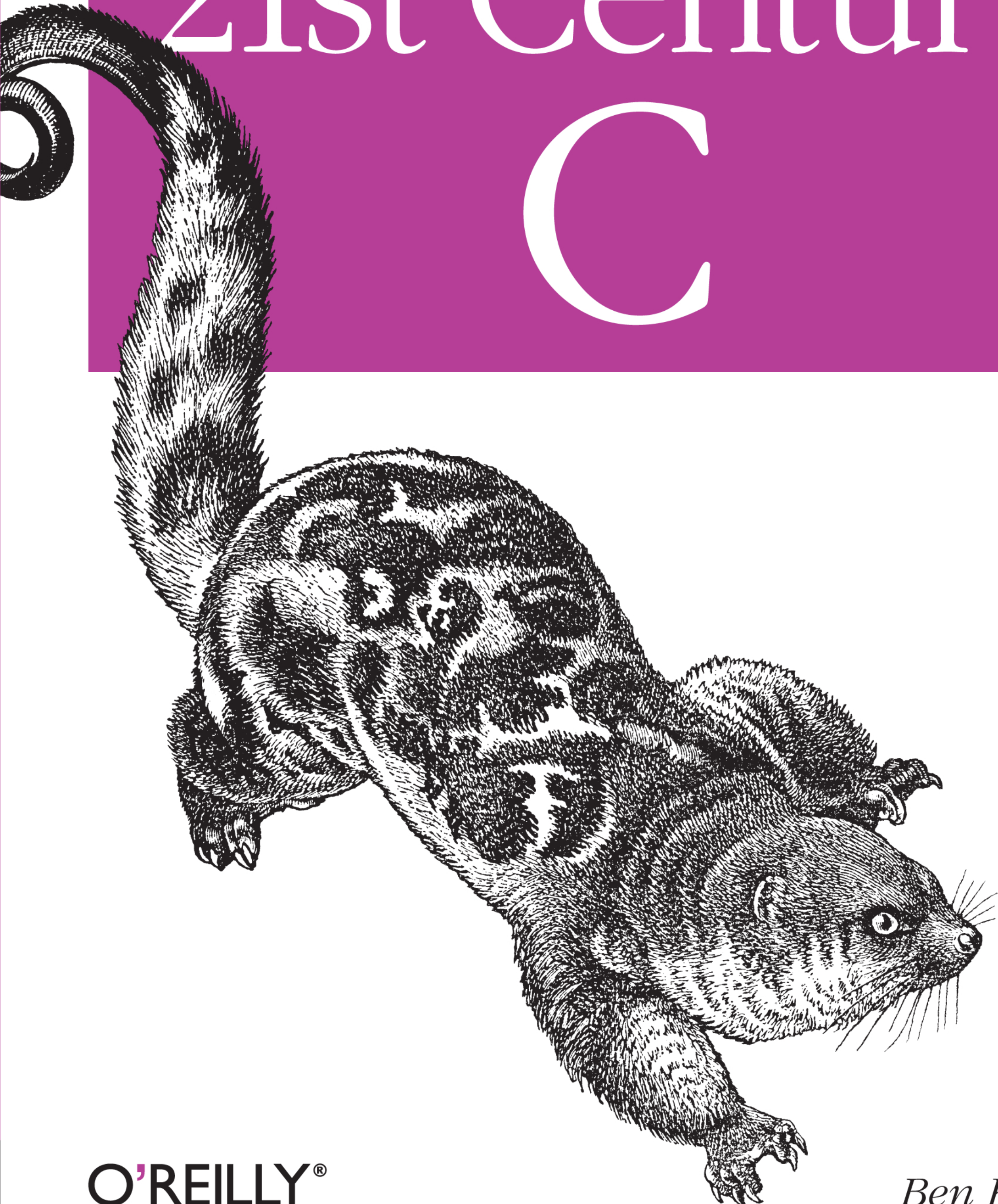
C Tips from the New School

21st Century C



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Ben Klemens

Programming/C++

21st Century C

Throw out your old ideas of C and relearn a programming language that's substantially outgrown its origins. With *21st Century C*, you'll discover up-to-date techniques that are absent from every other C text available. C isn't just the foundation of modern programming languages; it *is* a modern language, ideal for writing efficient, state-of-the-art applications. Learn to dump old habits that made sense on mainframes and pick up the tools you need to use this evolved and aggressively simple language. No matter what programming language you currently champion, you'll agree that C *rocks*.

- Set up a C programming environment with shell facilities, makefiles, text editors, debuggers, and memory checkers
- Use Autotools, C's de facto cross-platform package manager
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- Explore problematic C concepts that are too useful to throw out
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- Use modern syntactic features for functions that take structured inputs
- Build high-level object-based libraries and programs
- Apply existing C libraries for doing advanced math, talking to Internet servers, and running databases

Ben Klemens has written statistical analyses and computationally-intensive models for the Brookings Institution, the World Bank, the National Institute of Mental Health, and the US government. He has also worked with Brookings and the Free Software Foundation to ensure that authors retain the right to use the software they write.

"Is your C development environment limited to vi and cc? Does C memory management still plague you as it did in the '90s? Ben Klemens capably addresses these and other common problems, demonstrating how tools have emerged to make C programming easier—helping you debug, track down memory leaks, organize the compilation process, and manage source code versions."

—Dave Kitabjian
Director of Software Development at NetCarrier Telecom

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Part II. The Language

Preface

> Is it really punk rock
> Like the party line?
>
> —Wilco, *"Too Far Apart"*

C Is Punk Rock

C has only a handful of keywords and is a bit rough around the edges, and it rocks. You can do anything with it. Like the C, G, and D chords on a guitar, you can learn the basic mechanics quickly, and then spend the rest of your life getting better. The people who don't get it fear its power and think it too edgy to be safe. By all rankings, it is consistently the most popular language that doesn't have a corporation or foundation spending money to promote it.[1]

Also, the language is about 40 years old, which makes it middle-aged. It was written by a few guys basically working against management—the perfect punk rock origins—but that was in the 1970s, and there's been a lot of time for the language to go mainstream.

What did people do when punk rock went mainstream? In the decades since its advent in the 1970s, punk certainly has come in from the fringes: The Clash, The Offspring, Green Day, and The Strokes sold millions of albums worldwide (to name just a few), and I have heard lite instrumental versions of songs from the punk spinoff known as grunge at my local supermarket. The former lead singer of Sleater-Kinney now has a popular sketch comedy show that frequently lampoons punk rockers.[2] One reaction to the continuing evolution would be to take the hard line and say that the original stuff was punk and everything else is just easy punk pop for the masses. The traditionalists can still play their albums from the '70s, and if the grooves are worn out, they can

1. This preface owes an obvious and huge debt to "Punk Rock Languages: A Polemic," by Chris Adamson, at *http://pragprog.com/magazines/2011-03/punk-rock-languages*.
2. With lyrics like "Can't get to heaven with a three-chord song," maybe Sleater-Kinney was post-punk? Unfortunately, there is no ISO Punk standard we can look to for precise in-or-out definitions.

download a digitally mastered edition. They can buy Ramones hoodies for their toddlers.

Outsiders don't get it. Some of them hear the word *punk* and picture something out of the 1970s—a historic artifact about some kids that were, at the time, really doing something different. The traditionalist punks who still love and play their 1973 Iggy Pop LPs are having their fun, but they bolster the impression that punk is ossified and no longer relevant.

Getting back to the world of C, we have both the traditionalists, waving the banner of ANSI '89, and those who will rock out to whatever works and may not even realize that the code they are writing would not have compiled or run in the 1990s. Outsiders don't get the difference. They see still-in-print books from the 1980s and still-online tutorials from the 1990s, they hear from the hardcore traditionalists who insist on still writing like that today, and they don't even know that the language and the rest of its users continue to evolve. That's a shame, because they're missing out on some great stuff.

This is a book about breaking tradition and keeping C punk rock. I don't care to compare the code in this book to the original C specification in Kernighan & Ritchie's 1978 book. My *telephone* has 512 megabytes of memory, so why are our C textbooks still spending pages upon pages covering techniques to shave kilobytes off of our executables? I am writing this on a bottom-of-the-line red netbook that can accommodate 3,200,000,000 instructions per second; what do I care about whether an operation requires comparing 8 bits or 16? We should be writing code that we can write quickly and that is readable by our fellow humans. We're still writing in C, so our readable but imperfectly optimized code will still run an order of magnitude faster than if we'd written comparable code in any number of alternative, bloated languages.

Q & A (Or, the Parameters of the Book)

Q: How is this C book different from all others?

A: C textbooks are a somewhat uniform bunch (I've read *a lot* of them, including [Griffiths 2012], [Kernighan 1978], [Kernighan 1988], [Kochan 2004], [Oualline 1997], [Perry 1994], [Prata 2004], and [Ullman 2004]). Most were written before the C99 standard simplified many aspects of usage, and you can tell that some of those now in their *N*th edition just pasted in a few notes about updates rather than seriously rethinking how to use the language. They all mention that there might be libraries that you could maybe use in writing your own code, but they predate the installation tools and ecosystem we have now that make using those libraries reliable and reasonably portable. Those textbooks are still valid and still have value, but modern C code just doesn't look like the code in those textbooks.

This book picks up where they left off, reconsidering the language and the ecosystem in which it lives. The storyline here is about using libraries that provide linked lists and

XML parsers, not writing new ones from scratch. It is about writing code that is readable and function interfaces that are user-friendly.

Q: Who is this book for? Do I need to be a coding guru?

A: You have experience coding in any language, maybe Java or a scripting language such as Perl. I don't have to sell you on why your code shouldn't be one long routine with no subfunctions.

You have some knowledge of C, but don't worry if you don't know it too well—as I'll detail, there's a lot you're better off never learning. If you are a blank slate with respect to C syntax, it really is an aggressively simple language, and your search engine will point you to dozens of C tutorials online; if you have experience with another language, you should be able to get the basics in an hour or two.

I might as well point out to you that I have also written a textbook on statistical and scientific computing, *Modeling with Data* [Klemens 2008]. Along with lots of details of dealing with numeric data and using statistical models for describing data, it has a standalone tutorial on C, which I naturally think overcomes many of the failings of older C tutorials.

Q: I'm an application programmer, not a kernel hacker. Why should I use C instead of a quick-to-write scripting language like Python?

A: If you are an application programmer, this book is for you. I read people asserting that C is a systems language, which impresses me as so un-punk—who are they to tell us what we're allowed to write?

Statements in the way of "Our language is almost as fast as C, but is easier to write" are so common that they are almost cliché. Well, C is definitely as fast as C, and the purpose of this book is to show you that C is easier to write than the textbooks from decades past imply that it is. You don't have to call `malloc` and get elbow-deep in memory management half as often as the systems programmers of the 1990s did, we have facilities for easier string handling, and even the core syntax has evolved to make for more legible code.

I started writing C in earnest because I had to speed up a simulation in a scripting language, R. Like so many other scripting languages, R has a C interface and encourages the user to make use of it any time the host language is too slow. Eventually, I had so many functions jumping out from the R script to C code that I just dropped the host language entirely. Next thing you know, I'm writing a book on modern C technique.

Q: It's nice that application programmers coming from scripting languages will like this book, but I *am* a kernel hacker. I taught myself C in fifth grade and sometimes have dreams that correctly compile. What new material can there be for me?

A: C has evolved in the last 20 years. As I'll discuss later, the set of things we are guaranteed that all C compilers support has changed with time, thanks to two new C standards since the ANSI standard that defined the language for so long. Maybe have a look at Chapter 10 and see if anything there surprises you.

Also, the environment has advanced. Autotools has entirely changed how distribution of code happens, meaning that it is much easier to reliably call other libraries, meaning that our code should spend less time reinventing common structures and routines and more time calling the sort of libraries discussed throughout this book.

Q: I can't help but notice that about a third of this book has almost no C code in it.

A: Yes, good C practice requires gathering good C tools. If you're not using a debugger (standalone or part of your IDE), you're making your life much more difficult. If you tell me that it's impossible to track down memory leaks, then that means that you haven't heard of Valgrind, a system designed to point out the exact line where memory leaks and errors occurred. Python and company have built-in package managers; C's cross-platform package managers are standalone systems that are their own story.

If you use an attractive Integrated Development Environment (IDE) as a wrapper for all these various tools, you may still benefit from knowing how your IDE is dealing with environment variables and other minutiæ that have been hidden from you but still crop up and throw errors at you.

Q: Some of these tools you talk about are *old*. Aren't there more modern alternatives to these shell-oriented tools?

A: If we make fun of people who reject new things just because they're new, then we have no right to reject old things just because they're old.

One can find reasonable sources putting the first six-string guitar around 1200, the first four-string violin circa 1550, and the piano with keyboard around 1700. The odds are good that most (if not all) of the music you listen to today will involve one of these instruments. Punk rock didn't happen by rejecting the guitar, but by using it creatively, such as piping the guitar's output through new filters.

Q: I have the Internet, and can look up commands and syntax details in a second or two, so, really, why should I read this book?

A: It's true: you can get an operator precedence table from a Linux or Mac command prompt with `man operator`, so why am I going to put one here?

I've got the same Internet you've got, and I've spent a lot of time reading it. So I have a good idea of what isn't being talked about, and that's what I stick to here. When introducing a new tool, like gprof or GDB, I give you what you need to know to get your bearings and ask your search engine coherent questions, and what other textbooks missed (which is a lot).

Standards: So Many to Choose From

Unless explicitly stated otherwise, everything in this book conforms to the ISO C99 and C11 standards. To make sense of what that means, and give you some historical background, let us go through the list of major C standards (passing on the minor revisions and corrections).

K & R (circa 1978)
: Dennis Ritchie, Ken Thompson, and a handful of other contributors came up with C while putting together the Unix operating system. Brian Kernighan and Dennis Ritchie eventually wrote down a description of the language in the first edition of their book, which set the first *de facto* standard [Kernighan 1978].

ANSI C89
: Bell Labs handed over the stewardship of the language to the American National Standards Institute (ANSI). In 1989, they published their standard, which made a few improvements over K & R. The second edition of K & R's book included a full specification of the language, which meant that tens of thousands of programmers had a copy of the ANSI standard on their desks [Kernighan 1988]. The ANSI standard was adopted by the International Organization for Standardization (ISO) in 1990 with no serious changes, but *ANSI `89* seems to be the more common term (and would make a great t-shirt slogan).

A decade passed. C went mainstream, in the sense that the base code for more or less every PC and every Internet server was written in C, which is as mainstream as a human endeavor could possibly become.

During this period, C++ split off and hit it big (although not quite as big). C++ was the best thing to ever happen to C. While every other language was bolting on extra syntax to follow the object-oriented trend and whatever other new tricks came to the authors' minds, C stuck to the standard. The people who wanted stability and portability used C, the people who wanted more and more features so they could wallow in them like moist hundred dollar bills got C++, and everybody was happy.

ISO C99
: The C standard underwent a major revision a decade later. Additions were made for numeric and scientific computing, with a standard type for complex numbers and some type-generic functions. A few conveniences from C++ got lifted, including one-line comments (which originally came from one of C's predecessor languages, BCPL) and being able to declare variables at the head of `for` loops. Using structures was made easier thanks to a few additions to the rules for how they can be declared and initialized, plus some notational conveniences. Things were modernized to acknowledge that security matters and that not everybody speaks English.

: When you think about just how much of an impact C89 had, and how the entire globe was running on C code, it's hard to imagine the ISO being able to put out anything that wouldn't be widely criticized—even a refusal to make any changes would be reviled. And indeed, this standard was controversial. There are two common ways to express a complex variable (rectangular and polar coordinates)—so where does the ISO get off picking one? Why do we need a mechanism for variable-length macro inputs when all the good code got written without it? In other words, the purists accused the ISO of selling out to the pressure for more features.

As of this writing, most compilers support C99 plus or minus a few caveats; the `long double` type seems to cause a lot of trouble, for example. However, there is one notable exception to this broad consensus: Microsoft currently refuses to add C99 support to its Visual Studio C++ compiler. The section "Compiling C with Windows" on page 6 covers some of the many ways to compile C code for Windows, so not using Visual Studio is at most an inconvenience, and having a major establishment player tell us that we can't use ISO-standard C only bolsters the punk rock of it all.

C11

Self-conscious about the accusations of selling out, the ISO made few serious changes in the third edition of the standard. We got a means of writing type-generic functions, and things were modernized to further acknowledge that security matters and that not everybody speaks English.

I'm writing this in 2012, shortly after the C11 standard came out in December of 2011, and there's already some support from compilers and libraries.

The POSIX Standard

That's the state of things as far as C itself goes, but the language coevolved with the Unix operating system, and you will see throughout the book that the interrelationship matters for day-to-day work. If something is easy on the Unix command line, then it is probably because it is easy in C; Unix tools are often written to facilitate writing C code.

Unix

C and Unix were designed at Bell Labs in the early 1970s. During most of the 20th century, Bell was being investigated for monopolistic practices, and one of its agreements with the US federal government included promises that Bell would not expand its reach into software. So Unix was given away for free for researchers to dissect and rebuild. The name Unix is a trademark, originally owned by Bell Labs and subsequently traded off like a baseball card among a number of companies.

Variants of Unix blossomed, as the code was looked over, reimplemented, and improved in different ways by diverse hackers. It just takes one little incompatibility to make a program or script unportable, so the need for some standardization quickly became apparent.

POSIX

This standard, first established by the Institute of Electrical and Electronics Engineers (IEEE) in 1988, provided a common basis for Unix-like operating systems. It specifies how the shell should work, what to expect from commands like `ls` and `grep`, and a number of C libraries that C authors can expect to have available. For example, the pipes that command-line users use to string together commands are specified in detail here, which means C's `popen` (pipe open) function is POSIX-standard, not ISO C standard. The POSIX standard has been revised many times; the version as of this writing is POSIX:2008, and is what I am referring to when I say that something is POSIX-standard. A POSIX-standard system must have a C compiler available, via the command name `c99`.

This book will make use of the POSIX standard, though I'll tell you when.

With the exception of many members of a family of OSes from Microsoft, just about every current operating system you could name is built on a POSIX-compliant base: Linux, Mac OS X, iOS, webOS, Solaris, BSD—even Windows servers offer a POSIX subsystem. And for the hold-out OSes, "Compiling C with Windows" on page 6 will show you how to install a POSIX subsystem.

Finally, there are two more implementations of POSIX worth noting because of their prevalence and influence:

BSD

After Unix was made available from Bell Labs for the public to dissect, the researchers at the University of California, Berkeley, made major improvements, eventually rewriting the entire Unix code base to produce the Berkeley Software Distribution. If you are using a computer from Apple, Inc., you are using BSD with an attractive graphical frontend. BSD goes beyond POSIX in several respects, and we'll see some functions that are not part of the POSIX standard but are too useful to pass up (most notably the lifesaver that is `asprintf`).

GNU

It stands for GNU's Not Unix, and is the other big success story in independently reimplementing and improving on the Unix environment. The great majority of Linux distributions use GNU tools throughout. There are very good odds that you have the GNU Compiler Collection (gcc) on your POSIX box—even BSD uses it. Again, the gcc defines a *de facto* standard that extends C and POSIX in a few ways, and I will be explicit when making use of those extensions.

Legally, the BSD license is slightly more permissive than the GNU license. Because some parties are deeply concerned with the political and business implications of the licenses, one can typically find both GNU and BSD versions of most tools. For example, both the gcc and the BSD's `clang` are top-notch C compilers. The authors from both camps closely watch and learn from each other's work, so we can expect that the differences that currently exist will tend to even out over time.

The Legal Sidebar

US law no longer has a registration system for copyright: with few exceptions, as soon as anybody writes something down, it is copyrighted.

Of course, distribution of a library depends on copying from hard drive to hard drive, and there are a number of common mechanisms for granting the right to copy a copyrighted work with little hassle.

- The GNU Public License allows unlimited copying and use of the source code and its executable version. There is one major condition: If you *distribute* a program or library based on the GPLed source code, then you must distribute the source code to your program. Note well that if you use your program in-house and don't distribute it, this condition doesn't hold, and you have no obligation to distribute source. Running a GPLed program, like compiling your code with gcc, does not in itself obligate you to distribute source code, because the program output (such as the executable you just compiled) is not considered to be based on or a derivative of gcc. [Example: the GNU Scientific Library.]
- The Lesser GPL is much like the GPL, but it explicitly stipulates that if you are linking to an LGPL library as a shared library, then your code doesn't count as a derivative work, and you aren't obligated to distribute source. That is, you can distribute closed-source code that links to an LGPL library. [Example: GLib.]
- The BSD license requires that you preserve copyrights and disclaimers for BSD-licensed source code, but doesn't require that you redistribute source code. [Example: Libxml2, under the BSD-like MIT license.]

Please note the usual disclaimer: I am not a lawyer, and this is a sidebar summary of several rather long legal documents. Read the documents themselves or consult a lawyer if you are unsure about how the details apply to your situation.

Some Logistics

Conventions Used in This Book

The following typographical conventions are used in this book:

Italic
: Indicates new terms, filenames and file paths, URLs, and email addresses. Many new terms are defined in a glossary at the end of this book.

`Constant width`
: Used for program listings, as well as within paragraphs to refer to program elements such as variable or function names, databases, data types, environment variables, statements, and keywords.

`Constant width italic`
: Shows text that should be replaced with user-supplied values or by values determined by context.

This icon signifies a tip, suggestion, or general note.

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Rachel Steely: production.
Ulrik Sverdrup: pointing out that we can use repeated designated initializers to set default values.

Content Updates

June 14, 2013

- MSYS is correctly capitalized, and several other small tweaks made.
- Simplified notes on getting `gcc` or `Clang` to read from `stdin`.
- Added a note on wrapping macros to make them even safer.
- Replaced every instance of `memcpy` with `memmove`.
- Added more on large integer types such as `intmax_t` and `intptr_t`.
- Added a short segment on comparing negative `ints` with unsigned `ints`.
- Rewrote section on the `extern` keyword.
- Corrected misattribution of `__attribute__` to the ISO.
- Bug fix in *amortization.c*.

PART I
The Environment

In the wilds outside the scripting languages' walled gardens, there is an abundance of tools that solve the big annoyances about C, but you have to hunt for them. And I mean *have to*: many of these tools are absolutely necessary to write without pain. If you aren't using a debugger (standalone or within an IDE), then you're imposing arbitrary hardship on yourself.

There is also an abundance of existing libraries waiting to be used in your code, so you can work on the problem at hand instead of wasting time reimplementing linked lists, parsers, or other basics. It needs to be as easy as possible to compile your program using external libraries.

The following is an overview of Part I:

Chapter 1 covers setting up the basic environment, including getting a package manager and getting it to install all the requisite tools. This is all background for the interesting part, where we compile programs using libraries from elsewhere. The process is pretty standardized, involving a small set of environment variables and recipes.

Chapter 2 introduces tools for debugging, documenting, and testing, because what good is code until it's debugged, documented, and tested?

Chapter 3 addresses Autotools, a system for packaging your code for distribution. But the chapter takes the long way, and so also covers more about writing shell scripts and makefiles.

Nothing complicates life like other people. Therefore, Chapter 4 covers Git, a system for keeping track of the slightly different versions of a project on your and your collaborators' hard drives, and making the process of merging all those versions as simple as possible.

Other languages are a key part of the modern C environment, because so many languages advertise a C interface. Chapter 5 will offer some general notes on writing the interface, and give an extended example with Python.

CHAPTER 1

Set Yourself Up for Easy Compilation

> Look out honey 'cause I'm using technology.
>
> —Iggy Pop, "Search and Destroy"

The C standard library is just not enough to get serious work done.

Instead, the C ecosystem has expanded outside of the standard, which means that knowing how to easily call functions from common but not-ISO-standard libraries is essential if you want to get past doing textbook exercises. Unfortunately, this is the point where most textbooks taper off and leave you to work it out for yourself, which is why you can find C detractors who will say self-dissonant things like *C is 40 years old, so you have to write every procedure from scratch in it*—they never worked out how to link to a library.

Here is the agenda for the chapter:

- Setting up the requisite tools. This is much easier than it was in the dark days when you had to hunt for every component. You can set up a full build system with all the frills in maybe 10 or 15 minutes (plus all the download time to load so much good stuff).
- How to compile a C program. Yes, you know how to do this, but we need a setup that has hooks for the libraries and their locations; just typing `cc` ***`myfile.c`*** doesn't cut it anymore. *Make* is just about the simplest system to facilitate compiling programs, so it provides a good model for discussion. I'll show you the smallest possible makefile that offers enough room to grow.
- Whatever system we use will be based on a small set of environment-like variables, so I'll discuss what they do and how to set them. Once we have all that compilation machinery in place, adding new libraries will be an easy question of adjusting the variables we've already set up.
- As a bonus, we can use everything up to this point to set up a still simpler system for compilation, which will let us cut and paste code onto the command prompt.

A special note to IDE users: you may not be a make user, but this section will nonetheless be relevant to you, because for every recipe that make executes when compiling code, your IDE has an analogous recipe. If you know what make is doing, you'll have an easy time tweaking your IDE.

Use a Package Manager

If you are not using a package manager, you are missing out.

I bring up package managers for several reasons: first, some of you may not have the basics installed. For you, I put this section first in the book, because you need to get these tools, and fast. A good package manager will have you set up quite rapidly with a full POSIX subsystem, compilers for every language you've ever heard of, a half-decent array of games, the usual office productivity tools, a few hundred C libraries, et cetera.

Second, as C authors, the package manager is a key means by which we can get libraries for folding into our work.

Third, if you are making the jump from being somebody who downloads packages to being somebody producing a package, this book will take you halfway, showing you how to prepare your package for easy autoinstallation, so that when the administrator of a package repository decides to include your code in the repository, he or she will have no problem building the final package.

If you are a Linux user, you set up your computer with a package manager and have already seen how easy the software obtention process can be. For Windows users, I'll cover Cygwin in detail. Mac users have several options, such as Fink and Macports. All the Mac options depend on Apple's Xcode package, typically available on the OS install CD (or directory of installable programs, depending on the vintage), or by registering as a developer with Apple.

What packages will you need? Here's a quick rundown of the C development basics. Because every system has a different organization scheme, some of these may be bundled differently, installed by default in a base package, or oddly named. When in doubt about a package, install it, because we're past the days when installing too many things could somehow cause system instability or slowdown. However, you probably don't have the bandwidth (or maybe even the disk space) to install every package on offer, so some judgment will be required. If you find that you are missing something, you can always go back and get it later. Packages to definitely get:

- A compiler. Definitely install gcc; Clang may be available.
- gdb, a debugger.
- Valgrind, to test for C memory usage errors.
- gprof, a profiler.
- make, so you never have to call your compiler directly.

- pkg-config, for finding libraries.
- Doxygen, for documentation generation.
- A text editor. There are literally hundreds of text editors to choose from. Here are a few subjective recommendations:
  - Emacs and vim are the hardcore geek's favorites. Emacs is very inclusive (the *E* is for *extensible*); vim is more minimalist and is very friendly to touch typists. If you expect to spend hundreds of hours staring at a text editor, it is worth taking the time to learn one of them.
  - Kate is friendly and attractive, and provides a good subset of the conveniences we expect as programmers, such as syntax highlighting.
  - As a last resort, try nano, which is aggressively simple, and is text-based, and therefore works even when your GUI doesn't.
- If you are a fan of IDEs, get one—or several. Again, there are many to choose from; here are a few recommendations:
  - Anjuta: in the GNOME family. Friendly with Glade, the GNOME GUI builder.
  - KDevelop: in the KDE family.
  - Code::blocks: relatively simple, works on Windows.
  - Eclipse: the luxury car with lots of cupholders and extra knobs. Also cross-platform.

In later chapters, I'll get to these more heavy-duty tools:

- Autotools: Autoconf, Automake, libtool
- Git
- Alternate shells, such as the Z shell.

And, of course, there are the C libraries that will save you the trouble of reinventing the wheel (or, to be more metaphorically accurate, reinventing the locomotive). You might want more, but here are the libraries that will be used over the course of this book:

- libcURL
- libGlib
- libGSL
- libSQLite3
- libXML2

There is no consensus on library package naming schemes, and you will have to work out how your package manager likes to dissect a single library into subparts. There is typically one package for users and a second for authors who will use the library in their own work, so be sure to select both the base package and the `-dev` or `-devel` packages. Some systems separate documentation into yet another package. Some require that you download debugging symbols separately, in which case gdb should lead you through the steps the first time you run it on something lacking debugging symbols.

If you are using a POSIX system, then after you've installed the preceding items, you will have a complete development system and are ready to get coding. For Windows users, we'll take a brief detour to understand how the setup interacts with the main Windows system.

Compiling C with Windows

On most systems, C is the central, VIP language that all the other tools work to facilitate; on a Windows box, C is strangely ignored.

So I need to take a little time out to discuss how to set up a Windows box for writing code in C. If you aren't writing on a Windows box now, feel free to skip this segment and jump to "Which Way to the Library?" on page 9.

This section is not intended as a rant about Microsoft, and I am not going to speculate on Microsoft's motives or business strategies. However, if you want to get work done in C on a Windows box, you need to know the state of affairs and what you can do to get going.

POSIX for Windows

Because C and Unix coevolved, it's hard to talk about one and not the other. I think it's easier to start with POSIX. Also, those of you who are trying to compile code on a Windows box that you wrote elsewhere will find this to be the most natural route.

As far as I can tell, the world of things with filesystems divides into two (slightly overlapping) classes:

- POSIX-compliant systems
- The Windows family of operating systems

POSIX compliance doesn't mean that a system has to look and feel like a Unix box. For example, the typical Mac user has no idea that he or she is using a standard BSD system with an attractive frontend, but those in the know can go to the Accessories → Utilities folder, open the Terminal program, and run `ls`, `grep`, and `make` to their hearts' content.

Further, I doubt that many systems live up to 100% of the standard's requirements (like having a Fortran `77 compiler). For our purposes, we need a shell that can behave like the barebones POSIX shell, a handful of utilities (`sed`, `grep`, `make`, …), a C99 compiler, and additions to the standard C library such as `fork` and `iconv`. These can be added as a side note to the main system. The package manager's underlying scripts, Autotools, and almost every other attempt at portable coding will rely on these tools to some extent, so even if you don't want to stare at a command prompt all day, these tools will be handy to have for installations.

On server-class OSes and the full-featured editions of Windows 7, Microsoft offers what used to be called INTERIX and is now called the Subsystem for Unix-based Application (SUA), which provides the usual POSIX system calls, the Korn shell, and gcc. The subsystem is typically not provided by default but can be installed as an add-on component. But the SUA is not available for other current editions of Windows and will not be available for Windows 8, so we can't depend on Microsoft to provide a POSIX subsystem for its operating systems.

And so, Cygwin.

If you were to rebuild Cygwin from scratch, this would be your agenda:

1. Write a C library for Windows that provides all the POSIX functions. This will have to smooth over some Windows/POSIX incongruities, such as how Windows has distinct drives like *C:* while POSIX has one unified filesystem. In this case, alias *C:* as */cygdrive/c*, *D:* as */cygdrive/d*, and so on.
2. Now that you can compile POSIX-standard programs by linking to your library, do so: generate Windows versions of `ls`, `bash`, `grep`, `make`, `gcc`, `X`, `rxvt`, `libglib`, `perl`, `python`, and so on.
3. Once you have hundreds of programs and libraries built, set up a package manager that allows users to select the elements they want to install.

As a user of Cygwin, all you have to do is download the package manager from the setup link at Cygwin's website and pick packages. You will certainly want the preceding list, plus a decent terminal (try mintty, or install the X subsystem and use the xterm), but you will see that virtually all of the luxuries familiar from a development system are there somewhere. Now you can get to compiling C code.

Compiling C with POSIX

Microsoft provides a C++ compiler, in the form of Visual Studio, which has an ANSI C compatibility mode. This is the only means of compiling C code currently provided by Microsoft. Many representatives from the company have made it clear that C99 support (let alone C11 support) is not forthcoming. Visual Studio is the only major compiler that is still stuck on C89, so we'll have to find alternative offerings elsewhere.

Of course, Cygwin provides gcc, and if you've followed along and installed Cygwin, then you've already got a full build environment.

If you are compiling under Cygwin, then your program will depend on its library of POSIX functions, *cygwin1.dll* (whether your code actually includes any POSIX calls or not). If you are running your program on a box with Cygwin installed, then you obviously have no problem. Users will be able to click on the executable and run it as expected, because the system should be able to find the Cygwin DLL. A program compiled under Cygwin can run on boxes that don't have Cygwin installed if you distribute *cygwin1.dll* with your code. On my machine, this is ***(path to cygwin)**/bin/cygwin1.dll*. The *cygwin1.dll* file has a GPL-like license (see "The Legal Sidebar" on page xvi), in the sense that if you distribute the DLL separately from Cygwin as a whole, then you are required to publish the source code for your program.[1]

If this is a problem, then you'll have to find a way to recompile without depending on *cygwin1.dll*, which means dropping any POSIX-specific functions (like `fork` or `popen`) from your code and using MinGW, as discussed later. You can use `cygcheck` to find out which DLLs your program depends on, and thus verify that your executable does or does not link to *cygwin1.dll*.

Compiling C Without POSIX

If your program doesn't need the POSIX functions, then you can use MinGW (Minimalist GNU for Windows), which provides a standard C compiler and some basic associated tools. MSYS is a companion to MinGW that provides a shell and other useful utilities.

The lack of POSIX-style amenities is not the real problem with MinGW. MSYS provides a POSIX shell, or leave the command prompt behind entirely and try Code::blocks, an IDE that uses MinGW for compilation on Windows. Eclipse is a much more extensive IDE that can also be configured for MinGW, though that requires a bit more setup.

Or if you are more comfortable at a POSIX command prompt, then set up Cygwin anyway, get the packages providing the MinGW versions of gcc, and use those for compilation instead of the POSIX-linking default version of Cygwin gcc.

If you haven't already met Autotools, you'll meet it soon. The signature of a package built using Autotools is its three-command install: `./configure; make; make install`. MSYS provides sufficient machinery for such packages to stand a good chance of working. Or if you have downloaded the packages to build from Cygwin's command prompt, then you can use the following to set up the package to use Cygwin's Mingw32 compiler for producing POSIX-free code:

```
./configure --host=ming32
```

Then run `make; make install` as usual.

Once you've compiled under MinGW, via either command-line compilation or Autotools, you've got a native Windows binary. Because MinGW knows nothing of *cygwin1.dll*, and your program makes no POSIX calls anyway, you've now got an executable program that is a bona fide Windows program, that nobody will know you compiled from a POSIX environment.

1. Cygwin is a project run by Red Hat, Inc., who will also allow users to purchase the right to not distribute their source code as per the GPL.

No, the real problem with MinGW is the paucity of precompiled libraries.[2] If you want to be free of *cygwin1.dll*, then you can't use the version of *libglib.dll* that ships with Cygwin. You'll need to recompile GLib from source to a native Windows DLL—but GLib depends on GNU's gettext for internationalization, so you'll have to build that library first. Modern code depends on modern libraries, so you may find yourself spending a lot of time setting up the sort of things that in other systems are a one-line call to the package manager. We're back to the sort of thing that makes people talk about how C is 40 years old, so you need to write everything from scratch.

So, there are the caveats. Microsoft has walked away from the conversation, leaving others to implement a post-grunge C compiler and environment. Cygwin does this and provides a full package manager with enough libraries to do some or all of your work, but it is associated with a POSIX style of writing and Cygwin's DLL. If that is a problem, you will need to do more work to build the environment and the libraries that you'll need to write decent code.

Which Way to the Library?

OK, so you have a compiler, a POSIX toolchain, and a package manager that will easily install a few hundred libraries. Now we can move on to the problem of using those in compiling our programs.

We have to start with the compiler command line, which will quickly become a mess, but we'll end with three (sometimes three and a half) relatively simple steps:

1. Set a variable listing the compiler flags.
2. Set a variable listing the libraries to link to. The half-step is that you sometimes have to set only one variable for linking while compiling, and sometimes have to set two for linking at compile time and runtime.
3. Set up a system that will use these variables to orchestrate the compilation.

To use a library, you have to tell the compiler that you will be importing functions from the library twice: once for the compilation and once for the linker. For a library in a standard location, the two declarations happen via an `#include` in the text of the program and a `-l` flag on the compiler line.

Example 1-1 presents a quick sample program that does some amusing math (for me, at least; if the statistical jargon is Greek to you, that's OK). The C99-standard *error function*, `erf(x)`, is closely related to the integral from zero to x of the Normal distribution with mean zero and standard deviation $\sqrt{2}$. Here, we use `erf` to verify an area

2. Although MSYS, MinGW, and a few other elements are provided as packages, this handful of packages pales in comparison to the hundreds of packages provided by the typical package manager. Notably, precompiled libraries are not a one-click or one-command install. However, by the time you read this, my complaint may have been addressed, and there might be many more MinGW packages available.

popular among statisticians (the 95% confidence interval for a standard large-*n* hypothesis test). Let us name this file *erf.c*.

Example 1-1. A one-liner from the standard library. (erf.c)

```
#include <math.h>  //erf, sqrt
#include <stdio.h> //printf

int main(){
    printf("The integral of a Normal(0, 1) distribution "
           "between -1.96 and 1.96 is: %g\n", erf(1.96*sqrt(1/2.)));
}
```

The `#include` lines should be familiar to you. The compiler will paste *math.h* and *stdio.h* into the code file here, and thus paste in declarations for `printf`, `erf`, and `sqrt`. The declaration in *math.h* doesn't say anything about what `erf` does, only that it takes in a `double` and returns a `double`. That's enough information for the compiler to check the consistency of our usage and produce an object file with a note telling the computer: once you get to this note, go find the `erf` function, and replace this note with `erf`'s return value.

It is the job of the linker to reconcile that note by actually finding `erf`, which is in a library somewhere on your hard drive.

The math functions found in *math.h* are split off into their own library, and you will have to tell the linker about it by adding an `-lm` flag. Here, the `-l` is the flag indicating that a library needs to be linked in, and the library in this case has a single-letter name, `m`. You get `printf` for free, because there is an implicit `-lc` asking the linker to link the standard `libc` assumed at the end of the linking command. Later, we'll see GLib 2.0 linked in via `-lglib-2.0`, the GNU Scientific Library get linked via `-lgsl`, and so on.

So if the file were named *erf.c*, then the full command line using the gcc compiler, including several additional flags to be discussed shortly, would look like this:

```
gcc erf.c -o erf -lm -g -Wall -O3 -std=gnu11
```

So we've told the compiler to include math functions via an `#include` in the program, and told the linker to link to the math library via the `-lm` on the command line.

The `-o` flag gives the output name; otherwise, we'd get the default executable name of `a.out`.

A Few of My Favorite Flags

You'll see that I use a few compiler flags every time, and I recommend you do, too.

- `-g` adds symbols for debugging. Without it, your debugger won't be able to give you variable or function names. They don't slow down the program, and we don't care if the program is a kilobyte larger, so there's little reason to not use this. It works for gcc, Clang, and icc (Intel C Compiler).

- `-std=gnu11` is gcc-specific, and specifies that gcc should allow code conforming to the C11 and POSIX standards. Otherwise, gcc will count certain now-valid bits of syntax as invalid. As of this writing, some systems still predate C11, in which case, use `-std=gnu99`. This is gcc only; everybody else switched to C99 being the default a long time ago. The POSIX standard specifies that `c99` be present on your system, so the compiler-agnostic version of the above line would be:

  ```
  c99 erf.c -o erf -lm -g -Wall -O3
  ```

  In the following makefiles, I achieve this effect by setting the variable `CC=c99`.

  > On Macs, `c99` is a specially-hacked version of `gcc`, and is probably not what you want. If you have an undesirable version of `c99` or it is missing entirely, make your own. Put a file named `c99` in the directory at the head of your path with the text:
  >
  > ```
  > gcc --std=c99 $*
  > ```
  >
  > or just
  >
  > ```
  > clang $*
  > ```
  >
  > as you prefer. Make it executable via `chmod +x c99`.

- `-O3` indicates optimization level three, which tries every trick known to build faster code. If, when you run the debugger, you find that too many variables have been optimized out for you to follow what's going on, then change this to `-O0`. This will be a common tweak in the `CFLAGS` variable, later. This works for gcc, Clang, and icc.
- `-Wall` adds compiler warnings. This works for gcc, Clang, and icc. For icc, you might prefer `-w1`, which displays the compiler's warnings, but not its remarks.

> Use your compiler warnings, always. You may be fastidious and know the C standard inside out, but you aren't more fastidious or knowledgeable than your compiler. Old C textbooks filled pages admonishing you to watch out for the difference between `=` and `==`, or to check that all variables are initialized before use. As a more modern textbook author, I have it easy, because I can summarize all those admonishments into one single tip: use your compiler warnings, always.
>
> If your compiler advises a change, don't second-guess it or put off the fix. Do everything necessary to (1) understand why you got a warning and (2) fix your code so that it compiles with zero warnings and zero errors. Compiler messages are famously obtuse, so if you are having trouble with step (1), paste the warning message into your search engine to see how many thousands of others were confounded by this warning before you. You may want to add `-Werror` to your compiler flags so your compiler will treat warnings as errors.

Paths

I've got over 700,000 files on my hard drive, and one of them has the declarations for `sqrt` and `erf`, and another is the object file holding the compiled functions. (You can try `find / -type f | wc -l` to get a rough file count on any POSIX-standard system.) The compiler needs to know in which directories to look to find the correct header and object file, and the problem will only get more complex when we use libraries that are not part of the C standard.

In a typical setup, there are at least three places where libraries may be installed:

- The operating system vendor may define a standard directory or two where libraries are installed by the vendor.
- There may be a directory for the local sysadmin to install packages that shouldn't be overwritten on the next OS upgrade from the vendor. The sysadmin might have a specially hacked version of a library that should override the default version.
- Users typically don't have the rights to write to these locations, and so should be able to use libraries in their home directories.

The OS-standard location typically causes no problems, and the compiler should know to look in those places to find the standard C library, as well as anything installed alongside it. The POSIX standard refers to these directories as "the usual places."

But for the other stuff, you have to tell the compiler where to look. This is going to get Byzantine: there is no standard way to find libraries in nonstandard locations, and it rates highly on the list of things that frustrate people about C. On the plus side, your compiler knows how to look in the usual locations, and library distributors tend to put things in the usual locations, so you might never need to specify a path manually. On another plus side, there are a few tools to help you with specifying paths. And on one last plus side, once you have located the nonstandard locations on your system, you can set them in a shell or makefile variable and never think about them again.

Let us say that you have a library named Libuseful installed on your computer, and you know that its various files were put in the */usr/local/* directory, which is the location officially intended for your sysadmin's local libraries. You already put `#include <useful.h>` in your code; now you have to put this on the command line:

```
gcc -I/usr/local/include use_useful.c -o use_useful -L/usr/local/lib -luseful
```

- `-I` adds the given path to the include search path, which the compiler searches for header files you `#include`d in your code.
- `-L` adds to the library search path.
- Order matters. If you have a file named *specific.o* that depends on the Libbroad library, and Libbroad depends on Libgeneral, then you will need:

  ```
  gcc specific.o -lbroad -lgeneral
  ```

> Any other ordering, such as `gcc -lbroad -lgeneral specific.o`, will probably fail. You can think of the linker looking at the first item, `specific.o`, and writing down a list of unresolved function, structure, and variable names. Then it goes to the next item, `-lbroad`, and searches for the items on its still-missing list, all the while potentially adding new unresolved items, then checking `-lgeneral` for those items still on the missing list. If there are names still unlocated by the end of the list (including that implicit `-lc` at the end), then the linker halts and gives what is left of its missing-items list to the user.

OK, back to the location problem: where is the library that you want to link to? If it was installed via the same package manager that you used to install the rest of your operating system, then it is most likely in the usual places, and you don't have to worry about it.

You may have a sense of where your own local libraries tend to be, such as */usr/local* or */sw* or */opt*. You no doubt have on hand a means of searching the hard drive, such as a search tool on your desktop or the POSIX:

```
find /usr -name 'libuseful*'
```

to search */usr* for files with names beginning with *libuseful*. When you find Libuseful's shared object file is in */some/path/lib*, the headers are almost certainly in */some/path/include*.

Everybody else finds hunting the hard drive for libraries to be annoying, too, and `pkg-config` addresses this by maintaining a repository of the flags and locations that packages self-report as being necessary for compilation. Type `pkg-config` on your command line; if you get an error about specifying package names, then great, you have `pkg-config` and can use it to do the research for you. For example, on my PC, typing these two commands on the command line:

```
pkg-config --libs gsl libxml-2.0
pkg-config --cflags gsl libxml-2.0
```

gives me these two lines of output:

```
-lgsl -lgslcblas -lm -lxml2
-I/usr/include/libxml2
```

These are exactly the flags I need to compile using GSL and LibXML2. The `-l` flags reveal that GNU Scientific Library depends on a Basic Linear Algebra Subprograms (BLAS) library, and the GSL's BLAS library depends on the standard math library. It seems that all the libraries are in the usual places, because there are no `-L` flags, but the `-I` flag indicates the special location for LibXML2's header files.

Back to the command line, the shell provides a trick in that when you surround a command by backticks, the command is replaced with its output. That is, when I type:

```
gcc `pkg-config --cflags --libs gsl libxml-2.0` -o specific specific.c
```

the compiler sees:

```
gcc -I/usr/include/libxml2 -lgsl -lgslcblas -lm -lxml2 -o specific specific.c
```

So `pkg-config` does a lot of the work for us, but it is not sufficiently standard that we can expect everybody has it or that every library is registered with it. If you don't have `pkg-config`, then you'll have to do this sort of research yourself, by reading the manual for your library or searching your disk as we saw previously.

> There are often environment variables for paths, such as `CPATH` or `LIBRARY_PATH` or `C_INCLUDE_PATH`. You would set them in your `.bashrc` or other such user-specific list of environment variables. They are hopelessly nonstandard—gcc on Linux and gcc on the Mac use different variables, and any other compiler may use others still. I find that it's easier to set these paths on a per-project basis in the makefile or its equivalent, using `-I` and `-L` flags. If you prefer these path variables, check the end of your compiler's manpage for the list of relevant variables for your situation.

Even with `pkg-config`, the need for something that will assemble all this for us is increasingly apparent. Each element is easy enough to understand, but it is a long, mechanical list of tedious parts.

Runtime Linking

Static libraries are linked by the compiler by effectively copying the contents of the library into the final executable. So the program itself works as a more-or-less standalone system. *Shared libraries* are linked to your program at run-time, meaning that we have the same problem with finding the library that we had at compile time all over again at runtime. What is worse, *users* of your program may have this problem.

If the library is in one of the usual locations, life is good and the system will have no problem finding the library at runtime. If your library is in a nonstandard path, then you need to find a way to modify the runtime search path for libraries. Options:

- If you packaged your program with Autotools, Libtool knows how to add the right flags, and you don't have to worry about it.
- The most likely reason for needing to modify this search path is if you are keeping libraries in your home directory because you don't have (or don't want to make use of) root access. If you are installing all of your libraries into *libpath*, then set the environment variable `LD_LIBRARY_PATH`. This is typically done in your shell's startup script (`.bashrc`, `.zshrc`, or whatever is appropriate), via:

  ```
  export LD_LIBRARY_PATH=libpath:$LD_LIBRARY_PATH
  ```

  There are those who warn against overuse of the `LD_LIBRARY_PATH` (what if somebody puts a malicious impostor library in the path, thus replacing the real library without your knowledge?), but if all your libraries are in one place, it is not unreasonable to add one directory under your ostensible control to the path.

- When compiling the program with gcc, Clang, or icc based on a library in *libpath*, add:

  ```
  LDADD=-Llibpath -Wl,-Rlibpath
  ```

  to the subsequent makefile. The `-L` flag tells the compiler where to search for libraries to resolve symbols; the `-Wl` flag passes its flags through from gcc/Clang/icc to the linker, and the linker embeds the given `-R` into the runtime search path for libraries to link to. Unfortunately, `pkg-config` often doesn't know about runtime paths, so you may need to enter these things manually.

Using Makefiles

The *makefile* provides a resolution to all this endless tweaking. It is basically an organized set of variables and shell scripts. The POSIX-standard *make* program reads the makefile for instructions and variables, and then assembles the long and tedious command lines for us. After this segment, there will be little reason to call the compiler directly.

In "Makefiles vs. Shell Scripts" on page 62, I'll cover a few more details about the makefile; here, I'm going to show you the smallest practicable makefile that will compile a basic program that depends on a library. Here it is, all six lines of it:

```
P=program_name
OBJECTS=
CFLAGS = -g -Wall -O3
LDLIBS=
CC=c99

$(P): $(OBJECTS)
```

Usage:

- Once ever: Save this (with the name *makefile*) in the same directory as your *.c* files. If you are using GNU Make, you have the option of capitalizing the name to *Makefile* if you feel that doing so will help it to stand out from the other files. Set your program's name on the first line (use ***progname***, not ***progname.c***).
- Every time you need to recompile: Type `make`.

Your Turn: Here's the world-famous *hello.c* program, in two lines:

```
#include <stdio.h>
int main(){ printf("Hello, world.\n"); }
```

Save that and the preceding makefile to a directory, and try the previous steps to get the program compiled and running.

Setting Variables

We'll get to the actual functioning of the makefile soon, but five out of six lines of this makefile are about setting variables (most of which are currently set to be blank), indicating that we should take a moment to consider environment variables in a little more detail.

> Historically, there have been two main threads of shell grammar: one based primarily on the Bourne shell, and another based primarily on the C shell. The C shell has a slightly different syntax for variables, e.g., `set CFLAGS="-g -Wall -O3"` to set the value of `CFLAGS`. But the POSIX standard is written around the Bourne-type variable-setting syntax, so that is what I focus on through the rest of this book.

The shell and `make` use the `$` to indicate the value of a variable, but the shell uses `$`*`var`*, whereas `make` wants any variable names longer than one character in parens: `$(`*`var`*`)`. So, given the preceding makefile, `$(P): $(OBJECTS)` will be equivalent to

```
program_name:
```

There are several ways to get `make` to recognize a variable:

- Set the variable from the shell before calling `make`, and *export* the variable, meaning that when the shell spawns a child process, it has the variable in its list of environment variables. To set `CFLAGS` from a POSIX-standard command line:

  ```
  export CFLAGS='-g -Wall -O3'
  ```

  At home, I omit the first line in this makefile, `P=`*`program_name`*, and instead set it once per session via `export P=`*`program_name`*, which means I have to edit the makefile itself still less frequently.

- You can put these export commands in your shell's startup script, like `.bashrc` or `.zshrc`. This guarantees that every time you log in or start a new shell, the variable will be set and exported. If you are confident that your `CFLAGS` will be the same every time, you can set them here and never think about them again.

- You can export a variable for a single command by putting the assignment just before the command. The `env` command lists the environment variables it knows about, so when you run the following:

  ```
  PANTS=kakhi env | grep PANTS
  ```

  you should see the appropriate variable and its value. This is why the shell won't let you put spaces around the equals sign: the space is how it distinguishes between the assignment and the command.

  Using this form sets and exports the given variables for one line only. After you try this on the command line, try running `env | grep PANTS` again to verify that `PANTS` is no longer an exported variable.

Feel free to specify as many variables as you'd like:

```
PANTS=kakhi PLANTS="ficus fern" env | grep 'P.*NTS'
```

This trick is a part of the shell specification's *simple command* description, meaning that the assignment needs to come before an actual command. This will matter when we get to noncommand shell constructs. Writing:

```
VAR=val if [ -e afile ] ; then ./program_using_VAR ; fi
```

will fail with an obscure syntax error. The correct form is:

```
if [ -e afile ] ; then VAR=val ./program_using_VAR ; fi
```

- As in the earlier makefile, you can set the variable at the head of the makefile, with the lines like `CFLAGS=...`. In the makefile, you can have spaces around the equals sign without anything breaking.
- `make` will let you set variables on the command line, independent of the shell. Thus, these two lines are close to equivalent:

```
make CFLAGS="-g -Wall"    Set a makefile variable.
CFLAGS="-g -Wall" make    Set an environment variable that only make and its children see.
```

All of these means are equivalent, as far as your makefile is concerned, with the exception that child programs called by `make` will know new environment variables but won't know any makefile variables.

Environment Variables in C

In your C code, get environment variables with `getenv`. Because `getenv` is so easy to use, it's useful for quickly setting a variable on the C side, so you can try a few different values from the command prompt.

Example 1-2 prints a message to the screen as often as the user desires. The message is set via the environment variable `msg` and the number of repetitions via `reps`. Notice how we set defaults of 10 and "Hello." should `getenv` return `NULL` (typically meaning that the environment variable is unset).

Example 1-2. Environment variables provide a quick way to tweak details of a program (getenv.c)

```
#include <stdlib.h> //getenv, atoi
#include <stdio.h>  //printf

int main(){
    char *repstext = getenv("reps");
    int reps = repstext ? atoi(repstext) : 10;

    char *msg = getenv("msg");
    if (!msg) msg = "Hello.";

    for (int i=0; i< reps; i++)
        printf("%s\n", msg);
}
```

As previously, we can export a variable for just one line, which makes sending a variable to the program still more convenient. Usage:

```
reps=10 msg="Ha" ./getenv
msg="Ha" ./getenv
reps=20 msg=" " ./getenv
```

You might find this to be odd—the inputs to a program should come *after* the program name, darn it—but the oddness aside, you can see that it took little setup within the program itself, and we get to have named parameters on the command line almost for free.

When your program is a little further along, you can take the time to set up `getopt` to set input arguments the usual way.

`make` also offers several built-in variables. Here are the (POSIX-standard) ones that you will need to read the following rules:

`$@`
: The full target filename. By *target*, I mean the file that needs to be built, such as a *.o* file being compiled from a *.c* file or a program made by linking *.o* files.

`$*`
: The target file with the suffix cut off. So if the target is *prog.o*, `$*` is *prog*, and `$*.c` would become *prog.c*.

`$<`
: The name of the file that caused this target to get triggered and made. If we are making *prog.o*, it is probably because *prog.c* has recently been modified, so `$<` is *prog.c*.

The Rules

Now, let us focus on the procedures the makefile will execute, and then get to how the variables influence that.

Setting the variables aside, segments of the makefile have the form:

```
target: dependencies
        script
```

If the target gets called, via the command `make target`, then the dependencies are checked. If the target is a file, the dependencies are all files, and the target is newer than the dependencies, then the file is up-to-date and there's nothing to do. Otherwise, the processing of the target gets put on hold, the dependencies are run or generated, probably via another target, and when the dependency scripts are all finished, the target's script gets executed.

For example, before this was a book, it was a series of tips posted to a blog (at *http://modelingwithdata.org*). Every blog post had an HTML and PDF version, all generated via LaTeX. I'm omitting a lot of details for the sake of a simple example (like the many options for `latex2html`), but here's the sort of makefile one could write for the process.

> If you are copying any of these makefile snippets from a version on your screen or on paper to a file named *makefile*, don't forget that the whitespace at the head of each line must be a tab, not spaces. Blame POSIX.

```
all: html doc publish

doc:
    pdflatex $(f).tex

html:
    latex -interaction batchmode $(f)
    latex2html $(f).tex

publish:
    scp $(f).pdf $(Blogserver)
```

I set `f` on the command line via a command like `export f=tip-make`. When I then type `make` on the command line, the first target, `all`, gets checked. That is, the command `make` by itself is equivalent to `make` ***`first_target`***. That depends on `html`, `doc`, and `publish`, so those targets get called in sequence. If I know it's not yet ready to copy out to the world, then I can call `make html doc` and do only those steps.

In the simple makefile from earlier, we had only one target/dependency/script group. For example:

```
P=domath
OBJECTS=addition.o subtraction.o

$(P): $(OBJECTS)
```

This follows a sequence of dependencies and scripts similar to what my blogging makefile did, but the scripts are implicit. Here, `P=domath` is the program to be compiled, and it depends on the object files *addition.o* and *subtraction.o*. Because *addition.o* is not listed as a target, `make` uses an implicit rule, listed below, to compile from the *.c* to the *.o* file. Then it does the same for *subtraction.o* and *domath.o* (because GNU `make` implicitly assumes that `domath` depends on *domath.o* given the setup here). Once all the objects are built, we have no script to build the `$(P)` target, so GNU `make` fills in its default script for linking *.o* files into an executable.

POSIX-standard `make` has a specific recipe for compiling a *.o* object file from a *.c* source code file:

```
$(CC) $(CFLAGS) $(LDFLAGS) -o $@ $*.c
```

The `$(CC)` variable represents your C compiler; The POSIX standard specifies a default of `CC=c99`, but current editions of GNU `make` set `CC=cc`, which is typically a link to `gcc`. In the minimal makefile at the head of this segment, `$(CC)` is explicitly set to `c99`, `$(CFLAGS)` is set to the list of flags earlier, and `$(LDFLAGS)` is unset and therefore replaced with nothing. So if make determines that it needs to produce *your_program.o*, then this is the command that will be run, given that makefile:

```
c99 -g -Wall -O3 -o your_program.o your_program.c
```

When GNU make decides that you have an executable program to build from object files, it uses this recipe:

```
$(CC) $(LDFLAGS) first.o second.o $(LDLIBS)
```

Recall that order matters in the linker, so we will need two linker variables. In the previous example, we needed:

```
cc specific.o -lbroad -lgeneral
```

as the relevant part of the linking command. Comparing the correct compilation command to the recipe, we see that we need to set `LDLIBS=-lbroad -lgeneral`. If we had set `LDFLAGS=-lbroad -lgeneral`, then the recipe would produce `cc -lbroad -lgeneral specific.o`, which is likely to fail. Notice that `LDFLAGS` also appears in the recipe for compilation from *.c* to *.o* files.

> If you'd like to see the full list of default rules and variables built in to your edition of make, try:
>
> ```
> make -p > default_rules
> ```

So, that's the game: find the right variables and set them in the makefile. You still have to do the research as to what the correct flags are, but at least you can write them down in the makefile and never think about them again.

> **Your Turn:** Modify your makefile to compile *erf.c*.

If you use an IDE, or CMAKE, or any of the other alternatives to POSIX-standard make, you're going to be playing the same find-the-variables game. I'm going to continue discussing the preceding minimal makefile, and you should have no problem finding the corresponding variables in your IDE.

- The `CFLAGS` variable is an ingrained custom, but the variable that you'll need to set for the linker changes from system to system. Even `LDLIBS` isn't POSIX-standard, but is what GNU make uses.
- The `CFLAGS` and `LDLIBS` variables are where we're going to hook all the compiler flags locating and identifying libraries. If you have pkg-config, put the backticked calls here. For example, the makefile on my system, where I use Apophenia and GLib for just about everything, looks like:

```
CFLAGS=`pkg-config --cflags apophenia glib-2.0` -g -Wall -std=gnu11 -O3
LDLIBS=`pkg-config --libs apophenia glib-2.0`
```

Or, specify the `-I`, `-L`, and `-l` flags manually, like:

```
CFLAGS=-I/home/b/root/include -g -Wall -O3
LDLIBS=-L/home/b/root/lib -lweirdlib
```

- After you add a library and its locations to the `LIBS` and `CFLAGS` lines and you know it works on your system, there is little reason to ever remove it. Do you really care that the final executable might be 10 kilobytes larger than if you customized a new makefile for every program? That means you can write one makefile summarizing where all the libraries are on your system and copy it from project to project without any rewriting.
- If you have a second (or more) C file, add ***second*.o *third*.o**, and so on to the `OBJECTS` line (no commas, just spaces between names) in the makefile at the head of this section. `make` will use that to determine which files to build and which recipes to run.
- If you have a program that is one *.c* file, you may not need a makefile at all. In a directory with no makefile and *erf.c* from earlier, try using your shell to:

```
export CFLAGS='-g -Wall -O3 -std=gnu11'
export LDLIBS='-lm'
make erf
```

and watch `make` use its knowledge of C compilation to do the rest.

What Are the Linker Flags for Building a Shared Library?

To tell you the truth, I have no idea. It's different across operating systems, both by type and by year, and even on one system the rules are often hairy.

Instead, *Libtool*, one of the tools introduced in Chapter 3, knows every detail of every shared library generation procedure on every operating system. I recommend investing your time getting to know Autotools and thus solve the shared object compilation problem once and for all, rather than investing that time in learning the right compiler flags and linking procedure for every target system.

Using Libraries from Source

So far, the story has been about compiling your own code using `make`. Compiling code provided by others is often a different story.

Let's try a sample package. The GNU Scientific Library includes a host of numeric computation routines.

The GSL is packaged via *Autotools*, a set of tools that will prepare a library for use on any machine, by testing for every known quirk and implementing the appropriate workaround. Autotools is central to how code is distributed in the present day, and

"Packaging Your Code with Autotools" on page 64 will go into detail about how you can package your own programs and libraries with it. But for now, we can start off as users of the system and enjoy the ease of quickly installing useful libraries.

The GSL is often provided in precompiled form via package manager, but for the purposes of going through the steps of compilation, here's how to get the GSL as source code and set it up, assuming you have root privileges on your computer.

```
wget ftp://ftp.gnu.org/gnu/gsl/gsl-1.15.tar.gz ❶
tar xvzf gsl-*gz                               ❷
cd gsl-1.15
./configure                                    ❸
make
sudo make install                              ❹
```

❶ Download the zipped archive. Ask your package manager to install `wget` if you don't have it, or type this URL into your browser.

❷ Unzip the archive: `x`=extract, `v`=verbose, `z`=unzip via `gzip`, `f`=filename.

❸ Determine the quirks of your machine. If the `configure` step gives you an error about a missing element, then use your package manager to obtain it and run `configure` again.

❹ Install to the right location—if you have permissions.

If you are trying this at home, then you probably have root privileges, and this will work fine. If you are at work and using a shared server, the odds are low that you have superuser rights, so you won't be able to provide the password needed to do the last step in the script as superuser. In that case, hold your breath until the next section.

Did it install? Example 1-3 provides a short program to try finding that 95% confidence interval using GSL functions; try it and see if you can get it linked and running:

Example 1-3. Redoing Example 1-1 with the GSL (gsl_erf.c)

```
#include <gsl/gsl_cdf.h>
#include <stdio.h>

int main(){
    double bottom_tail = gsl_cdf_gaussian_P(-1.96, 1);
    printf("Area between [-1.96, 1.96]: %g\n", 1-2*bottom_tail);
}
```

To use the library you just installed, you'll need to modify the makefile of your library-using program to specify the libraries and their locations.

Depending on whether you have `pkg-config` on hand, you can do one of:

```
LDLIBS=`pkg-config --libs gsl`
#or
LDLIBS=-lgsl -lgslcblas -lm
```

If it didn't install in a standard location and `pkg-config` is not available, you will need to add paths to the heads of these definitions, such as `CFLAGS=-I/usr/local/include` and `LDLIBS=-L/usr/local/lib -Wl,-R/usr/local/lib`.

Using Libraries from Source (Even if Your Sysadmin Doesn't Want You To)

You may have noticed the caveats in the last section about how you have to have root privileges to install to the usual locations on a POSIX system. But you may not have root access if you are using a shared computer at work, or if you have an especially controlling significant other.

Then you have to go underground and make your own private root directory.

The first step is to simply create the directory:

```
mkdir ~/root
```

I already have a *~/tech* directory where I keep all my technical logistics, manuals, and code snippets, so I made a *~/tech/root* directory. The name doesn't matter, but I'll use *~/root* as the dummy directory here.

> Your shell replaces the tilde with the full path to your home directory, saving you a lot of typing. The POSIX standard only requires that the shell do this at the beginning of a word or just after a colon (which you'd need for a path-type variable), but most shells expand mid-word tildes as well. Other programs, like `make`, may or may not recognize the tilde as your home directory.

The second step is to add the right part of your new root system to all the relevant paths. For programs, that's the `PATH` in your *.bashrc* (or equivalent):

```
PATH=~/root/bin:$PATH
```

By putting the *bin* subdirectory of your new directory before the original `PATH`, it will be searched first, and your copy of any programs will be found first. Thus, you can substitute in your preferred version of any programs that are already in the standard shared directories of the system.

For libraries you will fold into your C programs, note the new paths to search in the preceding makefile:

```
LDLIBS=-L/home/your_home/root/lib  (plus the other flags, like -lgsl -lm ...)
CFLAGS=-I/home/your_home/root/include  (plus -g -Wall -O3 ...)
```

Now that you have a local root, you can use it for other systems as well, such as Java's `CLASSPATH`.

The last step is to install programs in your new root. If you have the source code and it uses Autotools, all you have to do is add `--prefix=$HOME/root` in the right place:

```
./configure --prefix=$HOME/root; make; make install
```

You didn't need `sudo` to do the install step, because everything is now in territory you control.

Because the programs and libraries are in your home directory and have no more permissions than you do, your sysadmin can't complain that they are an imposition on others. If your sysadmin complains anyway, then, as sad as it may be, it might be time to break up.

The Manual

I suppose there was once a time when the manual was actually a printed document, but in the present day, it exists in the form of the `man` command. For example, use `man strtok` to read about the `strtok` function, typically including what header to include, the input arguments, and basic notes about its usage. The manual pages tend to keep it simple, sometimes lack examples, and assume the reader already has a basic idea of how the function works. If you need a more basic tutorial, your favorite Internet search engine can probably offer several (and in the case of `strtok`, see the section "A Pæan to strtok" on page 152). The GNU C library manual, also easy to find online, is very readable and written for beginners.

- If you can't recall the name of what you need to look up, every manual page has a one-line summary, and `man -k` *`searchterm`* will search those summaries. Many systems also have the `apropos` command, which is similar to `man -k` but adds some features. For extra refinement, I often find myself piping the output of `apropos` through `grep`.
- The manual is divided into sections. Section 1 is command-line commands, and section 3 is library functions. If your system has a command-line program named `printf`, then `man printf` will show its documentation, and `man 3 printf` will show the documentation for the C library's `printf` command.
- For more on the usage of the `man` command (such as the full list of sections), try `man man`.
- Your text editor or IDE may have a means of calling up manpages quickly. For example, vi users can put the cursor on a word and use *`K`* to open that word's manpage.

Compiling C Programs via Here Document

At this point, you have seen the pattern of compilation a few times:

1. Set a variable expressing compiler flags.
2. Set a variable expressing linker flags, including a `-l` flag for every library that you use.
3. Use `make` or your IDE's recipes to convert the variables into full compile and link commands.

The remainder of this chapter will do all this one last time, using an absolutely minimal setup: just the shell. If you are a kinetic learner who picked up scripting languages by cutting and pasting snippets of code into the interpreter, you'll be able to do the same with pasting C code onto your command prompt.

Include Header Files from the Command Line

The gcc and Clang have a convenient flag for including headers. For example:

```
gcc -include stdio.h
```

is equivalent to putting

```
#include <stdio.h>
```

at the head of your C file; similarly for `clang -include stdio.h`.

By adding that to our compiler invocation, we can finally write *hello.c* as the one line of code it should be:

```
int main(){ printf("Hello, world.\n"); }
```

which compiles fine via:

```
gcc -include stdio.h hello.c -o hi --std=gnu99 -Wall -g -O3
```

or shell commands like:

```
export CFLAGS='-g -Wall -include stdio.h'
export CC=c99
make hello
```

This tip about `-include` is compiler-specific and involves moving information from the code to the compilation instructions. If you think this is bad form, well, skip this tip.

The Unified Header

There was once a time when compilers took several seconds or minutes to compile even relatively simple programs, so there was human-noticeable benefit to reducing the work the compiler has to do. My current copies of *stdio.h* and *stdlib.h* are each about 1,000 lines long (try `wc -l /usr/include/stdlib.h`) and *time.h* another 400, meaning that this seven-line program:

```
#include <time.h>
#include <stdio.h>
#include <stdlib.h>
int main(){
    srand(time(NULL));       // Initialize RNG seed.
    printf("%i\n", rand());  // Make one draw.
}
```

is actually a ~2,400-line program.

Your compiler doesn't think 2,400 lines is a big deal anymore, and this compiles in under a second. So why are we spending time picking out just the right headers for a given program?

You will see examples using Glib later, with an `#include <glib.h>` at the top. That header includes 74 sub-headers, covering all the subsections of the Glib library. This is good user interface design by the Glib team, because those of us who don't want to spend time picking just the right subsections of the library can speed through the header paperwork in one line, and those who want detailed control can pick and choose exactly the headers they need. It would be nice if the C standard library had a quick-and-easy header like this; it wasn't the custom in the 1980s, but it's easy to make one.

Your Turn: Write yourself a single header, let us call it *allheads.h*, and throw in every header you've ever used, so it'll look something like:

```
#include <math.h>
#include <time.h>
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <gsl/gsl_rng.h>
```

I can't tell you exactly what it'll look like, because I don't know exactly what you use day to day.

Now that you have this aggregate header, you can just throw one:

```
#include <allheads.h>
```

on top of every file you write, and you're done with thinking about headers. Sure, it will expand to perhaps 10,000 lines of extra code, much of it not relevant to the program at hand. But you won't notice, and unused declarations don't change the final executable.

Once you have a unified header, even a line like `#include <allheads.h>` is extraneous if you are a gcc or Clang user, because you can instead add `-include allheads.h` to your `CFLAGS` and never think about which out-of-project headers to include again.

Headers also serve the purpose of limiting scope, but this is generally more important for functions and structures you wrote than those in the libraries. The purpose of limiting scope is not to keep the namespace small so the computer won't overheat; it is to reduce cognitive load for you, the programmer. I'm guessing you're not even familiar with most of the functions to be found in the libraries you are using, and if you don't know about them, they can't possibly be taking up cognitive load. Other languages don't even make the distinction and heap on the keywords, like the R project, which has 752 words internally defined at startup.

Here Documents

Here documents are a feature of POSIX-standard shells that you can use for C, Python, Perl, or whatever else, and they will make this book much more useful and fun. Also, if you want to have a multilingual script, here documents are an easy way to do it. Do some parsing in Perl, do the math in C, then have Gnuplot produce the pretty pictures, and have it all in one text file.

Here's a Python example. Normally, you'd tell Python to run a script via:

```
python your_script.py
```

Python lets you give the filename `-` to use stdin as the input file:

```
echo "print 'hi.'" | python -
```

You could, in theory, put some lengthy scripts on the command line via `echo`, but you'll quickly see that there are a lot of small, undesired parsings going on—you might need `\"hi\"` instead of `"hi"`, for example.

Thus, the *here document*, which does no parsing at all. Try this:

```
python - <<"XXXX"
lines=2
print "\nThis script is %i lines long.\n" %(lines,)
XXXX
```

- Here documents are a standard shell feature, so they should work on any POSIX system.
- The `"XXXX"` is any string you'd like; `"EOF"` is also popular, and `"-----"` looks good as long as you get the dash count to match at top and bottom. When the shell sees your chosen string alone on a line, it will stop sending the script to the program's stdin. That's all the parsing that happens.
- There's also a variant that begins with `<<-`. This variant removes all tabs at the head of every line, so you can put a here document in an indented section of a shell script without breaking the flow of indentation. Of course, this would be disastrous for a Python here document.
- As another variant, there's a difference between `<<"XXXX"` and `<<XXXX`. In the second version, the shell parses certain elements, which means you can have the shell insert the value of `$shell_variables` for you. The shell relies heavily on the `$` for its variables and other expansions; the `$` is one of the few characters on a standard

keyboard that has no special meaning to C. It's as if the people who wrote Unix designed it from the ground up to make it easy to write shell scripts that produce C code....

Compiling from stdin

OK, back to C: we can use here documents to compile C code pasted onto the command line via gcc or Clang, or have a few lines of C in a multilingual script.

We're not going to use the makefile, so we need a single compilation command. To make life less painful, let us alias it. Paste this onto your command line, or add it to your *.bashrc*, *.zshrc*, or wherever applicable:

```
go_libs="-lm"
go_flags="-g -Wall -include allheads.h -O3"
alias go_c="c99 -xc - $go_libs $go_flags"
```

where ***allheads.h*** is the aggregate header you'd put together earlier. Using the `-include` flag means one less thing to think about when writing the C code, and I've found that bash's history gets wonky when there are #s in the C code.

On the compilation line, you'll recognize the `-` to mean that instead of reading from a named file, use stdin. The `-xc` identifies this as C code, because *gcc* stands for GNU Compiler Collection, not GNU C Compiler, and with no input filename ending in `.c` to tip it off, we have to be clear that this is not Java, Fortran, Objective C, Ada, or C++ (and similarly for Clang, even though its name is meant to invoke *C language*).

Whatever you did to customize the `LDLIBS` and `CFLAGS` in your makefile, do here.

Now we're sailing, and can compile C code on the command line:

```
go_c << '---'
int main(){printf("Hello from the command line.\n");}
---
./a.out
```

We can use a here document to paste short C programs onto the command line, and write little test programs without hassle. Not only do you not need a makefile, you don't even need an input file.

Don't expect this sort of thing to be your primary mode of working. But cutting and pasting code snippets onto the command line can be fun, and being able to have a single step in C within a longer shell script is pretty fabulous.

CHAPTER 2

Debug, Test, Document

> Crawling
> Over your window
> You think I'm confused,
> I'm waiting ...
> To complete my current ruse.
>
> —Wire, "I Am the Fly"

This chapter will cover tools for debugging, testing, and documenting your writing—the essentials to take your writing from a potentially useful set of scripts to something you and others can rely on.

Because C gives you the freedom to do idiotic things with memory, debugging means both the quotidian problem of checking logic (with gdb) and the more technical problem of checking for memory misallocations and leaks (with Valgrind). On the documentation side, this chapter covers one tool at the interface level (Doxygen) and another that helps you document and develop every step of the program (CWEB).

The chapter also gives a quick introduction to the *test harness*, which will allow you to quickly write lots of tests for your code, and concludes with some considerations about error reporting and handling input or user errors.

Using a Debugger

The first tip about the debugger is simple and brief:

Use a debugger, always.

Some of you will find this to be not much of a tip, because who possibly wouldn't use a debugger? But many users come from languages that throw up a backtrace at the first sign of trouble, and didn't get to the part where their C textbook introduces the debugger (it is often in the *other topics* segment, somewhere around Chapter 15). So now we're all on the same page: the debugger exists.

I've found other people who worry that bugs typically come from broad errors of understanding, while the debugger only gives information at the low level of variable states and backtraces. Indeed, after you pinpoint a bug using the debugger, it is worth taking the time to consider what underlying problem and failure of understanding you have just discovered, and whether it replicates itself elsewhere in your code. Some death certificates include an aggressive inquiry into the cause of death: *Subject died as a result of ______, as a result of ______, as a result of ______, as a result of ______, as a result of* ______. After the debugger has helped you understand your code better, you can encapsulate your understanding in more unit tests.

About that *always*: there is virtually no cost to running a program under the debugger. Nor is the debugger just something to pull out when something breaks. Linus Torvalds explains: "I use gdb all the time ... as a disassembler on steroids that you can program."[1] It's great being able to pause anywhere, increase the verbosity level with a quick `print verbose++`, force out of a `for (int i=0; i<10; i++)` loop via `print i=100` and `continue`, or test a function by throwing a series of test inputs at it. The fans of interactive languages are right that interacting with your code improves the development process all the way along; they just never got to the debugging chapter in the C textbook, and so never realized that all of those interactive habits apply to C as well.

Whatever your intent, you will need to have human-readable debugging information (i.e., names for variables and functions) compiled into the program for any debugger to be at all useful. To include debugging symbols, use the `-g` flag in the compiler switches (i.e., your `CFLAGS` variable). Reasons to not use the `-g` flag are rare indeed—it doesn't slow down your program, and adding a kilobyte to your executable is irrelevant for most situations.

I'm only covering GDB, because on most POSIX systems, it's the only game in town.[2] You might be working from an IDE or other visual frontend that runs your program under GDB every time you click run. I'm going to show you commands from GDB's command line, and you should have no trouble translating the basics here into mouse clicks on your screen. Depending on the frontend, you might be able to use the macros defined in *.gdbinit*.

When working with GDB directly, you will probably need to have a text editor in another window or terminal displaying your code. The simple GDB/editor combination provides many of the conveniences of an IDE, and may be all you need.

1. Torvalds writing to a colleague on 6 September 2000.

2. By the way, a C++ compiler engages in what is known as *mangling* of the code. In GDB, it shows, and I've always found debugging C++ code from the GDB prompt to be painful. Because C code compiles without mangling, I find GDB to be much more usable for C, and having a GUI that unmangles the names is not necessary.

The Stack of Frames

To start your program, you ask the system to execute a function called `main`. The computer generates a *frame* into which information about the function is placed, such as the inputs (which for `main` are customarily named `argc` and `argv`) and the variables that are created by the function.

Let us say that, in the course of its execution, `main` calls another function, `get_agents`. Then execution of `main` stops and a new frame is generated for `get_agents`, holding its various details and variables. Perhaps `get_agents` calls another function, `agent_address`, at which point we have a growing *stack* of frames. Eventually, `agent_address` will finish execution, at which point it pops off the stack and `get_agents` resumes.

If your question is just "Where am I?," the easy answer is the line number in the code, and sometimes this is all you need. But more often, your question is "How did I get here?," and the answer, the *backtrace*, is a listing of the stack of frames. Here's a sample backtrace:

```
#0  0x00000000000413bbe in agent_address (agent_number=312) at addresses.c:100
#1  0x00000000004148b6 in get_agents () at addresses.c:163
#2  0x0000000000404f9b in main (argc=1, argv=0x7fffffffe278) at addresses.c:227
```

The top of the stack is frame 0, down to `main`, which is currently frame 2 (but that will change as the stack grows and shrinks). The hexadecimal after the frame number gives the locations to which execution will return when the called function returns; I always took them as visual noise to ignore. After that, we have the function name, its inputs (which in the case of `argv` is again a hex address), and the line in the source code where execution is happening.

If you found that the house listed in `agent_address` is clearly wrong, then maybe the `agent_number` input is somehow wrong, in which case you have to jump to frame 1 and ask what the state of `get_agents` was that set up the strange state of `agent_address`. Much of the skill of interrogating a program is in jumping around in the stack and tracing causes and effects from one function's frame to the next.

You can experiment in GDB with any program that has at least one function beyond `main` (so you have a nontrivial stack), but if you don't have anything immediately on hand, try the *New York Times* headline downloader from the section "libxml and cURL" on page 247. On the shell command line, given an executable named `nyt_feed`, start GDB via `gdb nyt_feed`. You will then be at the GDB command line, where you can try any of a number of things:

- Pause your program at a certain point.
  - `break` ***`get_rss`*** or `break` ***`nyt_feeds.c:105`***, or if you are already in *nyt_feeds.c*, `break` ***`105`***. This will stop the program just before line 105 is executed.
  - List breakpoints with `info break`.

- Turn one off with, e.g., `disable 3` (where *3* is the breakpoint number you got from `info break`), and reenable it later with `enable 3`. If you have a lot of breakpoints set, `disable` by itself turns them all off, and then you can enable the one or two that you need at the moment.
- Delete a breakpoint entirely with `del 3`.
- Of course, you can't stop until you start; run your program with `run`, and if it needs command-line arguments, put them here: `run arg1 arg2`.

• Get the current value of any variables that exist in that function.
  - For one variable like *url*, use `print url`, or more simply, `p url`.
  - For all the function inputs: `info args`; for all the local variables: `info local`.
  - Use `display url` to print the value of *url* every time GDB stops, so you can watch it transform as you step line-by-line through a routine. Displayed elements will be numbered; use `undisplay 1` to turn off the display of item *1*.

• Jump to a parent function and check variable values there. Get the list of frames on the stack via `backtrace` or `bt`, then use `frame 2` or `f 2` to jump to frame 2.

• Step past the point where you paused, one line of code at a time. Typically one of `snuc`, but several options exist:
  - `s`: step one line, even if that means entering another function.
  - `n`: next line, but do not enter subfunctions, and possibly back up to the head of a loop.
  - `u`: until the next line forward from this (so let an already-visited loop run through until forward progress).
  - `c`: continue until the next breakpoint or the end of the program.
  - To return from the current function immediately, use `ret` (perhaps with a return value, like `ret 0`).
  - To make a more global move, `j` will jump to whatever line you please (within reason).
  - If you need to get your bearings from the GDB command prompt, you might need `list` (or just `l`) to get a printout of the 10 lines around the line you are currently on.
  - Just hitting Enter will repeat the last command, which makes stepping easier, or after `l` will list the next 10 lines after those you just saw.

GDB Variables

This segment covers some useful elements of GDB that will help you look at your data with as little cognitive effort as possible. All of the commands to follow go on the GDB command line; IDE debuggers based on GDB often provide a means of hooking in to these facilities as well.

Here's a sample program that does nothing, but that you can type in for the sake of having a variable to interrogate. Because it is such a do-nothing program, be sure to set the compiler's optimization flag to `-O0`, or else `x` will disappear entirely.

```
int main(){
    int x[20] = {};
    x[0] = 3;
}
```

Here's tip zero: the `@` shows you a sequence of elements in an array. For example, if you break on line 3 of this do-nothing program, you can display the first dozen elements of the array with:

```
p *x@12
```

Note the star at the head of the expression; without it, we'd get a sequence of a dozen hexadecimal addresses.

The next tip will only be new to those of you who didn't read the GDB manual [Stallman 2002], which is probably all of you. You can generate convenience variables, to save yourself some typing. For example, if you want to inspect an element deep within a hierarchy of structures, you can do something like:

```
set $vd = my_model->dataset->vector->data
p *$vd@10
```

That first line generated the convenience variable to substitute for the lengthy path. Following the lead of the shell, a dollar sign indicates a variable. Unlike the shell, you need `set` and a dollar sign on the variable's first use. The second line demonstrates a simple use. We don't save much typing here, but if you suspect a variable of guilty behavior, giving it a short name makes it easier to give it a thorough interrogation.

These aren't just names; they're real variables that you can modify. After breaking at line three or four of the do-nothing program, try:

```
set $ptr=&x[3]
p *$ptr = 8
p *($ptr++)  #print the pointee, and step forward one
```

The second line actually changes the value in the given location. On the third line, adding one to a pointer steps forward to the next item in the list (as per "All the Pointer Arithmetic You Need to Know" on page 111). Thus, after the third line, `$ptr` is now pointing to `x[4]`.

That last form is especially useful because hitting the Enter key without any input repeats the last command. Because the pointer stepped forward, you'll get a new next value every time you hit Enter, until you get the gist of the array. This is also useful should you find yourself dealing with a linked list. Pretend we have a function that displays an element of the linked list and sets `$list` equal to the given element, and we have the head of the list at `list_head`. Then:

```
p $list=list_head
show_structure $list->next
```

and leaning on the Enter key will step through the list. Later, we'll make that imaginary function to display a data structure a reality.

But first, here's one more trick about these `$` variables. Let me cut and paste a few lines of interaction with a debugger in the other screen:

```
(gdb) p x+3
$17 = (int *) 0xbffff9a4
```

You probably don't even look at it anymore, but notice how the output to the print statement starts with `$17`. Indeed, every output is assigned a variable name, which we can use like any other:

```
(gdb) p *$17
$18 = 8
(gdb) p *$17+3
$19 = 11
```

To be even more brief, a lone `$` is a shorthand variable assigned to the last output. So if you get a hex address when you thought you would get the value at that address, just put `p *$` on the next line to get the value. With this, the above steps could have been:

```
(gdb) p x+3
$20 = (int *) 0xbffff9a4
(gdb) p *$
$21 = 8
(gdb) p $+3
$22 = 11
```

Print Your Structures

GDB lets you define simple macros, which are especially useful for displaying nontrivial data structures—which is most of the work one does in a debugger. Even a simple 2D array hurts your eyes when it's displayed as a long line of numbers. In a perfect world, every major structure you deal with will have a debugger command associated to quickly view that structure in the manner(s) most useful to you.

The facility is rather primitive, but you probably already wrote a C-side function that prints any complex structures you might have to deal with, so the macro can simply call that function with a few keystrokes.

You can't use any of your C preprocessor macros at the GDB prompt, because they were substituted out long before the debugger saw any of your code. So if you have a valuable macro in your code, you may have to reimplement it in GDB as well.

Here is a function you can try by putting a breakpoint about halfway through the `parse` function in "libxml and cURL" on page 247, at which point you'll have a `doc` structure representing an XML tree. Put these macros in your *.gdbinit*.

```
define pxml
    p xmlElemDump(stdout, $arg0, xmlDocGetRootElement($arg0))
end
document pxml
```

```
    Print the tree of an already opened XML document (i.e., an xmlDocPtr) to the
    screen. This will probably be several pages long.
    E.g., given: xmlDocPtr doc = xmlParseFile(infile);
    use: pxml doc
    end
```

Notice how the documentation follows right after the function itself; view it via `help pxml` or `help user-defined`. The macro itself just saves some typing, but because the primary activity in the debugger is looking at data, those little things add up.

GLib has a linked list structure, so we should have a linked list viewer. Example 2-1 implements it via two user-visible macros (`phead` to view the head of the list, then `pnext` to step forward) and one macro the user should never have to call (`plistdata`, to remove redundancy between `phead` and `pnext`).

Example 2-1. A set of macros to easily display a linked list in GDB—about the most elaborate debugging macro you'll ever need (gdb_showlist)

```
define phead
    set $ptr = $arg1
    plistdata $arg0
end
document phead
Print the first element of a list. E.g., given the declaration
    Glist *datalist;
    g_list_add(datalist, "Hello");
view the list with something like
gdb> phead char datalist
gdb> pnext char
gdb> pnext char
This macro defines $ptr as the current pointed-to list struct,
and $pdata as the data in that list element.
end

define pnext
    set $ptr = $ptr->next
    plistdata $arg0
end
document pnext
You need to call phead first; that will set $ptr.
This macro will step forward in the list, then show the value at
that next element. Give the type of the list data as the only argument.

This macro defines $ptr as the current pointed-to list struct, and
$pdata as the data in that list element.
end

define plistdata
    if $ptr
        set $pdata = $ptr->data
    else
        set $pdata= 0
    end
```

```
    if $pdata
        p ($arg0*)$pdata
    else
        p "NULL"
    end
end
document plistdata
This is intended to be used by phead and pnext, q.v. It sets $pdata and prints its value.
end
```

Example 2-2 offers some simple code that uses the `GList` to store `char*`s. You can break around line 8 or 9 and call the previous macros.

Example 2-2. Some sample code for trying debugging, or a lightning-quick intro to GLib linked lists (glist.c)

```c
#include <stdio.h>
#include <glib.h>

GList *list;

int main(){
    list = g_list_append(list, "a");
    list = g_list_append(list, "b");
    list = g_list_append(list, "c");

    for ( ; list!= NULL; list=list->next)
        printf("%s\n", (char*)list->data);
}
```

You can define functions to run before or after every use of a given command. For example:

```
define hook-print
echo <----\n
end

define hookpost-print
echo ---->\n
end
```

will print cute brackets before and after anything you print. The most exciting hook is `hook-stop`. The `display` command will print the value of any expression every time the program stops, but if you want to make use of a macro or other GDB command at every stop, redefine `hook-stop`:

```
define hook-stop
pxml suspect_tree
end
```

When you are done with your suspect, redefine `hook-stop` to be nothing:

```
define hook-stop
end
```

Your Turn: GDB macros can also include a `while` that looks much like the `if`s in Example 2-2 (start with a line like `while $ptr` and conclude with `end`). Use this to write a macro to print an entire list at once.

Profiling

It doesn't matter how fast your program is: you will still want it faster. In most languages, the first piece of advice is to rewrite everything in C, but you're already writing in C. The next step is to find the functions that are taking up the most time and therefore would provide the most payoff to more optimization efforts.

First, add the `-pg` flag to `gcc`'s or `icc`'s `CFLAGS` (yes, this is compiler-specific; `gcc` will prep the program for `gprof`; Intel's compiler will prep the program for `prof`, and has a similar workflow to the gcc-specific details I give here). With this flag, your program will stop every few microseconds and note in which function it is currently working. The annotations get written in binary format to *gmon.out*.

Only the executable is profiled, not libraries that are linked to it. Therefore, if you need to profile a library as it runs a test program, you'll have to copy all of the library and program code into one place and recompile everything as one big executable.

After running your program, call `gprof` ***`your_program`*** `>` ***`profile`*** (or `prof …`), then open ***`profile`*** in your text editor to view a human-readable listing of functions, their calls, and what percentage of the program's time was spent in each function. You might be surprised by where the bottlenecks turn out to be.

Using Valgrind to Check for Errors

Most of our time spent debugging is spent finding the first point in the program where something looks wrong. Good code and a good system will find that point for you. That is, a good system fails fast.

C gets mixed scores on this. In some languages, a typo like `conut=15` would generate a new variable that has nothing to do with the `count` you meant to set; with C, it fails at the compilation step. On the other hand, C will let you assign to the 10th element of a 9-element array and then trundle along for a long time before you find out that there's garbage in what you thought was element 10.

Those memory mismanagement issues are a hassle, and so there are tools to confront them. Within these, Valgrind is a big winner. Get a copy via your package manager. Valgrind runs a virtual machine that keeps better tabs of memory than the real machine does, so it knows when you hit the 10th element in an array of 9 items.

Once you have a program compiled (with debugging symbols included via gcc's or Clang's `-g` flag, of course), run:

```
valgrind your_program
```

If you have an error, Valgrind will give you two backtraces that look a lot like the backtraces your debugger gives you. The first is where the misuse was first detected, and the second is Valgrind's best guess as to what line the misuse clashed with, such as where a double-freed block was first freed, or where the closest `malloc`ed block was allocated. The errors are often subtle, but having the exact line to focus on goes a long way toward finding the bug. Valgrind is under active development—programmers like nothing better than writing programming tools—so I'm amused to watch how much more informative the reports have gotten over time and only expect better in the future.

To give you an example of a Valgrind backtrace, I inserted an error in the code of Example 9-1 by doubling line 14, `free(cmd)`, thus causing the `cmd` pointer to be freed once on line 14 and again on line 15. Here's the backtrace I got:

```
Invalid free() / delete / delete[] / realloc()
   at 0x4A079AE: free (vg_replace_malloc.c:427)
   by 0x40084B: get_strings (sadstrings.c:15)
   by 0x40086B: main (sadstrings.c:19)
 Address 0x4c3b090 is 0 bytes inside a block of size 19 free'd
   at 0x4A079AE: free (vg_replace_malloc.c:427)
   by 0x40083F: get_strings (sadstrings.c:14)
   by 0x40086B: main (sadstrings.c:19)
```

The top frame in both backtraces is in the standard library code for freeing pointers, but we can be confident that the standard library is well debugged. Focusing on the part of the stack referring to code that I wrote, the backtrace points me to lines 14 and 15 of *sadstrings.c*, which are indeed the two calls to `free(cmd)` in my modified code.

You can also start the debugger at the first error, by running:

```
valgrind --db-attach=yes your_program
```

With this sort of startup, you'll get a line asking if you want to run the debugger on every detected error, and then you can check the value of the implicated variables as usual. At this point, we're back to having a program that fails on the first line where a problem is detected.

Valgrind also does memory leaks:

```
valgrind --leak-check=full your_program
```

This is typically slower, so you might not want to run it every time. When it finishes, you'll have a backtrace for where every leaked pointer was allocated.

A leak in a library function that could conceivably run a million times in the center of a user program's loop, or in a program that should have 100% runtime for months, will eventually cause potentially major problems for users. But it is easy to find programs broadly deemed to be reliable (on my machine, doxygen, git, TeX, vi, others) that Valgrind reports as definitely losing kilobytes. For such cases, we can adapt a certain cliché about trees falling in the woods: if a bug does not cause incorrect results or user-perceivable slowdowns, is it really a bug?

Unit Testing

Of course you're writing tests for your code. You're writing *unit tests* for the smaller components and *integration tests* to make sure that the components get along amicably. You may even be the sort of person who writes the unit tests first and then builds the program to pass the tests.

Now you've got the problem of keeping all those tests organized, which is where a *test harness* comes in. A test harness is a system that sets up a small environment for every test, runs the test, and reports whether the result is as expected. Like the debugger, I expect that some of you are wondering who it is that doesn't use a test harness, and to others, it's something you never really considered.

There are abundant choices. It's easy to write a macro or two to call each test function and compare its return value to the expected result, and more than enough authors have let that simple basis turn into yet another implementation of a full test harness. From [Page 2008]: "Microsoft's internal repository for shared tools includes more than 40 entries under *test harness*." For consistency with the rest of the book, I'll show you GLib's test harness, and because they are all so similar, and because I'm not going to go into so much detail that I'm effectively reading the GLib manual to you, what I cover here should carry over to other test harnesses as well.

A test harness has a few features that beat the typical homemade test macro:

- You need to test the failures. If a function is supposed to abort or exit with an error message, you need a facility to test that the program actually exited when you expected it to.
- Each test is kept separate, so you don't have to worry that test 3 affected the outcome to test 4. If you want to make sure the two procedures don't interact badly, run them in sequence as an integration test after running them separately.
- You probably need to build some data structures before you can run your tests. Setting up the scene for a test sometimes takes a good amount of work, so it would be nice to run several tests given the same setup.

Example 2-3 shows a few basic unit tests of the dictionary object from "Implementing a Dictionary" on page 210, implementing these three test harness features. It demonstrates how that last item largely dictates the flow of test harness use: a new struct type is defined at the beginning of the program, then there are functions for setting up and tearing down an instance of that struct type, and once we have all that in place it is easy to write several tests using the built environment.

The dictionary is a simple set of key-value pairs, so most of the testing consists of retrieving a value for a given key and making sure that it worked OK. Notice that a key of `NULL` is not acceptable, so we check that the program will halt if such a key gets sent in.

Example 2-3. A test of the dictionary from "Implementing a Dictionary" on page 210 (dict_test.c)

```
#include <glib.h>
#include "dict.h"

typedef struct {                                      ❶
    dictionary *dd;
} dfixture;

void dict_setup(dfixture *df, gconstpointer test_data){  ❷
    df->dd = dictionary_new();
    dictionary_add(df->dd, "key1", "val1");
    dictionary_add(df->dd, "key2", NULL);
}

void dict_teardown(dfixture *df, gconstpointer test_data){
    dictionary_free(df->dd);
}

void check_keys(dictionary const *d){                 ❸
    char *got_it = dictionary_find(d, "xx");
    g_assert(got_it == dictionary_not_found);
    got_it = dictionary_find(d, "key1");
    g_assert_cmpstr(got_it, ==, "val1");
    got_it = dictionary_find(d, "key2");
    g_assert_cmpstr(got_it, ==, NULL);
}

void test_new(dfixture *df, gconstpointer ignored){
    check_keys(df->dd);
}

void test_copy(dfixture *df, gconstpointer ignored){
    dictionary *cp = dictionary_copy(df->dd);
    check_keys(cp);
    dictionary_free(cp);
}

void test_failure(){                                  ❹
    if (g_test_trap_fork(0, G_TEST_TRAP_SILENCE_STDOUT | G_TEST_TRAP_SILENCE_STDERR)){
        dictionary *dd = dictionary_new();
        dictionary_add(dd, NULL, "blank");
    }
    g_test_trap_assert_failed();
    g_test_trap_assert_stderr("NULL is not a valid key.\n");
}

int main(int argc, char **argv){
    g_test_init(&argc, &argv, NULL);
    g_test_add ("/set1/new test", dfixture, NULL,     ❺
                              dict_setup, test_new, dict_teardown);
    g_test_add ("/set1/copy test", dfixture, NULL,
                              dict_setup, test_copy, dict_teardown);
    g_test_add_func ("/set2/fail test", test_failure); ❻
    return g_test_run();
}
```

❶ The elements used in a set of tests is called a *fixture*. GLib requires that each fixture be a struct, so we create a throwaway struct to be passed from the setup to the test to the teardown.

❷ Here are the setup and teardown scripts that create the data structure to be used for a number of tests.

❸ Now that the setup and teardown functions are defined, the tests themselves are just a sequence of simple operations on the structures in the fixture and assertions that the operations went according to plan. The GLib test harness provides some extra assertion macros, like the string comparison macro used here.

❹ GLib tests for failure via the POSIX `fork` system call (which means that this won't run on Windows without a POSIX subsystem). The `fork` call generates a new program that runs the contents of the `if` statement, which should fail and call `abort`. This program watches for the forked version and checks that it failed and that the right message was written to `stderr`.

❺ Tests are organized into sets via path-like strings. The `NULL` argument could be a pointer to a data set to be used by the test, but not built/torn down by the system. Notice how both the new and copy tests use the same setup and teardown.

❻ If you don't have setup/teardown to do before/after the call, use this simpler form to run the test.

Using a Program as a Library

The only difference between a function library and a program is that a program includes a `main` function that indicates where execution should start.

Now and then I have a file that does one thing that's not quite big enough to merit being set up as a standalone shared library. It still needs tests, and I can put them in the same file as everything else, via a preprocessor condition. In the following snippet, if `Test_operations` is defined (via the various methods discussed later), then the snippet is a program that runs the tests; if `Test_operations` is not defined (the usual case), then the snippet is compiled without `main` and so is a library to be used by other programs.

```
int operation_one(){
    ...
}

int operation_two(){
    ...
}

#ifdef Test_operations

    void optest(){
        ...
    }
```

```
    int main(int argc, char **argv){
        g_test_init(&argc, &argv, NULL);
        g_test_add_func ("/set/a test", test_failure);
    }

#endif
```

There are a few ways to define the `Test_operations` variable. In with the usual flags, probably in your makefile, add:

```
CFLAGS=-DTest_operations
```

The `-D` flag is the POSIX-standard compiler flag that is equivalent to putting `#define` ***`Test_operations`*** at the top of every *.c* file.

When you see Automake in Chapter 3, you'll see that it provides a `+=` operator, so given the usual flags in `AM_CFLAGS`, you could add the `-D` flag to the checks via:

```
check_CFLAGS  = $(AM_CFLAGS)
check_CFLAGS += -DTest_operations
```

The conditional inclusion of `main` can also come in handy in the other direction. For example, I often have an analysis to do based on some quirky data set. Before writing the final analysis, I first have to write a function to read in and clean the data, and then a few functions producing summary statistics sanity-checking the data and my progress. This will all be in *modelone.c*. Next week, I may have an idea for a new descriptive model, which will naturally make heavy use of the existing functions to clean data and display basic statistics. By conditionally including `main` in *modelone.c*, I can quickly turn the original program into a library. Here is a skeleton for *modelone.c*:

```
void read_data(){
    [database work here]
}

#ifndef MODELONE_LIB
int main(){
    read_data();
    ...
}
#endif
```

I use `#ifndef` rather than `#ifdef`, because the norm is to use *modelone.c* as a program, but this otherwise functions the same way as the conditional inclusion of `main` for testing purposes did.

Coverage

What's your test coverage? Are there lines of code that you wrote that aren't touched by your tests? gcc has the companion gcov, which will count how many times each line of code was touched by a program. The procedure:

- Add `-fprofile-arcs -ftest-coverage` to your `CFLAGS` for gcc. You might want to set the `-O0` flag, so that no lines of code are optimized out.
- When the program runs, each source file ***yourcode**.c* will produce one or two data files, ***yourcode**.gcda* and ***yourcode**.gcno*.
- Running `gcov` ***yourcode**.gcda* will write to `stdout` the percentage of runnable lines of code that your program hit (declarations, `#include` lines, and so on don't count) and will produce ***yourcode**.c.cov*.
- The first column of ***yourcode**.c.cov* will show how often each runnable line was hit by your tests, and will mark the lines not hit with a big fat `#####`. Those are the parts for which you should consider writing another test.

Example 2-4 shows a shell script that adds up all the steps. I use a here document to generate the makefile, so I could put all the steps in one script, and after compiling, running, and `gcov`-ing the program, I `grep` for the `#####` markers. The `-C3` flag to GNU `grep` requests three lines of context around matches. It isn't POSIX-standard, but then, neither are `pkg-config` or the test coverage flags.

Example 2-4. A script to compile for coverage testing, run the tests, and check for lines of code not yet tested (gcov.sh)

```
cat > makefile << '------'
P=dict_test
objects= keyval.o dict.o
CFLAGS = `pkg-config --cflags glib-2.0` -g -Wall -std=gnu99 \
           -O0 -fprofile-arcs -ftest-coverage
LDLIBS = `pkg-config --libs glib-2.0`
CC=gcc

$(P):$(objects)
------

make
./dict_test
for i in *gcda; do gcov $i; done;
grep -C3 '#####' *.c.gcov
```

Interweaving Documentation

You need documentation. You know this, and you know that you need to keep it current when the code changes. Yet, somehow, documentation is often the first thing to fall by the wayside. It is so very easy to say *it runs; I'll document it later*.

So you need to make writing the documentation as easy as physically possible. The immediate implication is that you have the documentation for the code in the same file as the code, as close as possible to the code being documented, and that implies that you're going to need a means of extracting the documentation from the code file.

Having the documentation right by the code also means you're more likely to read the documentation. It's a good habit to reread the documentation for a function before modifying it, both so that you have a better idea of what's going on, and so that you will be more likely to notice when your changes to the code will also require a change in the documentation.

I'll present two means of weaving documentation into the code: Doxygen and CWEB. Your package manager should be happy to install either of them.

Doxygen

Doxygen is a simple system with simple goals. It works best for attaching a description to each function, struct, or other such block. This is the case of documenting an interface for users who will never care to look at the code itself. The description will be in a comment block right on top of the function, struct, or whatever, so it is easy to write the documentation comment first, then write the function to live up to the promises you just made.

The syntax for Doxygen is simple enough, and a few bullet points will have you well on your way to using it:

- If a comment block starts with two stars, `/** like so */`, then Doxygen will parse the comment. One-star comments, `/* like so */`, are ignored.
- If you want Doxygen to parse a file, you will need a `/** \file */` comment at the head of the file; see the example. If you forget this, Doxygen won't produce output for the file and won't give you much of a hint as to what went wrong.
- Put the comment right before the function, struct, et cetera.
- Your function descriptions can (and should) include `\param` segments describing the input parameters and a `\return` line listing the expected return value. Again, see the example.
- Use `\ref` for cross-references to other documented elements (including functions or pages).
- You can use an `@` anywhere I used a backslash above: `@file`, `@mainpage`, et cetera. This is in emulation of JavaDoc, which seems to be emulating WEB. As a LaTeX user, I am more used to the backslash.

To run Doxygen, you will need a configuration file, and there are a lot of options to configure. Doxygen has a clever trick for handling this; run:

```
doxygen -g
```

and it will write a configuration file for you. You can then open it and edit as needed; it is of course very well documented. After that, run `doxygen` by itself to generate the outputs, including HTML, PDF, XML, or manual pages, as per your specification.

If you have Graphviz installed (ask your package manager for it), then Doxygen can generate *call graphs*: box-and-arrow diagrams showing which functions call and are called by which other functions. If somebody hands you an elaborate program and expects you to get to know it quickly, this can be a nice way to get a quick feel for the flow.

I documented "libxml and cURL" on page 247 using Doxygen; have a look and see how it reads to you as code, or run it through Doxygen and check out the HTML documentation it produces.

Every snippet throughout the book beginning with `/**` is also in Doxygen format.

The narrative

Your documentation should contain at least two parts: the technical documentation describing the function-by-function details, and a narrative explaining to users what the package is about and how to get their bearings.

Start the narrative in a comment block with the header `\mainpage`. If you are producing HTML output, this will be the *index.html* of your website—the first page readers should see. From there, add as many pages as you'd like. Subsequent pages have a header of the form:

```
/** \page onewordtag The title of your page
*/
```

Back on the main page (or any other, including function documentation), add `\ref` *`onewordtag`* to produce a link to the page you wrote. You can tag and name the main page as well, if need be.

The narrative pages can be anywhere in your code: you could put them close to the code itself, or the narrative might make sense as a separate file consisting entirely of Doxygen comment blocks, maybe named *documentation.h*.

Literate Code with CWEB

TeX, a document formatting system, is often held up as a paragon of a complicated system done very right. It is about 35 years old as of this writing, and (in this author's opinion) still produces the most attractive math of any typesetting system available. Many more recent systems don't even try to compete, and use TeX as a back-end for typesetting. Its author, Donald Knuth, used to offer a bounty for bugs, but eventually dropped the bounty after it went unclaimed for many years.

Dr. Knuth explains the high quality of TeX by discussing how it was written: *literate programming*, in which every procedural chunk is preceded by a plain English explanation of that chunk's purpose and functioning. The final product looks like a free-form description of code with some actual code interspersed here and there to formalize the description for the computer (in contrast to typical documented code, which is much more code than exposition). Knuth wrote TeX using WEB, a system that intersperses English expository text with PASCAL code. Here in the present day, the code will be in C, and now that TeX works to produce beautiful documentation, we might as well use it as the markup language for the expository side. Thus, CWEB.

As for the output, it's easy to find textbooks that use CWEB to organize and even present the content (e.g., [Hanson 1996]). If somebody else is going to study your code (for some of you this might be a coworker or a review team), then CWEB might make a lot of sense.

I wrote "An Agent-Based Model of Group Formation" on page 224 using CWEB; here's a rundown of what you need to know to compile it and follow its CWEB-specific features:

- Custom is to save CWEB files with a *.w* extension.
- Run `cweave` *groups.w* to produce a *.tex* file; then run `pdftex` *groups.tex* to produce a PDF.
- Run `ctangle` *groups.w* to produce a *.c* file. GNU make knows about this in its catalog of built-in rules, so `make groups` will run `ctangle` for you.

The tangle step removes comments, which means that CWEB and Doxygen are incompatible. Perhaps you could produce a header file with a header for each public function and struct for doxygenization, and use CWEB for your main code set.

Here is the CWEB manual reduced to seven bullet points:

- Every special code for CWEB has an `@` followed by a single character. Be careful to write `@<titles@>` and not `@<incorrect titles>@`.
- Every segment has a comment, then code. It's OK to have a blank comment, but that comment-code rhythm has to be there or else all sorts of errors turn up.
- Start a text section with an `@ ` following by a space. Then expound, using TeX formatting.
- Start an unnamed chunk of code with `@c`.
- Start a named block of code with a title followed by an equals sign (because this is a definition): `@<an operation@>=`.
- That block will get inserted verbatim wherever you use the title. That is, each chunk name is effectively a macro that expands to the chunk of code you specified, but without all the extra rules of C preprocessor macros.
- Sections (like the sections in the example about group membership, setting up, plotting with Gnuplot, and so on) start with `@*` and have a title ending in a period.

That should be enough for you to get started writing your own stuff in CWEB. Have a look at "An Agent-Based Model of Group Formation" on page 224 and see how it reads to you.

Becoming a Better Typist

I selected many of the topics in this book based on my experience helping colleagues work out C code, and in the process learning the things that give them trouble. For some, setting up the environment was a real roadblock, many had trouble getting comfortable with pointers, and a surprisingly large number of people are just uncomfortable with the keyboard. It might not be what we think about when discussing programming, but people who are not confident at the keyboard are disinclined to use a language where symbol-heavy text like `for (i=0; i<10; i++)` is standard fare.

Here's the advice I give when typing comes up: get a light t-shirt and drape it over the keyboard. Stick your hands under the shirt, and start typing.

The intent is to prevent that sneaking glance that we all do to check where the keys are. It turns out that the keys aren't very mobile and are always exactly where you left them. But those micropauses to check on things are how we keep our confidence and facility with the keyboard at a certain safe speed.

If not being able to see is frustrating at first, persist through the initial awkwardness, and get to know those occasional keys that you never quite learned. When you are more confident with the keyboard, you'll have more brain power to dedicate to writing.

Error Checking

A complete programming textbook must include at least one lecture to the reader about how important it is to handle errors sent by functions you have called.

OK, consider yourself lectured. Now let's consider the side of how and when you will return errors from the functions you write. There are a lot of different types of errors in a lot of different contexts, so we have to break down the inquiry into several subcases:

- What is the user going to do with the error message?
- Is the receiver a human or another function?
- How can the error be communicated to the user?

I will leave the third question for later ("Return Multiple Items from a Function" on page 175), but the first two questions already give us a lot of cases to consider.

What Is the User's Involvement in the Error?

Thoughtless error-handling, wherein authors pepper their code with error-checks because you can't have too many, is not necessarily the right approach. You need to maintain lines of error-handling code like any other, and every user of your function has internalized endless lectures about how every possible error code needs to be handled, so if you throw error codes that have no reasonable resolution, the function user will be left feeling guilty and unsure. There is such a thing as too much information (TMI).

To approach the question of how an error will be used, consider the complementary question of how the user was involved in the error to begin with.

- *Sometimes the user can't know if an input is valid before calling the function*, the classic example being looking up a key in a key/value list and finding out that the key is not in the list. In this case, you could think of the function as a lookup function that throws errors if the key is missing from the list, or you could think of it as a dual-purpose function that either looks up keys or informs the caller whether the key is present or not.

  Or to give an example from high-school algebra, the quadratic formula requires calculating `sqrt(b*b - 4*a*c)`, and if the term in parens is negative, the square root is not a real number. It's awkward to expect the function user to calculate `b*b - 4*a*c` to establish feasibility, so it is reasonable to think of the quadratic formula function as either returning the roots of the quadratic equation or reporting whether the roots will be real or not.

  In these examples of nontrivial input-checking, bad inputs aren't even an error, but are a routine and natural use of the function. If an error-handling function aborts or otherwise destructively halts on errors (as does the error-handler that follows), then it shouldn't be called in situations like these.

- *Users passed in blatantly wrong input*, such as a `NULL` pointer or other sort of malformed data. Your function has to check for these things, to prevent it from segfaulting or otherwise failing, but it is hard to imagine what the caller will do with the information. The documentation for ***`yourfn`*** told users that the pointer can't be `NULL`, so when they ignore it and call `int* indata=NULL;` *`yourfn`*`(indata)`, and you return an error like `Error: NULL pointer input`, it's hard to imagine what the caller will do differently.

  A function usually has several lines like `if (input1==NULL) return -1; ... if (input20==NULL) return -1;` at the head, and I find in the contexts where I work that reporting exactly which of the basic requirements enumerated in the documentation the caller missed is TMI.

- *The error is entirely an error of internal processing*, including "shouldn't happen" errors, wherein an internal calculation somehow got an impossible answer—what Hair (The American Tribal Love Rock Musical) called a failure of the flesh, such as unresponsive hardware or a dropped network or database connection.

  The flesh failures can typically be handled by the recipient (e.g., by wiggling the network cable). Or, if the user requests that a gigabyte of data be stored in memory and that gigabyte is not available, it makes sense to report an out-of-memory error. However, when allocation for a 20-character string fails, the machine is either overburdened and about to become unstable or it is on fire, and it's typically hard for a calling system to use that information to recover gracefully. Depending on the context in which you are working, *your computer is on fire*-type errors might be counterproductive and TMI.

Errors of internal processing (i.e., errors unrelated to external conditions and not directly tied to a somehow-invalid input value) cannot be handled by the caller. In this case, detailing to the user what went wrong is probably TMI. The caller needs to know that the output is unreliable, but enumerating lots of different error conditions just leaves the caller (duty-bound to handle all errors) with more work.

The Context in Which the User Is Working

As above, we often use a function to check on the validity of a set of inputs, and such usage is not an error *per se*, and the function is most useful if it returns a meaningful value for these cases rather than calling an error handler. The rest of this section considers the *bona fide* errors.

- If the user of the program has access to a debugger and is in a context where using one is feasible, then the fastest way to fail is to call `abort` and cause the program to stop. Then the user has the local variables and backtrace right at the scene of the crime. The `abort` function has been C-standard since forever (you'll need to `#include <stdlib.h>`).
- If the user of the program is actually a Java program, or has no idea what a debugger is, then `abort` is an abomination, and the correct response is to return some sort of error code indicating a failure.

Both of these cases are very plausible, so it is sensible to have an if/else branch that lets the user select the correct mode of operation for the context.

It's been a long time since I've seen a nontrivial library that didn't implement its own error-handling macro. It's at just that level where the C standard doesn't provide one, but it's easy to implement with what C does offer, and so everybody writes a new one.

The standard `assert` macro (hint: `#include <assert.h>`) will check a claim you make and then stop if and only if your claim turns out to be false. Every implementation will be a little bit different, but the gist is:

```
#define assert(test) (test) ? 0 : abort();
```

By itself, `assert` is useful to test whether intermediate steps in your function are doing what they should be doing. I also like to use `assert` as documentation: it's a test for the computer to run, but when I see `assert(matrix_a->size1 == matrix_b->size2)`, then I as a human reader am reminded that the dimensions of the two matrices will match in this manner. However, `assert` provides only the first kind of response (aborting), so assertions have to be wrapped.

Example 2-5 presents a macro that satisfies both conditions; I'll discuss it further in "Variadic Macros" on page 165 (and, for those of you unfamiliar with the custom, will give the rationale for the `do-while` wrapper in "Cultivate Robust and Flourishing Macros" on page 131). Note also that some users deal well with `stderr`, and some have no means to work with it.

Example 2-5. A macro for dealing with errors: report or record them, and let the user decide whether to stop on errors or move on (stopif.h)

```
#include <stdio.h>
#include <stdlib.h> //abort

/** Set this to \c 's' to stop the program on an error.
    Otherwise, functions return a value on failure.*/
char error_mode;

/** To where should I write errors? If this is \c NULL, write to \c stderr. */
FILE *error_log;

#define Stopif(assertion, error_action, ...) do {                 \
        if (assertion){                                            \
            fprintf(error_log ? error_log : stderr, __VA_ARGS__); \
            fprintf(error_log ? error_log : stderr, "\n");        \
            if (error_mode=='s') abort();                          \
            else                {error_action;}                    \
        } } while(0)
```

Here are some imaginary sample uses:

```
Stopif(!inval, return -1, "inval must not be NULL");
Stopif(isnan(calced_val), goto nanval, "Calced_val was NaN. Cleaning
up, leaving.");
...
nanval:
    free(scratch_space);
    return NAN;
```

The most common means of dealing with an error is to simply return a value, so if you use the macro as is, expect to be typing `return` often. This can be a good thing, however. Authors often complain that sophisticated try-catch setups are effectively an updated version of the morass of `goto`s that we all consider to be harmful. For example, Google's internal coding style guide advises against using try-catch constructs, using exactly the morass-of-`goto`s rationale. This advises that it is worth reminding readers that the flow of the program will be redirected on error (and to where), and that we should keep our error-handling simple.

How Should the Error Indication Be Returned?

I'll get to this question in greater detail in the chapter on struct-handling (notably, "Return Multiple Items from a Function" on page 175), because if your function is above a certain level of complexity, returning a struct makes a lot of sense, and then adding an error-reporting variable to that struct is an easy and sensible solution. For example, given a function that returns a struct named `out` that includes a `char*` element named `error`:

```
Stopif(!inval, out.error="inval must not be NULL"; return out
             , "inval must not be NULL");
```

GLib has an error-handling system with its own type, the `GError`, that must be passed in (via pointer) as an argument to any given function. It provides several additional features above the macro listed in Example 2-5, including error domains and easier passing of errors from subfunctions to parent functions, at the cost of added complexity.

CHAPTER 3

Packaging Your Project

If you've read this far, then you have met the tools that solve the core problems for dealing with C code, like debugging and documenting it. If you're eager to get going with C code itself, then feel free to skip ahead to Part II. This chapter and the next will cover some heavy-duty tools intended for collaboration and distribution to others: package-building tools and a revision-control system. Along the way, there will be many digressions about how you can use these tools to write better even when working solo.

In the present day, Autotools, a system for autogenerating the perfect makefile for a given system, is central to how code is distributed. You've already met it in "Using Libraries from Source" on page 21, where you used it to quickly install the GNU Scientific Library. Even if you've never dealt with it directly, it is probably how the people who maintain your package-management system produced just the right build for your computer.

But you'll have trouble following what Autotools is doing unless you have a good idea of how a makefile works, so we need to cover those in a little more detail first. But to a first approximation, makefiles are organized sets of shell commands, so you'll need to get to know the various facilities the shell offers for automating your work. The path is long, but at the end you will be able to:

- Use the shell to automate work.
- Use makefiles to organize all those tasks you have the shell doing.
- Use Autotools to let users autogenerate makefiles on any system.

This chapter is heavy on shell code and command-prompt work, because the distribution of code relies heavily on POSIX-standard shell scripts. So even if you are an IDE user who avoids the command prompt, this stuff is worth knowing. Also, your IDE is probably a thin wrapper around the shell commands covered here, so when your IDE spits out a cryptic error, this chapter might help you decipher it.

The Shell

A POSIX-standard shell will have the following:

- Abundant macro facilities, in which your text is replaced with new text—i.e., an *expansion* syntax
- A Turing-complete programming language
- An interactive frontend—the command prompt—which might include lots of user-friendly tricks
- A system for recording and reusing everything you typed: history
- Lots of other things I won't mention here, such as job control and many built-in utilities

There is *a lot* of shell scripting syntax, so this section covers only a few pieces of low-hanging syntactic fruit for these categories. There are many shells to be had (and later, a sidebar will suggest trying a different one from the one you're using now), but unless otherwise noted, this section will stick to the POSIX standard.

I won't spend much time on the interactive features, but I have to mention one that isn't even POSIX-standard: tab completion. In bash, if you type part of a filename and hit the Tab key, the name will be autocompleted if there's only one option, and if not, hit Tab again to see a list of options. If you want to know how many commands you can type on the command line, hit Tab twice on a blank line and bash will give you the whole list. Other shells go much further than bash: type `make <tab>` in the Z shell and it will read your makefile for the possible targets. The Friendly Interactive shell (fish) will check the manual pages for the summary lines, so when you type `man l<tab>` it will give you a one-line summary of every command beginning with L, which could save you the trouble of actually pulling up any manpage at all.

There are two types of shell users: those who didn't know about this tab-completion thing, and those who use it *all the time on every single line*. If you were one of those people in that first group, you're going to love being in the second.

Replacing Shell Commands with Their Outputs

A shell largely behaves like a macro language, wherein certain blobs of text get replaced with other blobs of text. These are called *expansions* in the shell world, and there are many types: this section touches on variable substitution, command substitution, a smattering of history substitution, and will give examples touching on tilde expansion and arithmetic substitution for quick desk calculator math. I leave you to read your shell's manual on alias expansion, brace expansion, parameter expansion, word splitting, pathname expansion, and glob expansion.

Variables are a simple expansion. If you set a variable like

```
onething="another thing"
```

on the command line, then when you later type:

```
echo $onething
```

then `another thing` will print to screen.

Your shell will require that there be no spaces on either side of the `=`, which will annoy you at some point.

When one program starts a new program (in POSIX C, when the `fork()` system call is used), a copy of all environment variables is sent to the child program. Of course, this is how your shell works: when you enter a command, the shell forks a new process and sends all the environment variables to the child.

Environment variables, however, are a subset of the shell variables. When you make an assignment like the previous one, you have set a variable for the shell to use; when you:

```
export onething="another thing"
```

then that variable is available for use in the shell, and its export attribute is set. Once the export attribute is set, you can still change the variable's value.

For our next expansion, how about the backtick, `` ` ``, which is not the more vertical-looking single tick `'`.

> The vertical tick (`'`, not the backtick) indicates that you don't want expansions done. The sequence:
>
> ```
> onething="another thing"
> echo "$onething"
> echo '$onething'
> ```
>
> will print:
>
> ```
> another thing
> $onething
> ```

The backtick replaces the command you give with its output, doing so macro-style, where the command text is replaced in place with the output text.

Example 3-1 presents a script that counts lines of C code by how many lines have a `;`, `)`, or `}` on them. Given that lines of source code is a lousy metric for most purposes anyway, this is as good a means as any, and has the bonus of being one line of shell code.

Example 3-1. Counting lines using shell variables and POSIX utilities (linecount.sh)

```
 # Count lines with a ;, ), or }, and let that count be named Lines.
Lines=`grep '[;)}]' *.c | wc -l`

 # Now count how many lines there are in a directory listing; name it Files.
Files=`ls *.c |wc -l`

echo files=$Files and lines=$Lines
```

```
 # Arithmetic expansion is a double-paren.
 # In bash, the remainder is truncated; more on this later.
echo lines/file = $(($Lines/$Files))

 # Or, use those variables in a here script.
 # By setting scale=3, answers are printed to 3 decimal places.
bc << ---
scale=3
$Lines/$Files
---
```

You can run the shell script via `.` *`linecount.sh`*. The dot is the POSIX-standard command to source a script. Your shell probably also lets you do this via the nonstandard but much more comprehensible `source` *`linecount.sh`*.

> On the command line, the backtick is largely equivalent to `$()`. For example: `` echo `date` `` and `echo $(date)`. However, `make` uses `$()` for its own purposes, so you'll need the backtick when writing makefiles.

Use the Shell's for Loops to Operate on a Set of Files

Let's get to some proper programming, with `if` statements and `for` loops.

But first, some caveats and annoyances about shell scripting:

- Scope is awkward—pretty much everything is global.
- It's effectively a macro language, so all those text interactions that they warned you about when you write a few lines of C preprocessor code (see "Cultivate Robust and Flourishing Macros" on page 131) are largely relevant for every line of your shell script.
- There isn't really a debugger that can execute the level-jumping basics from "Using a Debugger" on page 29, though modern shells will provide some facilities to trace errors or verbosely run scripts.
- You'll have to get used to the little tricks that will easily catch you, like how you can't have spaces around the `=` in `onething=another`, but you must have spaces around the `[` and `]` in `if [ -e ff ]` (because they're keywords that just happen to not have any letters in them).

Some people don't see these details as much of an issue, and ♥ the shell. Me, I write shell scripts to automate what I would type at the command line, and once things get complex enough that there are functions calling other functions, I take the time to switch to Perl, Python, awk, or whatever is appropriate.

My vote for greatest bang for the buck from having a programming language that you can type directly onto the command line goes to running the same command on several files. Let's back up every *.c* file the old fashioned way, by copying it to a new file with a name ending in *.bkup*:

```
for file in *.c;
do
 cp $file ${file}.bkup;
done
```

You see where the semicolon is: at the end of the list of files the loop will use, on the same line as the `for` statement. I'm pointing this out because when cramming this onto one line, as in:

```
for file in *.c; do cp $file ${file}.bkup; done
```

I always forget that the order is `; do` and not `do ;`.

The `for` loop is useful for dealing with a sequence of *N* runs of a program. By way of a simple example, *benford.sh* searches C code for numbers beginning with a certain digit (i.e., head of the line or a nondigit followed by the digit we are looking for), and writes each line that has the given number to a file, as shown in Example 3-2:

Example 3-2. For each digit i, search for the (nondigit)i sequence in the text; count those lines (benford.sh)

```
for i in 0 1 2 3 4 5 6 7 8 9; do grep -E '(^|[^0-9.])'$i *.c > lines_with_${i}; done
wc -l lines_with*           //A rough histogram of your digit usage.
```

Testing against *Benford's law* is left as an exercise for the reader.

The curly braces in `${i}` are there to distinguish what is the variable name and what is subsequent text; you don't need it here, but you would if you wanted a filename like `${i}lines`.

You probably have the `seq` command installed on your machine—it's BSD/GNU standard but not POSIX standard. Then we can use backticks to generate a sequence:

```
for i in `seq 0 9`; do grep -E '(^|[^0-9.])'$i *.c > lines_with_${i}; done
```

Running your program a thousand times is now trivial:

```
for i in `seq 1 1000`; do ./run_program > ${i}.out; done

#or append all output to a single file:
for i in `seq 1 1000`; do
  echo output for run $i: >> run_outputs
  ./run_program >> run_outputs
done
```

Test for Files

Now let's say that your program relies on a data set that has to be read in from a text file to a database. You only want to do the read-in once, or in pseudocode: if (database exists) then (do nothing), else (generate database from text).

On the command line, you would use `test`, a versatile command typically built into the shell. To try it, run a quick `ls`, get a filename you know is there, and use `test` to check that the file exists like this:

```
test -e a_file_i_know
echo $?
```

By itself, `test` outputs nothing, but because you're a C programmer, you know that every program has a `main` function that returns an integer, and we will use only that return value here. Custom is to read the return value as a problem number, so 0==no problem, and in this case 1==file does not exist (which is why, as will be discussed in "Don't Bother Explicitly Returning from main" on page 116, the default is that `main` returns zero). The shell doesn't print the return value to the screen, but stores it in a variable, `$?`, which you can print via `echo`.

The echo command itself has a return value, and `$?` will be set to that value after you run `echo $?`. If you want to use the value of `$?` for a specific command more than once, assign it to a variable, such as ***`returnval`***`=$?`.

Now let us use it in an `if` statement to act only if a file does not exist. As in C, `!` means *not*.

Example 3-3. An if/then statement built around test—run it several times (. iftest.sh; . iftest.sh; . iftest.sh) to watch the test file come in and out of existence (iftest.sh)

```
if test ! -e a_test_file; then
    echo test file had not existed
    touch a_test_file
else
    echo test file existed
    rm a_test_file
fi
```

Notice that, as with the `for` loops from last time, the semicolon is in what I consider an awkward position, and we have the super-cute rule that we end `if` blocks with `fi`. By the way, `else if` is not valid syntax; use the `elif` keyword.

To make it easier for you to run this repeatedly, let's cram it onto one margin-busting line. The keywords `[` and `]` are equivalent to `test`, so when you see this form in other people's scripts and want to know what's going on, the answer is in `man test`.

```
if [ ! -e a_test_file ]; then echo test file had not existed; ↩
   touch a_test_file; else echo test file existed; rm a_test_file; fi
```

Because so many programs follow the custom that zero==OK and nonzero==problem, we can use `if` statements without `test` to express the clause *if the program ran OK, then*…. For example, it's common enough to use `tar` to archive a directory into a single *.tgz* file, then delete the directory. It would be a disaster if the tar file somehow didn't get created but the directory contents were deleted anyway, so we should have some sort of test that the `tar` command completed successfully before deleting everything:

```
#generate some test files
mkdir a_test_dir
echo testing ... testing > a_test_dir/tt


if tar cz a_test_dir > archived.tgz; then
    echo Compression went OK. Removing directory.
    rm -r a_test_dir
else
    echo Compression failed. Doing nothing.
fi
```

If you want to see this fail after running once, try `chmod 000 archived.tgz` to make the destination archive unwritable, then rerun.

Try a Multiplexer

I always have two terminals open when coding: one with the code in an editor, and one for compiling and running the program (probably in a debugger). Add another source file or two, and being able to deftly jump among terminals becomes essential.

There are two major terminal multiplexers to choose from, on either side of the great GNU-BSD rivalry: GNU Screen and tmux. Your package manager will probably install either or both of them.

Both work via a single command key. GNU Screen defaults to Ctrl-A. Tmux defaults to Ctrl-B, but the consensus seems to be that everybody remaps that to use Ctrl-A instead, by adding:

```
unbind C-b
set -g prefix C-a
bind a send-prefix
```

to *.tmux_conf* in their home directories. The manuals will list dozens of other things that you can add to your configuration files. When searching for tips and documentation, by the way, notice that *GNU Screen* is the name to type into your Internet search engine, because *Screen* by itself will get you nowhere.

Having set Ctrl-A as command key, Ctrl-A Ctrl-A jumps between two windows, and you can read the manual for the Ctrl-A (otherkey) combinations that let you step forward or backward in the window list, or display the full list of windows so you can just pick from the list.

So both multiplexers solve the multiwindow problem. But they do so very much more:

- Ctrl-A D will detach the session, meaning that your terminal no longer displays the various virtual terminals under the multiplexer's control. But they're still running in the background.
  — At the end of a long day with GNU Screen/Tmux, detach. Later, reattach from home or at work tomorrow using `screen -r` or `tmux attach`, and pick up exactly where you left off. The ability to keep going after a disconnect is also nice when working via a spotty connection to your server in Belize or Ukraine.

— The multiplexer leaves the programs in its virtual terminals running even after you've detached, which is useful for long processes that have to run overnight.

- There's a cut/paste feature.
  — Once in copy mode, you can mouselessly page through what's passed through the terminal lately, highlight a section, and copy it to the multiplexer's internal clipboard via Ctrl-A (or one or two other keys). Then, back in regular mode, Ctrl-A pastes.
  — While you're browsing for things to cut, you can scroll through the history and search for specific strings.

These multiplexers really take that last step from the terminal being a place to work to being a fun place to work.

fc

`fc` is a (POSIX-standard) command for turning your noodling on the shell into a repeatable script. Try:

```
fc -l    # The l is for list and is important.
```

You now have on the screen a numbered list of your last few commands. Your shell might let you type `history` to get the same effect.

The `-n` flag suppresses the line numbers, so you can write history items 100 through 200 to a file via:

```
fc -l -n 100 200 > a_script
```

then remove all the lines that were experiments that didn't work, and you've converted your futzing on the command line into a clean shell script.

If you omit the `-l` flag, then `fc` becomes a more immediate and volatile tool. It pulls up an editor (which means if you redirect with `>`, you're basically hung), doesn't display line numbers, and when you quit your editor, whatever is in that file gets executed immediately. This is great for a quick repetition of the last few lines, but can be disastrous if you're not careful. If you realize that you forgot the `-l` or are otherwise surprised to see yourself in the editor, delete everything on the screen to prevent unintended lines from getting executed.

But to end on a positive note, `fc` stands for *fix command*, and that is its simplest usage. With no options, it edits the prior line only, so it's nice for when you need to make elaborate corrections to a command.

Try a New Shell

There are a lot of shells in the world beyond the shell your operating system vendor chose as the default. Here, I'll sample from the interesting things that the Z shell can do, to give you a hint as to what switching from bash can get you.

Z shell's feature and variable lists go for dozens of pages, so there goes parsimony—but why bother being Spartan with interactive conveniences. (If you have Spartan æsthetics, then you still want to switch out of bash; try ash.) Set variables in `~/.zshrc` (or just type them onto the command line to try them out); here is the one you'll need for the following examples:

```
setopt INTERACTIVE_COMMENTS
#now comments like this won't give an error
```

Expansion of globs, like replacing `file.*` with `file.c file.o file.h` is the responsibility of the shell. The most useful way in which Zsh extends this is that `**/` tells the shell to recurse the directory tree when doing the expansion. A POSIX-standard shell reads ~ to be your home directory, so if you want every *.c* file anywhere in your purview, try `ls ~/**/*.c`.

Let's back up every last one of our *.c* files:

```
# This line may create a lot of files all over your home directory.
for ff in ~/**/*.c; do cp $ff ${ff}.bkup; done
```

Remember how bash only gives you arithmetic expansion on integers, so `$((3/2))` is always 1? Zsh and Ksh (and others) are C-like in giving you a real (more than integer) answer if you cast the numerator or denominator to float:

```
echo $((3/2.))        #works for zsh, syntax error for bash

#repeating the line-count example from earlier:
Files=`ls *.c |wc -l`
Lines=`grep '[)};]' *.c | wc -l`

echo lines/file = $(($Lines/($Files+0.0)))      #Cast to floating point by adding 0.0
```

Spaces in filenames can break things in bash, because spaces separate list elements. Zsh has an array syntax that doesn't depend on using spaces as an element delimiter.

```
# Generate two files, one of which has spaces in the name.
echo t1 > "test_file_1"
echo t2 > "test file 2"

# This fails in bash, is OK in Zsh.
for f in test* ; do cat $f; done
```

If you decide to switch shells, there are two ways to do it: you can use `chsh` to make the change official in the login system (*/etc/passwd* gets modified), or if that's somehow a problem, you can add `exec -l /usr/bin/zsh` (or whatever shell you like) as the last line of your *.bashrc*, so bash will replace itself with your preferred shell every time it starts.

If you want your makefile to use a nonstandard shell, add:

```
SHELL=command -v zsh
```

(or whatever shell you prefer) to your makefile. The POSIX-standard `command -v` prints the full path to a command, so you don't have to look it up yourself. `SHELL` is an odd variable in that it has to be in the makefile or set as an argument to `make`, because `make` ignores the environment variable named `SHELL`.

Makefiles vs. Shell Scripts

You probably have a lot of little procedures associated with a project floating around (word count, spell check, run tests, write to revision control, push revision control out to a remote, make backup), all of which could be automated by a shell script. But rather than producing a new one- or two-line script for every little task you have for your project, you can put them all into a makefile.

Makefiles were first covered in "Using Makefiles" on page 15, but now that we've covered the shell in more detail, we have more that we can put into a makefile. Here's one more example target from my daily life, which uses the `if/then` shell syntax and `test`. I use Git, but there are three Subversion repositories I have to deal with, and I never remember the procedures. As in Example 3-4, I now have a makefile to remember for me.

Example 3-4. Folding an if/then and a test into a makefile (make_bit)

```
push:
    @if [ "x$(MSG)" = 'x' ] ; then \     ❶
            echo "Usage: MSG='whatever.' make push"; fi
    @test "x$(MSG)" != 'x'               ❷
    git commit -a -m "$(MSG)"
    git svn fetch
    git svn rebase
    git svn dcommit

pull:
    git svn fetch
    git svn rebase
```

❶ I need a message for each commit, so I do that via an environment variable set on the command line, via: `MSG="This is a commit." make push`. This line is an `if-then` statement that prints a reminder if I forget this.

❷ Test to make sure that `"x$(MSG)"` expands to something besides just `"x"`, meaning that `$(MSG)` is not empty. This is a common shell idiom to make up for an idiotic glitch about blank strings. If the test fails, `make` does not continue.

The commands executed in a makefile are in some ways just what you would type on the command line, and in some ways drastically different:

- *Every line runs independently, in a separate shell.* If you write this into your makefile:

  ```
  clean:
      cd junkdir
      rm -f *        # Do not put this in a makefile.
  ```

  then you will be a sad puppy. The two lines in the script are equivalent to C code like this:

  ```
  system("cd junkdir");
  system("rm -f *");
  ```

Or, because `system("cmd")` is equivalent to `sh -c "cmd"`, our `make` script is also equivalent to:

```
sh -c "cd junkdir"
sh -c "rm -f *"
```

And for the shell geeks, `(cmd)` runs *cmd* in a subshell, so the `make` snippet is also equivalent to typing this at the shell prompt:

```
(cd junkdir)
(rm -f *)
```

In all cases, the second subshell knows nothing of what happened in the first subshell. `make` will first spawn a shell that changes in to the directory you are emptying, then `make` is done with that subshell. Then it starts a new subshell from the directory you started in and calls `rm -f *`.

On the plus side, `make` will delete the erroneous makefile for you. If you want to express the thought in this form, do it like this:

```
cd junkdir && rm -f *
```

where the `&&` runs commands in short-circuit sequence just like in C (i.e., if the first command fails, don't bother running the second). Or use a backslash to join two lines into one:

```
cd junkdir&& \
rm -f *
```

Though for a case like this, I wouldn't trust just a backslash. In real life, you're better off just using `rm -f junkdir/*` anyway.

- `make` replaces instances of `$x` (for one-letter or one-symbol variable names) or `$(xx)` (for multiletter variable names) with the appropriate values.
- If you want the shell, not `make`, to do the substitution, then drop the parens and double your `$$`s. For example, to use the shell's variable mangling to name backups from a makefile: `for i in *.c; do cp $$i $${i%%.c}.bkup; done`.
- Recall the trick from "Using Makefiles" on page 15 where you can set an environment variable just before a command, e.g., `CFLAGS=-O3 gcc test.c`. That can come in handy now that each shell survives for a single line. Don't forget that the assignment has to come just before a command and not a shell keyword like `if` or `while`.
- An `@` at the head of a line means run the command but don't echo anything to the screen as it happens.
- A `-` at the head of a line means that if the command returns a nonzero value, keep going anyway. Otherwise, the script halts on the first nonzero return.

For simpler projects and most of your day-to-day annoyances, a makefile using all those features from the shell will get you very far. You know the quirks of the computer you use every day, and the makefile will let you write them down in one place and stop thinking about them.

Will your makefile work for a colleague? If your program is a common set of *.c* files and any necessary libraries are installed, and the `CFLAGS` and `LDLIBS` in your makefile are right for your recipient's system, then perhaps it will all work fine, and at worst will require an email or two clarifying things. If you are generating a shared library, then forget about it—the procedure for generating a shared library is very different for Mac, Linux, Windows, Solaris, or different versions of each. When distributing to the public at large, everything needs to be as automated as possible, because it's hard to trade emails about setting flags with dozens or hundreds of people, and most people don't want to put that much effort into making a stranger's code work anyway. For all these reasons, we need to add another layer for publicly distributed packages.

Packaging Your Code with Autotools

The Autotools are what make it possible for you to download a library or program, and run:

```
./configure
make
sudo make install
```

(and nothing else) to set it up. Please recognize what a miracle of modern science this is: the developer has no idea what sort of computer you have, where you keep your programs and libraries (*/usr/bin*? */sw*? */cygdrive/c/bin*?), and who knows what other quirks your machine demonstrates, and yet `configure` sorted everything out so that `make` could run seamlessly. And so, Autotools is central to how code gets distributed in the modern day. If you want anybody who is not on a first-name basis with you to use your code (or if you want a Linux distro to include your program in their package manager), then having Autotools generate the build for you will significantly raise your odds.

It is easy to find packages that depend on some existing framework for installation, such as Scheme, Python ≥2.4 but <3.0, Red Hat Package Manager (RPM), and so on. The framework makes it easy for users to install the package—right after they install the framework. Especially for users without root privileges, such requirements can be a show stopper. The Autotools stand out in requiring only that the user have a computer with rudimentary POSIX compliance.

Using the Autotools can get complex, but the basics are simple. By the end of this, we will have written six lines of packaging text and run four commands, and will have a complete (albeit rudimentary) package ready for distribution.

The actual history of Autoconf, Automake, and Libtool is somewhat involved: these are distinct packages, and there is a reason to run any of them without the other. But here's how I like to imagine it all happening.

Meno: I love `make`. It's so nice that I can write down all the little steps to building my project in one place.

Socrates: Yes, automation is great. Everything should be automated, all the time.

Meno: I have lots of targets in my makefile, so users can type `make` to produce the program, `make install` to install, `make check` to run tests, and so on. It's a lot of work to write all those makefile targets, but so smooth when it's all assembled.

Socrates: OK, I shall write a system—it will be called Automake—that will automatically generate makefiles with all the usual targets from a very short pre-makefile.

Meno: That's great. Producing shared libraries is especially annoying, because every system has a different procedure.

Socrates: It is annoying. Given the system information, I shall write a program for generating the scripts needed to produce shared libraries from source code, and then put those into Automade makefiles.

Meno: Wow, so all I have to do is tell you my operating system, and whether my compiler is named `cc` or `clang` or `gcc` or whatever, and you'll drop in the right code for the system I'm on?

Socrates: That's error-prone. I will write a system called Autoconf that will be aware of every system out there and that will produce a report of everything Automake and your program needs to know about the system. Then Autoconf will run Automake, which will use the list of variables in my report to produce a makefile.

Meno: I am flabbergasted—you've automated the process of autogenerating makefiles. But it sounds like we've just changed the work I have to do from inspecting the various platforms to writing configuration files for Autoconf and makefile templates for Automake.

Socrates: You're right. I shall write a tool, Autoscan, that will scan the *Makefile.am* you wrote for Automake, and autogenerate Autoconf's *configure.ac* for you.

Meno: Now all you have to do is autogenerate *Makefile.am*.

Socrates: Yeah, whatever. RTFM and do it yourself.

Each step in the story adds a little more automation to the step that came before it: Automake uses a simple script to generate makefiles (which already go far in automating compilation over manual command-typing); Autoconf tests the environment and uses that information to run Automake; Autoscan checks your code for what you need to make Autoconf run. Libtool works in the background to assist Automake.

An Autotools Demo

Example 3-5 presents a script that gets Autotools to take care of *Hello, World*. It is in the form of a shell script you can copy/paste onto your command line (as long as you make sure there are no spaces after the backslashes). Of course, it won't run until you ask your package manager to install the Autotools: Autoconf, Automake, and Libtool.

Example 3-5. Packaging Hello, World. (auto.conf)

```
if [ -e autodemo ]; then rm -r autodemo; fi
mkdir -p autodemo                        ❶
cd autodemo
cat > hello.c <<\
"--------------"
#include <stdio.h>

int main(){ printf("Hi.\n"); }
--------------

cat > Makefile.am <<\                    ❷
"--------------"
bin_PROGRAMS=hello
hello_SOURCES=hello.c
--------------

autoscan                                 ❸
sed -e 's/FULL-PACKAGE-NAME/hello/' \    ❹
    -e 's/VERSION/1/'   \
    -e 's|BUG-REPORT-ADDRESS|/dev/null|' \
    -e '10i\
AM_INIT_AUTOMAKE' \
       < configure.scan > configure.ac

touch NEWS README AUTHORS ChangeLog      ❺

autoreconf -iv                           ❻
./configure
make distcheck
```

❶ Create a directory and use a here document to write *hello.c* to it.

❷ We need to hand-write *Makefile.am*, which is two lines long. The `hello_SOURCES` line is optional, because Automake can guess that *hello* will be built from a source file named *hello.c*.

❸ `autoscan` produces *configure.scan*.

❹ Edit *configure.scan* to give the specs of your project (name, version, contact email), and add the line `AM_INIT_AUTOMAKE` to initialize Automake. (Yes, this is annoying, especially given that Autoscan used Automake's *Makefile.am* to gather info, so it is well aware that we want to use Automake.) You could do this by hand; I used `sed` to directly stream the customized version to *configure.ac*.

❺ These four files are required by the GNU coding standards, and so GNU Autotools won't proceed without them. I cheat by creating blank versions using the POSIX-standard `touch` command; yours should have actual content.

❻ Given *configure.ac*, run `autoreconf` to generate all the files to ship out (notably, *configure*). The `-i` flag will produce extra boilerplate files needed by the system.

How much do all these macros do? The *hello.c* program itself is a leisurely three lines and *Makefile.am* is two lines, for five lines of user-written text. Your results may differ a little, but when I run `wc -l *` in the post-script directory, I find 11,000 lines of text, including a 4,700-line `configure` script.

It's so bloated because it's so portable: your recipients probably don't have Autotools installed, and who knows what else they're missing, so this script depends only on rudimentary POSIX-compliance.

I count 73 targets in the 600-line makefile.

- The default target, when you just type `make` on the command line, produces the executable.
- `sudo make install` would install this program if you so desire; run `sudo make uninstall` to clear it out.
- There is even the mind-blowing option to `make Makefile` (which actually comes in handy if you make a tweak to *Makefile.am* and want to quickly regenerate the makefile).
- As the author of the package, you will be interested in `make distcheck`, which generates a tar file with everything a user would need to unpack and run the usual `./configure; make; sudo make install` (without the aid of the Autotools system that you have on your development box), and verifies that the distribution is OK, such as running any tests you may have specified.

Figure 3-1 summarizes the story as a flow diagram.

You will only be writing two of these files (the shaded ones); everything else is autogenerated by the given command. Let's start from the bottom portion: the user gets your package as a tarball, and untars it via `tar xvzf` ***`your_pkg`***`.tgz`, which produces a directory with your code, *Makefile.am*, *configure*, and a host of other auxiliary files that aren't worth discussing here. The user types `./configure`, and that produces *configure.h* and the *Makefile*. Now everything is in place for the user to type `make; sudo make install`.

As an author, your goal is to produce that tarball, with a high-quality *configure* and *Makefile.am*, so the user can run his or her part without a hitch. Start by writing *Makefile.am* yourself. Run `autoscan` to get a preliminary *configure.scan*, which you will manually edit to *configure.ac*. (Not shown: the four files required by the GNU coding standards: *NEWS*, *README*, *AUTHORS*, and *ChangeLog*.) Then run `autoreconf -iv` to generate the `configure` script (plus many other auxiliary files). Given the configure script, you can now run it to produce the makefile; given the makefile, you can run `make distcheck` to generate the tarball to ship out.

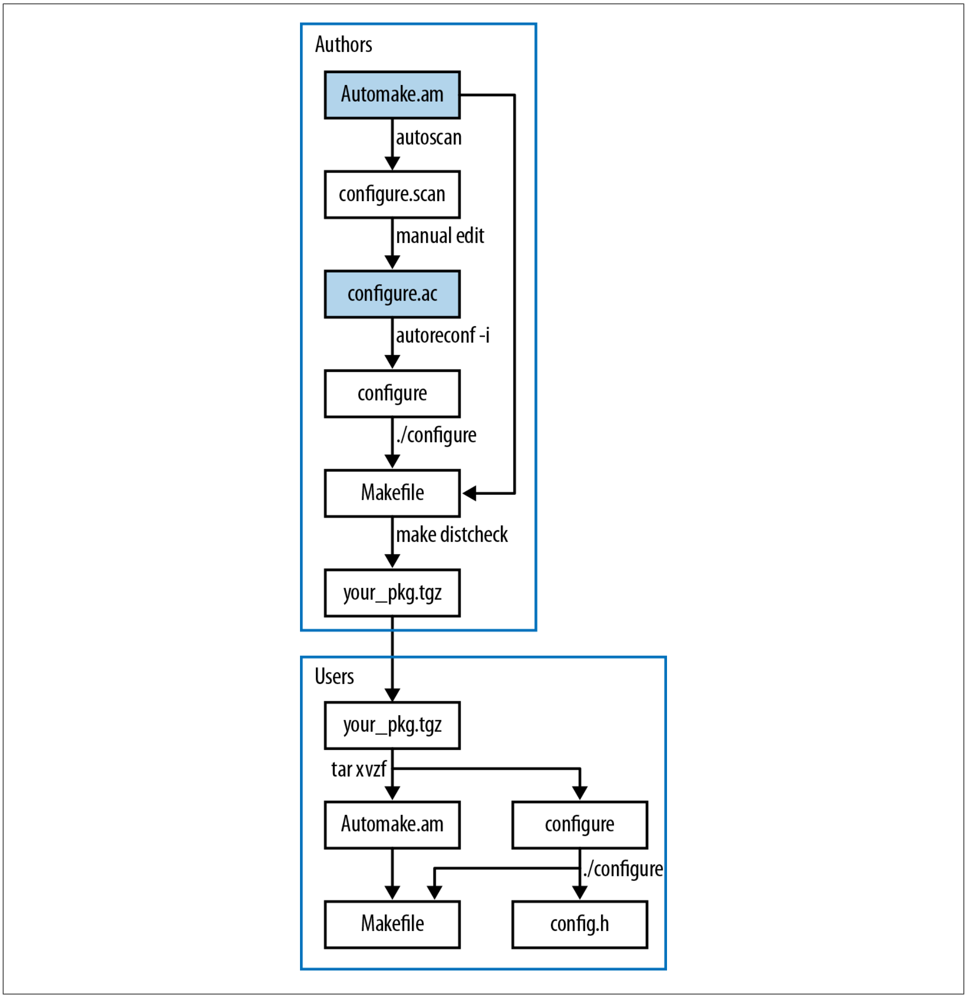


Figure 3-1. An Autotools flowchart. You will only be writing two of these files (the shaded ones); everything else is autogenerated by the given command.

Notice that there is some overlap: you will be using the same *configure* and *Makefile* as the user does, though your purpose is to produce a package and the user's purpose is to install the package. That means you have the facilities to install and test the code without fully packaging it, and users have the facility to repackage the code if somehow so inclined.

Describing the Makefile with Makefile.am

A typical makefile is half about the structure of what parts of your project depend on what other parts, and half about the specific variables and procedures to execute. Your

Makefile.am will focus on the structure of what needs to be compiled and what it depends on, and the specifics will be filled in by Autoconf and Automake's built-in knowledge of compilation on different platforms.

Makefile.am will consist of two types of entry, which I will refer to as *form variables* and *content variables*.

Form variables

A file that has to be handled by the makefile may have any of a number of intents, each of which Automake annotates by a short string.

bin
: Install to wherever programs go on the system, e.g., */usr/bin* or */usr/local/bin*.

include
: Install to wherever headers go, e.g., */usr/local/include*.

lib
: Install to wherever libraries go, e.g., */usr/local/lib*.

pkgbin
: If your project is named ***`project`***, install to a subdirectory of the main program directory, e.g., */usr/local/bin/**`project/`*** (similarly for `pkginclude` or `pkglib`).

check
: Use for testing the program, when the user types `make check`.

noinst
: Don't install; just keep the file around for use by another target.

Automake generates boilerplate make scripts, and it's got different boilerplate for:

`PROGRAMS`	
`HEADERS`	
`LIBRARIES`	*static libraries*
`LTLIBRARIES`	*shared libraries generated via Libtool*
`DIST`	*items to be distributed with the package, such as data files that didn't go elsewhere*

An intent plus a boilerplate format equals a form variable. For example:

`bin_PROGRAMS`	*programs to build and install*
`check_PROGRAMS`	*programs to build for testing*
`include_HEADERS`	*headers to install in the system-wide **`include`** directory*
`lib_LTLIBRARIES`	*dynamic and shared libraries, via Libtool*
`noinst_LIBRARIES`	*static library (no Libtool), to keep on hand for later*
`noinst_DIST`	*distribute with the package, but that's all*
`python_PYTHON`	*Python code, to byte-compile and install wherever Python packages go*

Now that you have the form down, you can use these to specify how each file gets handled. In the Hello, World example earlier, there was only one file that had to be dealt with:

```
bin_PROGRAMS = hello
```

To give another example, noinst_DIST is where I put data that is needed for the post-compilation tests but is not worth installing. Put as many items on each line as you'd like. For example:

```
pkginclude_HEADERS = firstpart.h secondpart.h
noinst_DIST = sample1.csv sample2.csv \
            sample3.csv sample4.csv
```

Content variables

Items under noinst_DIST just get copied into the distribution package, and HEADERS just get copied to the destination directory and have their permissions set appropriately. So those are basically settled.

For the compilation steps such as …_PROGRAMS and …_LDLIBRARIES, Automake needs to know more details about how the compilation works. At the very least, it needs to know what source files are being compiled. Thus, for every item on the right side of an equals sign of a form variable about compilation, we need a variable specifying the sources. For example, with these two programs we need two SOURCES lines:

```
bin_PROGRAMS= weather wxpredict
weather_SOURCES= temp.c barometer.c
wxpredict_SOURCES=rng.c tarotdeck.c
```

This may be all you need for a basic package.

> Here we have another failure of the principle that things that do different things should look different: the content variables have the same lower_UPPER look as the form variables shown earlier, but they are formed from entirely different parts and serve entirely different purposes.

Recall from the discussion about plain old makefiles that there are certain default rules built into make, which use variables like CFLAGS to tweak the details of what gets done. Automake's form variables effectively define more default rules, and they each have their own set of associated variables.

For example, the rule for linking together object files to form an executable might look something like:

```
$(CC) $(LDFLAGS) temp.o barometer.o $(LDADD) -o weather
```

> GNU Make uses LDLIBS for the library variable at the second half of the link command, and GNU Automake uses LDADD for the second half of the link command.

It's not all that hard to use your favorite Internet search engine to find the documentation that explains how a given form variable blows up into a set of targets in the final makefile, but I've found that the fastest way to find out what Automake does is to just run it and look at the output makefile in a text editor.

You can set all of these variables on a per-program or per-library basis, such as `weather_CFLAGS=-O1`. Or, use `AM_VARIABLE` to set a variable for all compilations or linkings. Here are my favorite compiler flags, which you met in the section "Using Makefiles" on page 15:

```
AM_CFLAGS=-g -Wall -O3
```

I didn't include `-std=gnu99` to get gcc to use a less obsolete standard, because this is a compiler-specific flag. If I put `AC_PROG_CC_C99` in *configure.ac*, then Autoconf will set the `CC` variable to `gcc -std=gnu99` for me. Autoscan isn't (yet) smart enough to put this into the *configure.scan* that it generates for you, so you will probably have to put it into *configure.ac* yourself. (As of this writing, there isn't yet an `AC_PROG_CC_C11` macro.)

Specific rules override `AM_`-based rules, so if you want to keep the general rules and add on an override for one flag, you would need a form like:

```
AM_CFLAGS=-g -Wall -O3
hello_CFLAGS = $(AM_CFLAGS) -O0
```

Adding testing

I haven't yet presented to you the dictionary library (which is covered all the way in "Extending Structures and Dictionaries" on page 205), but I have shown you the test harness for it, in "Unit Testing" on page 39. When Autotools pushes out the library, it makes sense to run the tests again. The agenda is now to build:

- A library, based on *dict.c* and *keyval.c*. It has headers, *dict.h* and *keyval.h*, which will need to ship out with the library.
- A testing program, which Automake needs to be aware is for testing, not for installation.
- The program, `dict_use`, that makes use of the library.

Example 3-6 expresses this agenda. The library gets built first, so that it can be used to generate the program and the test harness. The `TESTS` variable specifies which programs or scripts get run when the user types `make check`.

Example 3-6. An Automake file that handles testing (dict.automake)

```
AM_CFLAGS=`pkg-config --cflags glib-2.0` -g -O3 -Wall ❶

lib_LTLIBRARIES=libdict.la                                ❷
libdict_la_SOURCES=dict.c keyval.c                        ❸

include_HEADERS=keyval.h dict.h

bin_PROGRAMS=dict_use
dict_use_SOURCES=dict_use.c
dict_use_LDADD=libdict.la                                 ❹
```

```
TESTS=$(check_PROGRAMS)                               ❺
check_PROGRAMS=dict_test
dict_test_LDADD=libdict.la
```

❶ Here, I cheated, because other users might not have pkg-config installed. If we can't assume `pkg-config`, the best we can do is check for the library via Autoconf's `AC_CHECK_HEADER` and `AC_CHECK_LIB`, and if something is not found, ask the user to modify the `CFLAGS` or `LDFLAGS` environment variables to specify the right `-I` or `-L` flags. Because we haven't gotten to the discussion of *configure.ac*, I just use pkg-config.

❷ The first course of business is generating the shared library (via Libtool, and thus the *`LT`* in `LTLIBRARIES`).

❸ When writing a content variable from a filename, change anything that is not a letter, number, or @ sign into an underscore, as with `libdict.la` ⇒ `libdict_la`.

❹ Now that we've specified how to generate a shared library, we can use the shared library for assembling the program and tests.

❺ The `TESTS` variable specifies the tests that run when users type `make check`. Because these are often shell scripts that need no compilation, it is a distinct variable from `check_PROGRAMS`, which specifies programs intended for checking that have to be compiled. In our case, the two are identical, so we set one to the other.

Adding makefile bits

If you've done the research and found that Automake can't handle some odd target, then you can write it into *Makefile.am* as you would to the usual makefile. Just write a target and its associated actions as in:

```
target: deps
    script
```

anywhere in your *Makefile.am*, and Automake will copy it into the final makefile verbatim. For example, the *Makefile.am* in "Python Host" on page 93 explicitly specifies how to compile a Python package, because Automake by itself doesn't know how (it just knows how to byte-compile standalone *.py* files).

Variables outside of Automake's formats also get added verbatim. This will especially be useful in conjunction with Autoconf, because if *Makefile.am* has variable assignments such as:

```
TEMP=@autotemp@
HUMIDITY=@autohum@
```

and your `configure.ac` has:

```
#configure is a plain shell script; these are plain shell variables
autotemp=40
autohum=.8
```

```
AC_SUBST(autotemp)
AC_SUBST(autohum)
```

then the final makefile will have text reading:

```
TEMP=40
HUMIDITY=.8
```

So you have an easy conduit from the shell script that Autoconf spits out to the final makefile.

The configure Script

The *configure.ac* shell script produces two outputs: a makefile (with the help of Automake), and a header file named *config.h*.

If you've opened one of the sample *configure.ac* files produced so far, you might have noticed that it looks nothing at all like a shell script. This is because it makes heavy use of a set of macros (in the m4 macro language) that are predefined by Autoconf. Rest assured that every one of them will blow up into familiar-looking lines of shell script. That is, *configure.ac* isn't a recipe or specification to generate the `configure` shell script, it *is* `configure`, just compressed by some very impressive macros.

The m4 language doesn't have all that much syntax. Every macro is function-like, with parens after the macro name listing the comma-separated arguments (if any; else the parens are typically dropped). Where most languages write `'literal text'`, m4-via-Autoconf writes `[literal text]`, and to prevent surprises where m4 parses your inputs a little too aggressively, wrap all of your macro inputs in those square brackets.

The first line that Autoscan generated is a good example:

```
AC_INIT([FULL-PACKAGE-NAME], [VERSION], [BUG-REPORT-ADDRESS])
```

We know that this is going to generate a few hundred lines of shell code, and somewhere in there, the given elements will be set. Change the values in square brackets to whatever is relevant. You can often omit elements, so something like:

```
AC_INIT([hello], [1.0])
```

is valid if you don't want to hear from your users. At the extreme, one might give zero arguments to a macro like `AC_OUTPUT`, in which case you don't need to bother with the parentheses.

> The current custom in m4 documentation is to mark optional arguments with—I am not making this up—square brackets. So bear in mind that in m4 macros for Autoconf, square brackets mean literal not-for-expansion text, and in m4 macro documentation it means an optional argument.

What macros do we need for a functional Autoconf file? In order of appearance:

- `AC_INIT(…)`, already shown.
- `AM_INIT_AUTOMAKE`, to have Automake generate the makefile.
- `LT_INIT` sets up Libtool, which you need if and only if you are installing a shared library.
- `AC_CONFIG_FILES([`*`Makefile subdir/Makefile`*`])`, which tells Autoconf to go through those files listed and replace variables like `@cc@` with their appropriate value. If you have several makefiles (typically in subdirectories), then list them here.
- `AC_OUTPUT` to ship out.

So we have the specification for a functional build package for any POSIX system anywhere in four or five lines, three of which Autoscan probably wrote for you.

But the real art that takes *configure.ac* from functional to intelligent is in predicting problems some users might have and finding the Autoconf macro that detects the problem (and, where possible, fixes it). You saw one example earlier: I recommended adding `AC_PROG_CC_C99` to *configure.ac* to check for a C99 compiler. The POSIX standard requires that one be present via the command name `c99`, but just because POSIX says so doesn't mean that every system will have one, so it is exactly the sort of thing that a good configure script checks for.

Having libraries on hand is the star example of a prerequisite that has to be checked. Getting back to Autoconf's outputs for a moment, *config.h* is a standard C header consisting of a series of `#define` statements. For example, if Autoconf verified the presence of the GSL, you would find:

```
#define HAVE_LIBGSL 1
```

in *config.h*. You can then put `#ifdef`s into your C code to behave appropriately under appropriate circumstances.

Autoconf's check doesn't just find the library based on some naming scheme and hope that it actually works. It writes a do-nothing program using any one function somewhere in the library, then tries linking the program with the library. If the link step succeeds, then the linker was able to find and use the library as expected. So Autoscan can't autogenerate a check for the library, because it doesn't know what functions are to be found in it. The macro to check for a library is a one-liner, to which you provide the library name and a function that can be used for the check. For example:

```
AC_CHECK_LIB([glib-2.0],[g_free])
AC_CHECK_LIB([gsl],[gsl_blas_dgemm])
```

Add one line to *configure.ac* for every library you use that is not 100% guaranteed by the C standard, and those one-liners will blossom into the appropriate shell script snippets in `configure`.

You may recall how package managers always split libraries into the binary shared object package and the devel package with the headers. Users of your library might not remember (or even know) to install the header package, so check for it with, for example:

```
AC_CHECK_HEADER([gsl/gsl_matrix.h], , [AC_MSG_ERROR(
    [Couldn't find the GSL header files (I searched for \
    <gsl/gsl_matrix.h> on the include path). If you are \
    using a package manager, don't forget to install the \
    libgsl-devel package, as well as libgsl itself.])])
```

Notice the two commas: the arguments to the macro are (header to check, action if found, action if not found), and we are leaving the second blank.

What else could go wrong in a compilation? It's hard to become an authority on all the glitches of all the world's computers, given that we each have only a couple of machines at our disposal. Autoscan will give you some good suggestions, and you might find that running `autoreconf` also spits out some further warnings about elements to add to *configure.ac*. It gives good advice—follow its suggestions. But the best reference I have seen—a veritable litany of close readings of the POSIX standard, implementation failures, and practical advice—is the Autoconf manual itself. Some of it catalogs the glitches that Autoconf takes care of and are thus (thankfully) irrelevant nitpicking for the rest of us,[1] some of it is good advice for your code-writing, and some of the descriptions of system quirks are followed by the name of an Autoconf macro to include in your project's *configure.ac* should it be relevant to your situation.

More Bits of Shell

Because *configure.ac* is a compressed version of the `configure` script the user will run, you can throw in any arbitrary shell code you'd like. Before you do, double-check that what you want to do isn't yet handled by any macros—is your situation really so unique that it never happened to any Autotools users before?

If you don't find it in the Autoconf package itself, you can check the GNU Autoconf macro archive for additional macros, which you can save to an *m4* subdirectory in your project directory, where Autoconf will be able to find and use them. See also [Calcote 2010], an invaluable overview of the hairy details of Autotools.

A banner notifying users that they've made it through the configure process might be nice, and there's no need for a macro, because all you need is `echo`. Here's a sample banner:

```
echo \
"-----------------------------------------------------------

Thank you for installing ${PACKAGE_NAME} version ${PACKAGE_VERSION}.

Installation directory prefix: '${prefix}'.
Compilation command: '${CC} ${CFLAGS} ${CPPFLAGS}'
```

1. For example, "Solaris 10 dtksh and the UnixWare 7.1.1 Posix shell ... mishandle braced variable expansion that crosses a 1024- or 4096-byte buffer boundary within a here-document."

```
Now type 'make; sudo make install' to generate the program
and install it to your system.

------------------------------------------------------------"
```

The banner uses several variables defined by Autoconf. There's documentation about what shell variables the system defines for you to use, but you can also find the defined variables by skimming `configure` itself.

There's one more extended example of Autotools at work, linking to a Python library in "Python Host" on page 93.

CHAPTER 4

Version Control

> Look at the world through your Polaroid glasses
> Things'll look a whole lot better for the working classes.
>
> —Gang of Four, "I Found that Essence Rare"

This chapter is about revision control systems (RCSes), which maintain snapshots of the many different versions of a project as it develops, such as the stages in the development of a book, a tortured love letter, or a program. A revision control system gives us three major powers:

- Our filesystem now has a time dimension, so we can see what a file looked like last week and how it changed from then to now. Even without the other powers, this alone makes me a more confident writer.
- We can keep track of multiple versions of a project, such as my copy and my coauthor's copy. Even within my own work, I may want one version of a project (a *branch*) with an experimental feature, which should be kept segregated from the stable version that needs to be able to run without surprises.

  Further, the website *http://github.com* has about 45,000 projects that self-report as being primarily in C as of this writing, plus other smaller hosts for RCS repositories, such as the GNU's Savannah. Even if you aren't going to modify the code, cloning these repositories is a quick way to get the program or library onto your hard drive for your own use. When your own project is ready for public use (or before then), you can make the repository public as another means of distribution.
- Now that you and I both have versions of the same project, and both have equal ability to hack our versions of the code base, revision control gives us the power to merge together our multiple threads as easily as possible.

This chapter will cover Git, which is a *distributed revision control system*, meaning that any given copy of the project works as a standalone repository of the project and its history. There are others, with Mercurial and Bazaar the other front-runners in the category. There is largely a one-to-one mapping among the features of these systems, and what major differences had existed have merged over the years, so you should be able to pick the others up immediately after reading this chapter.

Changes via diff

The most rudimentary means of revision control is via `diff` and `patch`, which are POSIX-standard and therefore most certainly on your system. You probably have two files on your drive somewhere that are reasonably similar, and if not, grab any text file, change a few lines, and save the modified version with a new name. Try:

```
diff f1.c f2.c
```

and you will get a listing, a little more machine-readable than human-readable, that shows the lines that have changed between the two files. Piping output to a text file via `diff f1.c f2.c > diffs` and then opening *diffs* in your text editor may give you a colorized version that is easier to follow. You will see some lines giving the name of the file and location within the file, perhaps a few lines of context that did not change between the two files, and lines beginning with `+` and `-` showing the lines that got added and removed. Run `diff` with the `-u` flag to get a few lines of context around the additions/subtractions.

Given two directories holding two versions of your project, *v1* and *v2*, generate a single diff file in the unified diff format for the entire directories via the recursive (`-r`) option:

```
diff -ur v1 v2 > diff-v1v2
```

The `patch` command reads diff files and executes the changes listed there. If you and a friend both have *v1* of the project, you could send *diff-v1v2* to your friend, and she could run:

```
patch < diff-v1v2
```

to apply all of your changes to her copy of *v1*.

Or, if you have no friends, you can run `diff` from time to time on your own code and thus keep a record of the changes you have made over time. If you find that you have inserted a bug in your code, the diffs are the first place to look for hints about what you touched that you shouldn't have. If that isn't enough, and you already deleted *v1*, you could run the patch in reverse from the *v2* directory, `patch -R < diff-v1v2`, reverting version 2 back to version 1. If you were at version 4, you could even conceivably run a sequence of diffs to move further back in time:

```
cd v4
patch -R < diff-v3v4
patch -R < diff-v2v3
patch -R < diff-v1v2
```

I say *conceivably* because maintaining a sequence of diffs like this is tedious and error-prone. Thus, the revision control system, which will make and track the diffs for you.

Git's Objects

Git is a C program like any other, and is based on a small set of objects. The key object is the commit object, which is akin to a unified diff file. Given a previous commit object and some changes from that baseline, a new commit object encapsulates the information. It gets some support from the *index*, which is a list of the changes registered since the last commit object, the primary use of which will be in generating the next commit object.

The commit objects link together to form a tree much like any other tree. Each commit object will have (at least) one parent commit object. Stepping up and down the tree is akin to using `patch` and `patch -R` to step among versions.

The repository itself is not formally a single object in the Git source code, but I think of it as an object, because the usual operations one would define, such as new, copy, and free, apply to the entire repository. Get a new repository in the directory you are working in via:

```
git init
```

OK, you now have a revision control system in place. You might not see it, because Git stores all its files in a directory named *.git*, where the dot means that all the usual utilities like `ls` will take it to be hidden. You can look for it via, e.g., `ls -a` or via a *show hidden files* option in your favorite file manager.

Alternatively, copy a repository via `git clone`. This is how you would get a project from Savannah or Github. To get the source code for Git using `git`:

```
git clone git://github.com/gitster/git.git
```

If you want to test something on a repository in *~/myrepo* and are worried that you might break something, go to a temp directory (say `mkdir ~/tmp; cd ~/tmp`), clone your repository with `git clone` *~/myrepo*, and experiment away. Deleting the clone when done (`rm -rf` *~/tmp/myrepo*) has no effect on the original.

Given that all the data about a repository is in the *.git* subdirectory of your project directory, the analog to freeing a repository is simple:

```
rm -rf .git
```

Having the whole repository so self-contained means that you can make spare copies to shunt between home and work, copy everything to a temp directory for a quick experiment, and so on, without much hassle.

We're almost ready to generate some commit objects, but because they summarize diffs since the starting point or a prior commit, we're going to have to have on hand some diffs to commit. The index (Git source: `struct index_state`) is a list of changes that are to be bundled into the next commit. It exists because we don't actually want every change in the project directory to be recorded. For example, *gnomes.c* and *gnomes.h* will beget *gnomes.o* and the executable *gnomes*. Your RCS should track *gnomes.c* and *gnomes.h* and let the others get regenerated as needed. So the key operation with the index is adding elements to its list of changes. Use:

```
git add gnomes.c gnomes.h
```

to add these files to the index. Other typical changes to the list of files tracked also need to be recorded in the index:

```
git add newfile
git rm oldfile
git mv flie file
```

Changes you made to files that are already tracked by Git are not automatically added to the index, which might be a surprise to users of other RCSes (but see below). Add each individually via `git add changedfile`, or use:

```
git add -u
```

to add to the index changes to all the files Git already tracks.

At some point you have enough changes listed in the index that they should be recorded as a commit object in the repository. Generate a new commit object via:

```
git commit -a -m "here is an initial commit."
```

The `-m` flag attaches a message to the revision, which you'll read when you run `git log` later on. If you omit the message, then Git will start the text editor specified in the environment variable `EDITOR` so you can enter it (the default editor is typically vi; export that variable in your shell's startup script, e.g., *.bashrc* or *.zshrc*, if you want something different).

The `-a` flag tells Git that there are good odds that I forgot to run `git add -u`, so please run it just before committing. In practice, this means that you never have to run `git add -u` explicitly, as long as you always remember the `-a` flag in `git commit -a`.

It is easy to find Git experts who are concerned with generating a coherent, clean narrative from their commits. Instead of commit messages like "added an index object, plus some bug fixes along the way," an expert Git author would create two commits, one with the message "added an index object" and one with "bug fixes." Our authors have such control because nothing is added to the index by default, so they can add only enough to express one precise change in the code, write the index to a commit object, then add a new set of items to a clean index to generate the next commit object. I found one blogger who took several pages to describe his commit routine: "For the most complicated cases, I will print out the diffs, read them over, and mark them up in six colors of highlighter…" However, until you become a Git expert, this will be much more control over the index than you really need or want. That is, not using `-a` with `git commit` is an advanced use that many people never bother with. In a perfect world, the `-a` would be the default, but it isn't, so don't forget it.

Calling `git commit -a` writes a new commit object to the repository based on all of the changes the index was able to track, and clears the index. Having saved your work, you can now continue to add more. Further—and this is the real, major benefit of revision control so far—you can delete whatever you want, confident that it could be recovered if you need it back. Don't clutter up the code with large blocks of commented-out obsolete routines—delete!

> After you commit, you will almost certainly slap your forehead and realize something you forgot. Instead of performing another commit, you can run `git commit --amend -a` to redo your last commit.

Diff/Snapshot Duality

Physicists sometimes prefer to think of light as a wave and sometimes as a particle; similarly, a commit object is sometimes best thought of as a complete snapshot of the project at a moment in time and sometimes as a diff from its parent. From either perspective, it includes a record of the author, the name of the object (as we'll see later), the message you attached via the `-m` flag, and (unless it is the initial commit) a pointer to the parent commit object(s).

Internally, is a commit a diff or a snapshot? It could be either or both. There was once a time when Git always stored a snapshot, unless you ran `git gc` (garbage collect) to compress the set of snapshots into a set of deltas (aka diffs). Users complained about having to remember to run `git gc`, so it now runs automatically after certain commands, meaning that Git is probably (but by no means always) storing diffs.

Having generated a commit object, your interactions with it will mostly consist of looking at its contents. You'll use `git diff` to see the diffs that are the core of the commit object and `git log` to see the metadata.

The key metadata is the name of the object, which is assigned via an unpleasant but sensible naming convention: the SHA1 hash, a 40-digit hexadecimal number that can be assigned to an object, in a manner that lets us assume that no two objects will have the same hash, and that the same object will have the same name in every copy of the repository. When you commit your files, you'll see the first few digits of the hash on the screen, and you can run `git log` to see the list of commit objects in the history of the current commit object, listed by their hash and the human language message you wrote when you did the commit (and see `git help log` for the other available metadata). Fortunately, you need only as much of the hash as will uniquely identify your commit. So if you look at the log and decide that you want to check out revision number fe9c49cddac5150dc974de1f7248a1c5e3b33e89, you can do so with:

```
git checkout fe9c4
```

This does the sort of time-travel via diffs that `patch` almost provided, rewinding to the state of the project at commit `fe9c4`.

Because a given commit only has pointers to its parents, not its children, when you check `git log` after checking out an old commit, you will see the trace of objects that led up to this commit, but not later commits. The rarely used `git reflog` will show you the full list of commit objects the repository knows about, but the easier means of jumping back to the most current version of the project is via a *tag*, a human-friendly name that you won't have to look up in the log. Tags are maintained as separate objects in the repository and hold a pointer to a commit object being tagged. The most frequently used tag is `master`, which refers to the last commit object on the master branch (which, because we haven't covered branching yet, is probably the only branch you have). Thus, to return from back in time to the latest state, use:

```
git checkout master
```

Getting back to `git diff`, it shows what changes you have made since the last committed revision. The output is what would be written to the next commit object via `git commit -a`. As with the output from the plain `diff` program, `git diff > diffs` will write to a file that may be more legible in your colorized text editor.

Without arguments, `git diff` shows the diff between the index and what is in the project directory; if you haven't added anything to the index yet, this will be every change since the last commit. With one commit object name, `git diff` shows the sequence of changes between that commit and what is in the project directory. With two names, it shows the sequence of changes from one commit to the other:

```
git diff                Show the diffs between the working directory and the index.
git diff 234e2a         Show the diffs between the working directory and the given commit object.
git diff 234e2a 8b90ac  Show the changes from one commit object to another.
```

At this point, you know how to:

- Save frequent incremental revisions of your project.
- Get a log of your committed revisions.
- Find out what you changed or added recently.
- Check out earlier versions so that you can recover earlier work if needed.

Having a backup system organized enough that you can delete code with confidence and recover as needed will already make you a better writer.

The Stash

Commit objects are the reference points from which most Git activity occurs. For example, Git prefers to apply patches relative to a commit, and you can jump to any commit, but if you jump away from a working directory that does not match a commit you have no way to jump back. When there are uncommitted changes in the current working directory, Git will warn you that you are not at a commit and typically refuse to perform the operation you asked it to do. One way to go back to a commit would be to write down all the work you had done since the last commit, revert your project to the last commit, execute the operation, then redo the saved work after you are finished jumping or patching.

Thus we employ the *stash*, a special commit object mostly equivalent to what you would get from `git commit -a`, but with a few special features, such as retaining all the untracked junk in your working directory. Here is the typical procedure:

```
git stash
# Code is now as it was at last checkin.
git checkout fe9c4

# Look around here.

git checkout master      # Or whatever commit you had started with
# Code is now as it was at last checkin, so replay stashed diffs with:
git stash pop
```

Another sometimes-appropriate alternative for checking out given changes in your working directory is `git reset --hard`, which takes the working directory back to the state it was in when you last checked out. The command sounds severe because it is: you are about to throw away all work you had done since the last checkout.

Trees and Their Branches

There is one tree in a repository, which got generated when the first author of a new repository ran `git init`. You are probably familiar with tree data structures, consisting of a set of nodes, where each node has links to some number of children and a link to a parent (and in exotic trees like Git's, possibly several parents).

Indeed, all commit objects but the initial one have a parent, and the object records the diffs between itself and the parent commit. The terminal node in the sequence, the tip of the branch, is tagged with a branch name. For our purposes, there is a one-to-one correspondence between branch tips and the series of diffs that led to that branch. The one-to-one correspondence means we can interchangeably refer to branches and the commit object at the tip of the branch. Thus, if the tip of the `master` branch is commit `234a3d`, then `git checkout master` and `git checkout 234a3d` are entirely equivalent (until a new commit gets written, and that takes on the `master` label). It also means that the list of commit objects on a branch can be rederived at any time by starting at the commit at the named tip and tracing back to the origin of the tree.

The typical custom is to keep the master branch fully functional at all times. When you want to add a new feature or try a new thread of inquiry, create a new branch for it. When the branch is fully functioning, you will be able to merge the new feature back into the master using the methods to follow.

There are two ways to create a new branch splitting off from the present state of your project:

```
git branch newleaf          # Create a new branch...
git checkout newleaf        # then check out the branch you just created.
    # Or execute both steps at once with the equivalent:
git checkout -b newleaf
```

Having created the new branch, switch between the tips of the two branches via `git checkout master` and `git checkout` *`newleaf`*.

What branch are you on right now? Find out with:

```
git branch
```

which will list all branches and put a * by the one that is currently active.

What would happen if you were to build a time machine, go back to before you were born, and kill your parents? If we learned anything from science fiction, it's that if we change history, the present doesn't change, but a new alternate history splinters off. So if you check out an old version, make changes, and check in a new commit object with your newly made changes, then you now have a new branch distinct from the master branch. You will find via `git branch` that when the past forks like this, you will be on `(no branch)`. Untagged branches tend to create problems, so if ever you find that you are on `(no branch)`, then run `git branch -m` *`new_branch_name`* to name the branch to which you've just splintered.

> **Visual Aids**
>
> There are several graphical interfaces to be had, which are especially useful when tracing how branches diverged and merged. Try `gitk` or `git gui` for Tk-based GUIs, or `git instaweb` to start a web server that you can interact with in your browser, or ask your package manager or Internet search engine for several more.

Merging

So far, we have generated new commit objects by starting with a commit object as a starting point and applying a list of diffs from the index. A branch is also a series of diffs, so given an arbitrary commit object and a list of diffs from a branch, we should be able to create a new commit object in which the branch's diffs are applied to the existing commit object. This is a *merge*. To merge all the changes that occurred over the course of *`newleaf`* back into `master`, switch to `master` and use `git merge`:

```
git checkout master
git merge newleaf
```

For example, you have used a branch off of `master` to develop a new feature, and it finally passes all tests; then applying all of the diffs from the development branch to `master` would create a new commit object with the new feature soundly in place.

Let us say that, while working on the new feature, you never checked out `master` and so made no changes to it. Then applying the sequence of diffs from the other branch would simply be a fast replay of all of the changes recorded in each commit object in the branch, which Git calls a *fast-forward*.

But if you made any changes to `master`, then this is no longer a simple question of a fast application of all of the diffs. For example, say that at the point where the branch split off, *gnomes.c* had:

```
short int height_inches;
```

In `master`, you removed the derogatory type:

```
int height_inches;
```

The purpose of ***`newleaf`*** was to convert to metric:

```
short int height_cm;
```

At this point, Git is stymied. Knowing how to combine these lines requires knowing what you as a human intended. Git's solution is to modify your text file to include both versions, something like:

```
<<<<<<< HEAD
int height_inches;
=======
short int height_cm;
>>>>>>> 3c3c3c
```

The merge is put on hold, waiting for you to edit the file to express the change you would like to see. In this case, you would probably reduce the five-line chunk Git left in the text file to:

```
int height_cm;
```

Here is the procedure for committing merges in a non-fast-forward, meaning that there have been changes in both branches since they diverged:

1. Run `git merge` *`other_branch`*.
2. In all likelihood, get told that there are conflicts you have to resolve.
3. Check the list of unmerged files using `git status`.
4. Pick a file to manually check on. Open it in a text editor and find the merge-me marks if it is a content conflict. If it's a filename or file position conflict, move the file into place.
5. Run `git add` *`your_now_fixed_file`*.
6. Repeat steps 3–5 until all unmerged files are checked in.
7. Run `git commit` to finalize the merge.

Take comfort in all this manual work. Git is conservative in merging and won't automatically do anything that could, under some storyline, cause you to lose work.

When you are done with the merge, all of the relevant diffs that occurred in the side branch are represented in the final commit object of the merged-to branch, so the custom is to delete the side branch:

```
git delete other_branch
```

The ***other_branch*** tag is deleted, but the commit objects that led up to it are still in the repository for your reference.

The Rebase

Say you have a main branch and split off a testing branch from it on Monday. Then on Tuesday through Thursday, you make extensive changes to both the main and testing branch. On Friday, when you try to merge the test branch back into the main, you have an overwhelming number of little conflicts to resolve.

Let's start the week over. You split the testing branch off from the main branch on Monday, meaning that the last commits on both branches share a common ancestor of Monday's commit on the main branch. On Tuesday, you have a new commit on the main branch; let it be commit `abcd123`. At the end of the day, you replay all the diffs that occurred on the main branch onto the testing branch:

```
git branch testing   # get on the testing branch
git rebase abcd123   # or equivalently: git rebase main
```

With the `rebase` command, all of the changes made on the main branch since the common ancestor are replayed on the testing branch. You might need to manually merge things, but by only having one day's work to merge, we can hope that the task of merging is more manageable.

Now that all changes up to `abcd123` are present in both branches, it is as if the branches had actually split off from that commit, rather than Monday's commit. This is where the name of the procedure comes from: the testing branch has been rebased to split off from a new point on the main branch.

You also perform rebases at the end of Wednesday, Thursday, and Friday, and each of them is reasonably painless, as the testing branch kept up with the changes on the main branch throughout the week.

Rebases are often cast as an advanced use of Git, because other systems that aren't as capable with diff-application don't have this technique. But in practice rebasing and merging are about on equal footing: both apply diffs from another branch to produce a commit, and the only question is whether you are tying together the ends of two branches (in which case, merge) or want both branches to continue their separate lives for a while longer (in which case, rebase). The typical usage is to rebase the diffs from the master into the side branch, and merge the diffs from the side branch into the master, so there is a symmetry between the two in practice. And as noted, letting diffs pile up on multiple branches can make the final merge a pain, so it is good form to rebase reasonably often.

Remote Repositories

Everything to this point has been occurring within one tree. If you cloned a repository from elsewhere, then at the moment of cloning, you and the origin both have identical trees with identical commit objects. However, you and your colleagues will continue working, so you will all be adding new and different commit objects.

Your repository has a list of *remotes*, which are pointers to other repositories related to this one elsewhere in the world. If you got your repository via `git clone`, then the repository from which you cloned is named `origin` as far as the new repository is concerned. In the typical case, this is the only remote you will ever use.

When you first clone and run `git branch`, you'll see one lonely branch, regardless of how many branches the origin repository had. But run `git branch -a` to see all the branches that Git knows about, and you will see those in the remote as well as the local ones. If you cloned a repository from Github, et al, you can use this to check whether other authors had pushed other branches to the central repository.

Those copies of the branches in your local repository are as of the first time you pulled. Next week, to update those remote branches with the information from the origin repository, run `git fetch`.

Now that you have up-to-date remote branches in your repository, you could merge using the full name of the branch, for example, `git merge remotes/origin/master`.

As a shortcut to `git fetch; git merge remotes/origin/master`, use:

```
git pull origin master
```

to fetch the remote changes and merge them into your current repository all at once.

The converse is `push`, which you'll use to update the repository with your last commit (not the state of your index or working directory). If you are working on a branch named `bbranch` and want to push to the remote with the same name, use:

```
git push origin bbranch
```

There are good odds that when you push your changes, applying the diffs from your branch to the remote branch will not be a fast-forward (if it is, then your colleagues haven't been doing any work). Resolving a non-fast-forward merge typically requires human intervention, and there is probably not a human at the remote. Thus, Git will allow only fast-forward pushes. How can you guarantee that your push is a fast forward?

1. Run `git pull origin` to get the changes made since your last pull.
2. Merge as seen earlier, wherein you as a human resolve those changes a computer cannot.
3. Run `git commit -a -m "`*`dealt with merges`*`"`.
4. Run `git push origin master`, because now Git only has to apply a single diff, which can be done automatically.

The Central Repository

Despite all the discussion of decentralization, the easiest setup for sharing is still to have a central repository that everybody clones, meaning that everybody has the same origin repository. This is how downloading from Github and Savannah typically works. When setting up a repository for this sort of thing, use `git init --bare`, which means that nobody can actually do work in that directory, and users will have to clone to do anything at all. There are also some permissions flags that come in handy, such as `--shared=group` to allow all members of a POSIX group to read and write to the repository.

You can't push to a branch in a nonbare remote repository that the repository owner has checked out; doing so will cause chaos. If this happens, ask your colleague to `git branch` to a different branch, then push while the target branch is in the background.

Or, your colleague can set up a public bare repository and a private working repository. You push to the public repository, and your colleague pulls the changes to his working repository when convenient.

The structure of a Git repository is not especially complex: there are commit objects representing the changes since the parent commit object, organized into a tree, with an index gathering together the changes to be made in the next commit. But with these elements, you can organize multiple versions of your work, confidently delete things, create experimental branches and merge them back to the main thread when they pass all their tests, and merge your colleagues' work with your own. From there, `git help` and your favorite Internet search engine will teach you many more tricks and ways to do these things more smoothly.

CHAPTER 5

Playing Nice with Others

The count of programming languages approaches infinity, and a huge chunk of them have a C interface. This short chapter offers some general notes about the process and demonstrates in detail the interface with one language, Python.

Every language has its own customs for packaging and distribution, which means that after you write the bridge code in C and the host language, you get to face the task of getting the packaging system to compile and link everything. This gives me a chance to present more advanced tricks for Autotools, such as conditionally processing a subdirectory and adding install hooks.

The Process

I can't give you details about how to write the bridge code for every language that calls C code (herein the host language), but the same problems must be surmounted in every case:

- On the C side, writing functions to be easy to call from other languages.
- Writing the wrapper function that calls the C function in the host language.
- Handling C-side data structures. Can they be passed back and forth?
- Linking to the C library. That is, once everything is compiled, we have to make sure that at runtime, the system knows where to find the library.

Writing to Be Read by Nonnatives

The host language has no access to your source code, and there will be constraints in calling C code from the host.

- Macros are read by the preprocessor, so that the final shared library has no trace of them. In Chapter 10, I discuss all sorts of ways for you to use macros to make using functions more pleasant from within C, so that you don't even need to rely on a scripting language for a friendlier interface. But when you do need to link to the library from outside of C, you won't have those macros on hand, and your wrapper function will have to replicate whatever the function-calling macro does.

- Each call to the C side from the host will have a small cost to set up, so limiting the number of interface functions will be essential. Some C libraries have a set of functions for full control, and "easy" wrapper functions to do typical workflows with one call; if your library has dozens of functions, consider writing a few such easy interface functions. It's better to have a host package that provides only the core functionality of the C-side library than to have a host package that is unmaintainable and eventually breaks.
- Objects are great for this situation. The short version of Chapter 11, which discusses this in detail, is that one file defines a struct and several functions that interface with the struct, including `*struct*_new`, `*struct*_copy`, `*struct*_free`, `*struct*_print`, and so on. A well-designed object will have a small number of interface functions, or will at least have a minimal subset for use by the host language. As discussed in the next section, having a central structure holding the data will also make things easier.

The Wrapper Function

For every C function you expect that users will call, you will also need a wrapper function on the host side. This function serves a number of purposes:

- Customer service. Users of the host language who don't know C don't want to have to think about the C-calling system. They expect the help system to say something about your functions, and the help system is probably directly tied to functions and objects in the host language. If users are used to functions being elements of objects, and you didn't set them up as such on the C side, then you can set up the object as per custom on the host side.
- Translation in and out. The host language's representation of integers, strings, and floating-point numbers may be `int`, `char*`, and `double`, but in most cases, you'll need some sort of translation between host and C data types. In fact, you'll need the translation twice: once from host to C, then after you call your C function, once from C to host. See the example for Python that follows.

Users will expect to interact with a host-side function, so it's hard to avoid having a host function for every C-side function, but suddenly you've doubled the number of functions you have to maintain. There will be redundancy, as defaults you specify for inputs on the C side will typically have to be respecified on the host side, and argument lists sent by the host will typically have to be checked every time you modify them on the C side. There's no point fighting it: you're going to have redundancy and will have to remember to check the host-side code every time you change the C side interfaces. So it goes.

Smuggling Data Structures Across the Border

Forget about a non-C language for now; let's consider two C files, *struct.c* and *user.c*, where a data structure is generated as a local variable with internal linkage in the first and needs to be used by the second.

The easiest way to reference the data across files is a simple pointer: *struct.c* allocates the pointer, *user.c* receives it, and all is well. The definition of the structure might be public, in which case the user file can look at the data pointed to by the pointer and make changes as desired. Because the procedures in the user are modifying the pointed-to data, there's no mismatch between what *struct.c* and *user.c* are seeing.

Conversely, if *struct.c* sent a copy of the data, then once the user made any modification, we'd have a mismatch between data held internally by the two files. If we expect the received data to be used and immediately thrown away, or treated as read-only, or that *struct.c* will never care to look at the data again, then there's no problem handing ownership over to the user.

So for data structures that *struct.c* expects to operate on again, we should send a pointer; for throwaway results, we can send the data itself.

What if the structure of the data structure isn't public? It seems that the function in *user.c* would receive a pointer, and then won't be able to do anything with it. But it can do one thing: it can send the pointer back to *struct.c*. When you think about it, this is a common form. You might have a linked list object, allocated via a list allocation function (though GLib doesn't have one), then use `g_list_append` to add elements, then use `g_list_foreach` to apply an operation to all list elements, and so on, simply passing the pointer to the list from one function to the next.

When bridging between C and another language that doesn't understand how to read a C struct, this is referred to as an *opaque pointer* or an *external pointer*. As in the case between two *.c* files, there's no ambiguity about who owns the data, and with enough interface functions, we can still get a lot of work done. That solves the problem of data sharing for a good percentage of the host languages in the world, because there is an explicit mechanism for passing an opaque pointer.

If the host language doesn't support opaque pointers, then return the pointer anyway. An address is an integer, and writing it down as such doesn't produce any ambiguity (Example 5-1).

Example 5-1. We can treat a pointer address as a plain integer. There's little if any reason to do this in plain C, but it may be necessary for talking to a host language (`intptr.c`)

```
#include <stdio.h>
#include <stdint.h> //intptr_t

int main(){
    char *astring = "I am somwhere in memory.";
    intptr_t location = (intptr_t)astring;  ❶
```

```
    printf("%s\n", (char*)location);        ❷
}
```

❶ The `intptr_t` type is guaranteed to have a range large enough to store a pointer address (C99 §7.18.1.4(1) & C11 §7.20.1.4(1)).

❷ Of course, casting a pointer to an integer loses all type information, so we have to explicitly respecify the type of the pointer. This is error-prone, which is why this technique is only useful in the context of dealing with systems that don't understand pointers.

What can go wrong? If the range of the integer type in your host language is too small, then this will fail depending on where in memory your data lives, in which case you might do better to write the pointer to a string, then when you get the string back, parse it back via `atol` (ASCII to long int). There's always a way.

Also, we are assuming that the pointer is not moved or freed between when it first gets handed over to the host and when the host asks for it again. For example, if there is a call to `realloc` on the C side, the new opaque pointer will have to get handed to the host.

Linking

Dynamic linking works via the POSIX-standard `dlopen` function, which opens a shared library, and the `dlsym` function, which takes in a handle from `dlopen` and an object name and returns a pointer to that object. Windows systems have a similar setup, but the functions are named `LoadLibrary` and `GetProcAddress`; for simplicity of exposition, I'll stick to the POSIX names. Your host language will need you to tell it which C functions and variables to call up via `dlsym`. That is, you can expect that there will be a registration step where you list the objects that `dlsym` will get called on. Some systems automatically handle both the `dlopen` and `dlsym` steps for C code packaged with the host's packaging tools; some require that you specify everything, though this is at worst a line of boilerplate per symbol.

But there's one more level to linking: what if your C code requires a library on the system and thus needs runtime linking (as per "Runtime Linking" on page 14)? The easy answer in the C world is to use Autotools to search the library path for the library you need and set the right compilation flags. If your host language's build system supports Autotools, then you will have no problem linking to other libraries on the system. If you can rely on pkg-config, then that might also do what you need. If Autotools and pkg-config are both out, then I wish you the best of luck in working out how to robustly get the host's installation system to correctly link your library. There seem to be a lot of authors of scripting languages who still think that linking one C library to another is an eccentric special case that needs to be handled manually every time.

Python Host

The remainder of this chapter presents an example via Python, which goes through the preceding considerations for the ideal gas function that will be presented in Example 10-11; for now, take the function as given as we focus on packaging it. Python has extensive online documentation to show you how the details work, but Example 5-2 suffices to show you some of the abstract steps at work: registering the function, converting the host-format inputs to common C formats, and converting the common C outputs to the host format. Then we'll get to linking.

The ideal gas library only provides one function, to calculate the pressure of an ideal gas given a temperature input, so the final package will be only slightly more interesting than one that prints "Hello, World" to the screen. Nonetheless, we'll be able to start up Python and run:

```
from pvnrt import *
pressure_from_temp(100)
```

and Python will know where to find the `pvnrt` package, and how to find the C function (`ideal_pressure`) that gets called when you call the `pressure_from_temp` Python command.

The story starts with Example 5-2, which provides C code using the Python API to wrap the C function and register it as part of the Python package to be set up subsequently.

Example 5-2. The wrapper for the ideal gas function (py/ideal.py.c)

```
#include <Python.h>
#include "../ideal.h"

static PyObject *ideal_py(PyObject *self, PyObject *args){
    double intemp;
    if (!PyArg_ParseTuple(args, "d", &intemp)) return NULL;          ❶
    double out = ideal_pressure(.temp=intemp);
    return Py_BuildValue("d", out);                                   ❷
}

static PyMethodDef method_list[] = {                                  ❸
    {"pressure_from_temp",  ideal_py, METH_VARARGS,
     "Get the pressure from the temperature of one mole of gunk"},
    {NULL, NULL, 0, NULL}
};

PyMODINIT_FUNC initpvnrt(void) {
    Py_InitModule("pvnrt", method_list);
}
```

❶ Python sends a single object listing all of the function arguments, akin to `argv`. This line reads them into a list of C variables, as specified by the format specifiers (akin to `scanf`). If we were parsing a double, a string, and an integer, it would look like: `PyArg_ParseTuple(args, "dsi", &indbl, &instr, &inint)`.

❷ The output also takes in a list of types and C values, returning a single bundle for Python's use.

❸ The rest of this file is registration. We have to build a `{NULL, NULL, 0, NULL}`-terminated list of the methods in the function (including Python name, C function, calling convention, one-line documentation), then write a function named `init`*`pkgname`* to read in the list.

The example shows how Python handles the input- and output-translating lines without much fuss (on the C side, though some other systems do it on the host side). The file concludes with a registration section, which is also not all that bad.

Now for the problem of compilation, which can require some real problem solving.

Compiling and Linking

As you saw in "Packaging Your Code with Autotools" on page 64, setting up Autotools to generate the library requires a two-line *Makefile.am* and a slight modification of the boilerplate in the *configure.ac* file produced by Autoscan. On top of that, Python has its own build system, Distutils, so we need to set that up, then modify the Autotools files to make Distutils run automatically.

The Conditional Subdirectory for Automake

I decided to put all the Python-related files into a subdirectory of the main project folder. If Autoconf detects the right Python development tools, then I'll ask it to go into that subdirectory and get to work; if the development tools aren't found, then it can ignore the subdirectory.

Example 5-3 shows a *configure.ac* file that checks for Python and its development headers, and compiles the *py* subdirectory if and only if the right components are found. The first several lines are as before, taken from what `autoscan` gave me, plus the usual additions from before. The next lines check for Python, which I cut and pasted from the Automake documentation. They will generate a `PYTHON` variable with the path to Python; for *configure.ac*, two variables by the name of `HAVE_PYTHON_TRUE` and `HAVE_PYTHON_FALSE`; and for the makefile, a variable named `HAVE_PYTHON`.

If Python or its headers are missing, then the `PYTHON` variable is set to `:`, which we can check for later. If the requisite tools are present, then we use a simple shell if-then-fi block to ask Autoconf to configure the *py* subdirectory as well as the current directory.

Example 5-3. A configure.ac file for the Python building task (py/configure.ac)

```
AC_PREREQ([2.68])
AC_INIT([pvnrt], [1], [/dev/null])
AC_CONFIG_SRCDIR([ideal.c])
AC_CONFIG_HEADERS([config.h])
```

```
AM_INIT_AUTOMAKE
AC_PROG_CC_C99
LT_INIT

AM_PATH_PYTHON(,, [:])                                  ❶
AM_CONDITIONAL([HAVE_PYTHON], [test "$PYTHON" != :])

if test "$PYTHON" != : ; then                           ❷
AC_CONFIG_SUBDIRS([py])
fi

AC_CONFIG_FILES([Makefile py/Makefile])                 ❸
AC_OUTPUT
```

❶ These lines check for Python, setting a `PYTHON` variable to `:` if it is not found, then add a `HAVE_PYTHON` variable appropriately.

❷ If the `PYTHON` variable is set, then Autoconf will continue into the *py* subdirectory; else it will ignore this subdirectory.

❸ There's a *Makefile.am* in the *py* subdirectory that needs to be turned into a makefile; Autoconf needs to be told about that task as well.

> You'll see a lot of new little bits of Autotools syntax in this chapter, such as the `AM_PATH_PYTHON` snippet from earlier, and Automake's `all-local` and `install-exec-hook` targets later. The nature of Autotools is that it is a basic system (which I hope I communicated in Chapter 3) with a hook for every conceivable contingency or exception. There's no point memorizing them, and for the most part, they can't be derived from basic principles. The nature of working with Autotools, then, is that when odd contingencies come up, we can expect to search the manuals or the Internet at large for the right recipe.

We also have to tell Automake about the subdirectory, which is also just another if/then block, as in Example 5-4.

Example 5-4. A Makefile.am file for the root directory of a project with a Python subdirectory (py/Makefile.am)

```
pyexec_LTLIBRARIES=libpvnrt.la
libpvnrt_la_SOURCES=ideal.c

SUBDIRS=.

if HAVE_PYTHON      ❶
SUBDIRS += py
endif
```

❶ Autoconf produced this `HAVE_PYTHON` variable, and here is where we use it. If it exists, Automake will add *py* to its list of directories to handle; or else it will only deal with the current directory.

The first two lines specify that Libtool should set up a shared library to be installed with Python executables, named `libpvnrt`, based on source code in `ideal.c`. After that, I specify the first subdirectory to handle, which is `.` (the current directory). The static library has to be built before the Python wrapper for the library, and we guarantee that it is handled first by putting `.` at the head of the `SUBDIRS` list. Then, if `HAVE_PYTHON` checks out OK, we can use Automake's `+=` operator to add the *py* directory to the list.

At this point, we have a setup that handles the *py* directory if and only if the Python development tools are in place. Now, let us descend into the *py* directory itself and look at how to get Distutils and Autotools to talk to each other.

Distutils Backed with Autotools

By now, you are probably very used to the procedure for compiling even complex programs and libraries:

- Specify the files involved (e.g., via ***`your_program`***`_SOURCES` in *Makefile.am*, or go straight to the `objects` list in the sample makefile used throughout this book).
- Specify the flags for the compiler (universally via a variable named `CFLAGS`).
- Specify the flags and additional libraries for the linker (e.g., `LDLIBS` for GNU Make or `LDADD` for GNU Autotools).

Those are the three steps, and although there are many ways to screw them up, the contract is clear enough. To this point in the book, I've shown you how to communicate the three parts via a simple makefile, via Autotools, and even via shell aliases. Now we have to communicate them to Distutils. Example 5-5 provides a *setup.py* file to control the production of a Python package.

Example 5-5. A setup.py file to control the production of a Python package (py/setup.py)

```
from distutils.core import setup, Extension

py_modules= ['pvnrt']

Emodule = Extension('pvnrt',
       libraries=['pvnrt'],       ❶
       library_dirs=['..'],       ❷
       sources = ['ideal.py.c'])  ❸

setup (name = 'pvnrt',            ❹
       version = '1.0',
       description = 'pressure * volume = n * R * Temperature',
       ext_modules = [Emodule])
```

❶ The sources and the linker flags. The `libraries` line indicates that there will be a `-lpvnrt` sent to the linker.

❷ This line indicates that a `-L..` will be added to the linker's flags to indicate that it should search for libraries there. This needs to be manually written.

❸ List the sources here, as you would in Automake.

❹ Here we provide the metadata about the package for use by Python and Distutils.

The specification of the production process for Python's Distutils is given in *setup.py*, as per Example 5-5, which has some typical boilerplate about a package: its name, its version, a one-line description, and so on. This is where we will communicate the three elements listed:

- The C source files that represent the wrapper for the host language (as opposed to the library handled by Autotools itself) are listed in `sources`.
- Python recognizes the `CFLAGS` environment variable. Makefile variables are not exported to programs called by make, so the *Makefile.am* for the *py* directory, in Example 5-6, sets a shell variable named `CFLAGS` to Autoconf's `@CFLAGS@` just before calling `python setup.py build`.
- Python's Distutils require that you segregate the libraries from the library paths. Because they don't change very often, you can probably manually write the list of libraries, as in the example (don't forget to include the static library generated by the main Autotools build). The directories, however, differ from machine to machine, and are why we had Autotools generate `LDADD` for us. So it goes.

I chose to write a setup package where the user will call Autotools, and then Autotools calls Distutils. So the next step is to get Autotools to know that it has to call Distutils.

In fact, that is Automake's only responsibility in the *py* directory, so the *Makefile.am* for that directory deals only with that problem. As in Example 5-6, we need one step to compile the package and one to install, each of which will be associated with one makefile target. For setup, that target is `all-local`, which will be called when users run `make`; for installation, the target is `install-exec-hook`, which will be called when users run `make install`.

Example 5-6. Setting up Automake to drive Python's Distutils (py/Makefile.py.am)

```
all-local: pvnrt

pvnrt:
	CFLAGS='@CFLAGS@' python setup.py build

install-exec-hook:
	python setup.py install
```

At this point in the story, Automake has everything it needs in the main directory to generate the library, Distutils has all the information it needs in the *py* directory, and Automake knows to run Distutils at the right time. From here, the user can type the usual `./configure;make;sudo make install` sequence and build both the C library and its Python wrapper.

PART II
The Language

This is the part where we reconsider everything about the C language.

There are two parts to the process: working out what bits of the language not to use, and then finding out about the new things. Some of the new things are syntactic features, such as being able to initialize a list of struct elements by name; some of the new things are functions that have been written for us and are now common, such as the functions that will allow us to write to strings without quite as much pain.

The chapters cover the material as follows:

Chapter 6 provides a guide for those perplexed (or perhaps made a bit uneasy) by pointers.

Chapter 7 is where we start building by tearing down. We'll go over a survey of concepts covered by the typical textbooks that I believe should be downplayed or considered deprecated.

Chapter 8 addresses C concepts that are too useful to throw out, but that have a number of subtle awkwardnesses.

In Chapter 9, we pay special attention to strings and work out how to handle them without memory allocation or character-counting madness. `malloc` will be lonely, because you'll never call it.

Chapter 10 presents newer syntax, which will let us write function calls in ISO-standard C with inputs such as lists of arbitrary length (e.g., `sum(1, 2.2, [...] 39, 40)`) or named, optional elements (e.g., `new_person(.name="Joe", .age=32, .sex='M')`). Like rock and roll, these syntactic features saved my life. If I hadn't known about them, I would have abandoned C a long time ago.

Your typical library works via a few central structures and a set of functions that use them—an object-oriented setup. We don't have the voluminous, bloated object syntax of certain other languages, but Chapter 11 shows that you still have on hand everything you need to build high-level, object-based libraries and programs.

Having covered the idea of how one would structure a library, let's use a few in Chapter 12 to do advanced math, talk to an Internet server via whatever protocol it speaks, run a database, and otherwise kick some ass.

CHAPTER 6

Your Pal the Pointer

> He's the one
> Who likes all our pretty songs
> And he likes to sing along
> And he likes to shoot his gun
> But he don't know what it means.
>
> —Nirvana, "In Bloom"

Like a song about music, or a movie about Hollywood, a pointer is data describing other data. It's certainly easy to get overwhelmed: all at once, you have to deal with getting lost in references to references, aliases, memory management, and `malloc`. But our outrageous fortune breaks down into separate components. For example, we can use pointers as aliases without bothering with `malloc`, which doesn't have to appear nearly as often as the textbooks from the '90s told us it did. On the one hand, C's syntax can be confusing with its use of stars; on the other hand, C's syntax provides us with tools for dealing with especially complicated pointer setups like pointers to functions.

Automatic, Static, and Manual Memory

C provides three basic models of memory management, which is two more than most languages and two more than you really want to care about. And for you, dear reader, I'll even throw in two—yes, two—bonus memory models later on in Chapter 12.

Automatic
: You declare a variable on first use, and it is removed when it goes out of scope. Without the `static` keyword, any variable inside a function is automatic. Your typical programming language has only automatic-type data.

Static
: Static variables exist in the same place throughout the life of the program. Array sizes are fixed at startup, but values can change (so it's not entirely static). Data is initialized before `main` starts, and thus any initializations have to be done with constants that require no calculations. Variables declared outside of functions (in

file scope) and inside functions with the `static` keyword are static. As a bonus, if you forget to initialize a static variable, it is initialized to all zeros (or `NULL`).

Manual

The manual type involves `malloc` and `free`, and is where most of your segfaults happen. This memory model is why Jesus weeps when he has to code in C. Also, this is the only type of memory where arrays can be resized after declaration.

Here's a little table of the differences in the three places you could put data. I discuss most of these points at length over the next few chapters.

	Static	Auto	Manual
Set to zero on startup	◊		
Scope-limited	◊	◊	
Can set values on init	◊	◊	
Can set nonconstant values on init		◊	
`sizeof` measures array size	◊	◊	
Persists across function calls	◊		◊
Can be global	◊		◊
Set array size at runtime		◊	◊
Can be resized			◊
Jesus weeps			◊

Some of these things are features that you're looking for in a variable, such as resizing or convenient initialization. Some of these things, such as whether you get to set values on initialization, are technical consequences of the memory system. So if you want a different feature, such as being able to resize at runtime, suddenly you have to care about `malloc` and the pointer heap. If we could bomb it all out and start over, we wouldn't tie together three sets of features with three sets of technical annoyances. But here we are.

All of this is about where you put your data in memory. This is distinct from the variables themselves, which can make for another level of fun:

1. If you declared your `struct`, `char`, `int`, `double`, or other variable either outside of a function or inside a function with the `static` keyword, then it's static; otherwise, it's automatic.
2. If you declared a pointer, the pointer itself has a memory type, probably auto or static as per rule 1. But the pointer could be pointing to any of the three types of data: static pointer to `malloc`ed data, automatic pointer to static data—all the combinations are possible.

Rule 2 means that you can't identify the memory model by the notation. On the one hand, it's nice that we don't have to deal with one notation for auto arrays and one notation for manual arrays; on the other hand, you still have to be aware of which you have going, so you don't get tripped up resizing an automatic array or not freeing a manual array. This is why the statement "C pointers and arrays are identical" is about as reliable as the rule about "i before e except after c."

> **Your Turn:** Check back on some code you have and go through the typology: what data is static memory, auto, manual; what variables are auto pointers to manual memory, auto pointers to static values, et cetera. If you don't have anything immediately on hand, try this exercise with Example 6-6.

The Stack and the Heap

Any one function has a space in memory, a *frame*, holding information about the function, such as where to return to when finished and spaces for all of the automatically allocated variables.

When a function (such as `main`) calls another function, action in the first function's frame halts, and a new function is added to the *stack* of frames. When a function completes, its frame is popped off the stack, and all variables in that frame disappear in the process.

Unfortunately, the stack has arbitrary size limits that are much smaller than general memory, in the ballpark of maybe 2 or 3 megabytes (via Linux defaults as of this writing). That's about enough to hold all of Shakespeare's tragedies, so don't worry about allocating an array of 10,000 integers. But it's easy to find data sets much larger, and the current limits on the stack will require that we allocate space for them elsewhere, using `malloc`.

Memory allocated via `malloc` is not on the stack, but is elsewhere in the system, in a space called the *heap*. The heap may or may not be size-restricted; on a typical PC, it is not unreasonable to assume that the size of the heap is roughly the size of all available memory.

Persistent State Variables

This chapter is mostly about the interaction of automatic memory, manual memory, and pointers, which leaves static variables somewhat out of the narrative. But it's worth pausing to consider the good work static variables can do for us.

Static variables can have local scope. That is, you can have variables that exist only in one function, but when the function exits, the variable retains its value. This is great for having an internal counter or a reusable scratch space. Because a static variable never moves, a pointer to a static variable will remain valid after a function exits.

Example 6-1 presents a traditional textbook example: the Fibonacci sequence. We declare the first two elements to be zero and one, and each element after those is the sum of the two prior elements.

Example 6-1. The Fibonacci sequence generated by a state machine (fibo.c)

```
#include <stdio.h>

long long int fibonacci(){
    static long long int first = 0;
    static long long int second = 1;
    long long int out = first+second;
    first=second;
    second=out;
    return out;
}

int main(){
    for (int i=0; i< 50; i++)
        printf("%lli\n", fibonacci());
}
```

Check out how insignificant `main` is. The `fibonacci` function is a little machine that runs itself; `main` just has to bump the function and it spits out another value. That is, the function is a simple *state machine*, and static variables are the key trick for implementing state machines via C.

How can we use these static state machines in a world where every function has to be thread safe? The ISO C committee saw us coming, and C11 includes a `_Thread_local` memory type. Just put that into your declarations:

```
static _Thread_local int counter;
```

and you've got a distinct counter for each thread. I discuss this in greater detail in "Easy Threading with Pthreads" on page 234.

Declaring Static Variables

Static variables, even those inside of a function, are initialized when the program starts, before `main`, so you can't initialize them with a nonconstant value.

```
//this fails: can't call gsl_vector_alloc() before main() starts
static gsl_vector *scratch = gsl_vector_alloc(20);
```

This is an annoyance, but easily solved with a macro to start at zero and allocate on first use:

```
#define Staticdef(type, var, initialization) \
    static type var = 0; \
    if (!(var)) var = (initialization);
```

```
//usage:
Staticdef(gsl_vector*, scratch, gsl_vector_alloc(20));
```

This works as long as we don't ever expect `initialization` to be zero (or in pointer-speak, `NULL`). If it is, it'll get reinitialized on the next go-round. Maybe that's OK anyway.

Pointers Without malloc

When I tell my computer *set `A` to `B`*, I could mean one of two things:

- Copy the value of `B` into `A`. When I increment `A` with `A++`, then `B` doesn't change.
- Let `A` be an alias for `B`. Then `A++` also increments `B`.

Every time your code says *set `A` to `B`*, you need to know whether you are making a copy or an alias. This is in no way C specific.

For C, you are always making a copy, but if you are copying the address of the data you care about, a copy of the pointer is a new alias for the data. That's a fine implementation of aliasing.

Other languages have different customs: LISP family languages lean heavily on aliasing and have `set` commands to copy; Python generally copies scalars but aliases lists (unless you use `copy` or `deepcopy`). Again, knowing which to expect will clear up a whole lot of bugs all at once.

The GNU Scientific Library includes vector and matrix objects, which both have a `data` element, which is itself an array of `double`s. Let us say that we have some vector/matrix pairs, via a typedef, and an array of these pairs:

```
typedef struct {
    gsl_vector* vector;
    gsl_matrix* matrix;
} datapair;

datapair your_data[100];
```

Say we have been dealing with this structure for a while, and are frequently dealing with first element of the first matrix:

```
your_data[0].matrix->data[0]
```

If you are familiar with how the blocks fit together, this is easy to follow, but is it ever annoying to type. Let's alias it:

```
double *elmt1 = your_data[0].matrix->data;
```

Among the two types of assignment shown, the equals sign here is the aliasing type: only a pointer gets copied, and if we change `*elmt1`, then the data point buried in `your_data` gets modified as well.

Aliasing is a `malloc`-free experience, and demonstrates that we can get mileage out of pointers without fretting about memory management.

To give another example where `malloc` sometimes needlessly turns up, if you have a function that takes in a pointer as input:

```
void increment(int *i){
    (*i)++;
}
```

users of the function who too closely associate pointers with `malloc` might think that this means that they have to allocate memory to pass in to the function:

```
int *i = malloc(sizeof(int)); //so much effort, wasted
*i = 12;
increment(i);
...
free(i);
```

Rather, the easiest use is to let automatic memory allocation do the work:

```
int i=12;
increment(&i);
```

Your Turn: I gave you that advice earlier that every time you have a line that says *set* `A` *to* `B`, you need to know whether you are asking for an alias or a copy. Grab some code you have on hand (in whatever language) and go through line by line and ask yourself which is which. Were there cases where you could sensibly replace a copying with an alias?

Structures Get Copied, Arrays Get Aliased

As in Example 6-2, copying the contents of a structure is a one-line operation.

Example 6-2. No, you don't need to copy the elements of a struct element by element (copystructs.c)

```
#include <assert.h>

typedef struct{
    int a, b;
    double c, d;
    int *efg;
} demo_s;

int main(){
    demo_s d1 = {.b=1, .c=2, .d=3, .efg=(int[]){4,5,6}};
    demo_s d2 = d1;

    d1.b=14;              ❶
    d1.c=41;
    d1.efg[0]=7;

    assert(d2.a==0);      ❷
    assert(d2.b==1);
    assert(d2.c==2);
    assert(d2.d==3);
```

```
    assert(d2.efg[0]==7);
}
```

❶ Let's change `d1` and see if `d2` changed.

❷ These assertions will all pass.

As before, you should always know whether your assignment is a copy of the data or a new alias, so which is it here? We changed `d1.b`, and `d1.c` and `d2` didn't change, so this is a copy. But a copy of a pointer still points to the original data, so when we change `d1.efg[0]`, the change also affects the copy of a pointer `d2.efg`. This advises that if you need a *deep copy* where pointer contents are copied, you will need a struct copying function, and if you don't have any pointers to trace through, then a copy function is overkill and an equals sign will do.

For arrays, the equals sign will copy an alias, not the data itself. In Example 6-3, let's try the same test of making a copy, changing the original, and checking the copy's value.

Example 6-3. Structs get copied, but setting one array to the other creates an alias (copystructs2.c)

```
#include <assert.h>

int main(){
    int abc[] = {0, 1, 2};
    int *copy = abc;

    copy[0] = 3;
    assert(abc[0]==3); ❶
}
```

❶ Passes: the original changed when the copy did.

Example 6-4 is a slow buildup to a train wreck. It is mostly two functions that automatically allocate two blocks: the first allocates a struct and the second allocates a short array. Being automatic memory, we know that at the end of each function, the respective blobs of memory will be freed.

A function that ends in `return x` will return the value of `x` to the calling function (C99 & C11 §6.8.6.4(3)). Seems simple enough, but that value has to be copied out to the calling function, whose frame is about to be destroyed. As previously, for a struct, a number, or even a pointer, the calling function will get a copy of the returned value; for an array, the calling function will get a *pointer* to the array, not a copy of the data in the array.

That last one is a nasty trap, because the pointer returned may be pointing to an automatically allocated array of data, which is destroyed on function exit. A pointer to a block of memory that has already been automatically freed is worse than useless.

Example 6-4. You can return a struct from a function, but not an array (automem.c)

```
#include <stdio.h>

typedef struct powers {
    double base, square, cube;
} powers;

powers get_power(double in){
    powers out = {.base   = in,                                    ❶
                  .square = in*in,
                  .cube   = in*in*in};
    return out;                                                    ❷
}

int *get_even(int count){
    int out[count];
    for (int i=0; i< count; i++)
        out[i] = 2*i;
    return out;   //bad.                                           ❸
}

int main(){
    powers threes = get_power(3);
    int *evens = get_even(3);
    printf("threes: %g\t%g\t%g\n", threes.base, threes.square, threes.cube);
    printf("evens: %i\t%i\t%i\n", evens[0], evens[1], evens[2]); ❹
}
```

❶ The initialization is via designated initializers. If you've never met them, hold tight for a few chapters.

❷ This is valid. On exit, a copy of the local, automatically allocated `out` is made, then the local copy is destroyed.

❸ This is invalid. Here, arrays really are treated like pointers, so on exit, a copy of the pointer to `out` gets made. But once the autoallocated memory is destroyed, the pointer is now pointing to bad data. If your compiler is on the ball, it will warn you of this.

❹ Back in the function that called `get_even`, `evens` is a valid pointer-to-int, but it is pointing to already freed data. This may segfault, print garbage, or get lucky and print the correct values (this time).

If you need a copy of an array, you can still do it on one line, but we're back to memory-twiddling syntax, as in Example 6-5.

Example 6-5. Copying an array requires memmove—it's antediluvian, but it works (memmove.c)

```
#include <assert.h>
#include <string.h> //memmove

int main(){
    int abc[] = {0, 1, 2};
```

```
    int *copy1, copy2[3];

    copy1 = abc;
    memmove(copy2, abc, sizeof(int)*3);

    abc[0] = 3;
    assert(copy1[0]==3);
    assert(copy2[0]==0);
}
```

malloc and Memory-Twiddling

Now for the memory part, in which we deal with addresses in memory directly. These will often be allocated manually via `malloc`.

The easiest way to avoid bugs related to `malloc` is not to use `malloc`. Historically (in the 1980s and 1990s), we needed `malloc` for all sorts of string manipulations; Chapter 9 gives full coverage of strings without using `malloc` once. We needed `malloc` to deal with arrays for which length had to be set at runtime, which is pretty common; as per "Let Declarations Flow" on page 116, that is also obsolete.

Here is my roughly comprehensive list of reasons left for using `malloc`:

1. Resizing an already extant array requires `realloc`, which only makes sense on blocks of memory initially allocated via `malloc`.
2. As explained earlier, you can't return an array from a function.
3. Some objects should persist long after their initialization function. Though, in "Base Your Code on Pointers to Objects" on page 214, we'll wrap the memory management for these into new/copy/free functions so that they don't sully our procedures.
4. Automatic memory is allocated on the stack of function frames, which may be restricted to a few megabytes (or less). Therefore, large chunks of data (i.e., anything measured in megabytes) should be allocated on the heap, not the stack. Again, you probably have a function to store your data in an object of some sort, so this will in practice be a call to an ***`object`***`_new` function rather than to `malloc` itself.
5. Now and then, you will find function forms that require that a pointer be returned. For example, in "Easy Threading with Pthreads" on page 234, the template requires that we write a function that returns a `void *`. We dodge that bullet by just returning `NULL`, but now and then, we hit a form where we're stuck. Note also that "Return Multiple Items from a Function" on page 175 discusses returning structs from a function, so we can send back relatively complex return values without memory allocation, obviating another common use of allocations within a function.

I wrote this list to show you that it's not all that long—and item 5 is a rarity, and item 4 is often a special case of item 3, because giant data sets tend to get put into object-like data structures. Production code tends to have few uses of `malloc`, typically wrapped in new/copy/free functions so the main code doesn't have to deal further with memory management.

The Fault Is in Our Stars

OK, so we're clear that pointers and memory allocation are separate concepts, but dealing with pointers themselves can still be a problem, because, well, all those stars are just confusing.

The ostensible rationale for the pointer declaration syntax is that the use and the declaration look alike. What they mean by this is that when you declare:

```
int *i;
```

`*i` is an integer, so it's only natural that we'd declare that `*i` is an integer via `int *i`.

So that's all well and good, and if it helps you, then great. I'm not sure if I could invent a less ambiguous way of doing it.

Here's a common design rule, espoused throughout The Design of Everyday Things, for example: *things that have drastically different functions should not look similar* [Norman 2002]. That book gives the example of airplane controls, where two identical-looking levers often do entirely different things. In a crisis situation, that's an invitation for human error.

Here, C syntax crashes and burns, because `*i` in a declaration and `*i` outside of a declaration do very different things. For example:

```
int *i = malloc(sizeof(int)); //right
*i = 23;                      //right
int *i = 23;                  //wrong
```

I've thrown the rule that declaration looks like usage out of my brain. Here's the rule I use, which has served me well: when used for a declaration, a star indicates a pointer; when not used as a declaration, a star indicates the value of the pointer.

Here is a valid snippet:

```
int i = 13;
int *j = &i;
int *k = j;
*j = 12;
```

Using the rule given, you can see that on the second line, the initialization is correct, because `*j` is a declaration, and so a pointer. On the third line, `*k` is also the declaration of a pointer, so it makes sense to assign to it `j`, also a pointer. On the last line, `*j` is not in a declaration, so it indicates a plain integer, and so we can assign 12 to it (and `i` will change as a result).

So there's your first tip: bear in mind that when you see `*i` on a declaration line, it is a pointer to something; when you see `*i` on a nondeclaration line, it is the pointed-to value.

After some pointer arithmetic, I'll come back with another tip for dealing with weird pointer declaration syntax.

All the Pointer Arithmetic You Need to Know

An element of an array can be expressed as being at some offset from the base of the array. You could declare a pointer `double *p`; then that's your base, and you can use the offsets from that base as an array: at the base itself, you will find the contents of the first element, `p[0]`; go one step from the base and you have the contents of the second, `p[1]`; et cetera. So if you give me a pointer and the distance from one element to the next, I've got an array.

You could just write the base plus offset directly and literally, via a form like `(p+1)`. As your textbooks will tell you, `p[1]` is exactly equivalent to `*(p+1)`, which explains why the first element in an array is `p[0] == *(p+0)`. K & R spend about six pages on this stuff [2nd ed. sections 5.4 and 5.5].

The theory implies a few rules for notating arrays and their elements in practice:

- Declare arrays either via the explicit pointer form, `double *p` or the static/automatic form, `double p[100]`.
- In either case, the *n*th array item is `p[n]`. Don't forget that the first item is zero, not one; it can be referred to with the special form `p[0] == *p`.
- If you need the address of the *n*th element (not its actual value), use the ampersand: `&p[n]`. Of course, the zeroth pointer is just `&p[0] == p`.

Example 6-6 shows some of these rules in use.

Example 6-6. Some simple pointer arithmetic (arithmetic.c)

```
#include <stdio.h>

int main(){
    int evens[5] = {0, 2, 4, 6, 8};
    printf("The first even number is, of course, %i\n", *evens);          ❶
    int *positive_evens = &evens[1];                                       ❷
    printf("The first positive even number is %i\n", positive_evens[0]); ❸
}
```

❶ Writing `evens[0]` using the special form `*evens`.

❷ The address of element 1, assigned to a new pointer.

❸ The usual way of referring to the first element of an array.

I'll throw in one nice trick, based on the pointer arithmetic rule that `p+1` is the address of the next point in an array—`&p[1]`. With this rule, you don't need an index for `for` loops that step through an array. Example 6-7 uses a spare pointer that starts at the head of a list, and then steps through the array with `p++` until it hits the `NULL` marker at the end. The next pointer declaration tip will make this much more legible.

Example 6-7. We can use the fact that **p++** *means "step to the next pointer" to streamline for loops (pointer_arithmetic1.c)*

```
#include <stdio.h>

int main(){
    char *list[] = {"first", "second", "third", NULL};
    for (char **p=list; *p != NULL; p++){
        printf("%s\n", p[0]);
    }
}
```

Your Turn: How would you implement this if you didn't know about `p++`?

Base-plus-offset thinking doesn't give us much payoff in terms of cute syntactic tricks, but it does explain a lot about how C works. In fact, consider the `struct`. Given:

```
typedef struct{
    int a, b;
    double c, d;
} abcd_s;

abcd_s list[3];
```

As a mental model, you can think of `list` as our base, and `list[0].b` is just far enough past that to refer to `b`. That is, given that the location of `list` is the integer `(size_t)&list`, `b` is located at `(size_t)&list + sizeof(int)`; and so `list[2].d` would be at the position `(size_t)&list + 6*sizeof(int) + 5*sizeof(double)`. Under this thinking, a struct is much like an array, except the elements have names instead of numbers and are of different types and sizes.

It's not quite correct, because of *alignment*: the system may decide that the data needs to be in chunks of a certain size, so fields may have extra space at the end so that the next field begins at the right point, and the struct may have padding at its end so that a list of structs is appropriately aligned [C99 & C11 §6.7.2.1(15) and (17)]. The header *stddef.h* defines the `offsetof` macro, which makes the base-plus-offset thinking accurate again: `list[2].d` really is at `(size_t)&list + 2*sizeof(abcd_s) + offsetof(abcd_s, d)`.

By the way, there can't be padding at the beginning of a struct, so `list[2].a` is at `(size_t)&list+ 2*sizeof(abcd_s)`.

Here is a silly function to recursively count the number of elements in a list until we hit a zero-valued element. Let us say (and this is a bad idea) that we'd like to be able to use this function for any type of list where a zero value makes sense, so it will take in a `void` pointer.

```
int f(void *in){
    if (*(int*)in==0) return 1;
    else return 1 + f(&(in[1]));   //This won't work.
}
```

The base-plus-offset rule explains why this won't work. To refer to `a_list[1]`, the compiler needs to know the exact length of `a_list[0]`, so it knows how far to offset from the base. But without a type attached, it can't calculate that size.

Typedef as a teaching tool

Any time you find yourself putting together a complex type, which frequently means a pointer-to-pointer-to-pointer sort of situation, ask yourself whether a typedef could clarify things.

For example, this popular definition:

```
typedef char* string;
```

reduces the visual clutter around arrays of strings and clarifies their intent.

In the preceding pointer-arithmetic `p++` example, did the declarations communicate to you that `char *list[]` is a list of strings, and that `*p` is a string?

Example 6-8 shows a rewrite of the `for` loop of Example 6-7, replacing `char *` with `string`.

Example 6-8. Adding a typedef makes awkward code a little more legible (pointer_arithmetic2.c)

```
#include <stdio.h>
typedef char* string;

int main(){
    string list[] = {"first", "second", "third", NULL};
    for (string *p=list; *p != NULL; p++){
        printf("%s\n", *p);
    }
}
```

The declaration line for `list` is now as easy as C gets and clearly indicates that it is a list of strings, and the snippet `string *p` should indicate to you that `p` is a pointer-to-string, so `*p` is a string.

In the end, you'll still have to remember that a string is a pointer-to-`char`; for example, `NULL` is a valid value.

One could even take this further, such as declaring a 2D array of strings using the typedef above plus `typedef stringlist string*`. Sometimes this helps; sometimes it's just more notation to memorize.

Typedefs save the day when dealing with pointers to functions. If you have a function with a header like:

```
double a_fn(int, int); //a declaration
```

then just add a star (and parens to resolve precedence) to describe a pointer to this type of function:

```
double (*a_fn_type)(int, int);    //a type: pointer-to-function
```

Then put `typedef` in front of that to define a type:

```
typedef double (*a_fn_type)(int, int); //a typedef for a pointer to function
```

Now you can use it as a type like any other, such as to declare a function that takes another function as input:

```
double apply_a_fn(a_fn_type f, int first_in, int second_in){
    return f(first_in, second_in);
}
```

Being able to define specific pointer-to-function types takes writing functions that take other functions as inputs from being a daunting test of star placement to being kind of trivial.

In the end, the pointer thing is much simpler than the textbooks make it out to be, because it really is just a location or an alias—it's not about the different types of memory management at all. Complex constructs like pointers-to-pointers-to-strings are always confusing, but that's because our hunter-gatherer ancestors never encountered such things. With the typedef, C at least gives us a tool to deal with them.

CHAPTER 7
C Syntax You Can Ignore

> I believe it is good
> Let's destroy it.
>
> —Porno for Pyros, "Porno for Pyros"

In the 1980s, the synthesizer became a common, viable tool for musicians. Now, it's not hard to recognize music that made use of the then-new technology as being decidedly '80s. A similar but somewhat more subtle thing happened with the drum machine in the late 1990s. Compare with dance music up to the swing era, which was all about horns that could carry in a music hall before we had all this electronic equipment amplifying the instruments.

There was a time when C was a cutting-edge language, intended to replace assembly code and compete with FORTRAN, COBOL, and other all-caps languages that have not withstood the test of time quite as well as C (which, when you think about it, also has an all-caps name). But looking at C code from the 1980s, you can tell it was written then.

This isn't about stylistic details like where we put the curly braces. Yes, older code tends to be more sparse, like:

```
if (x > 0)
{
    return 1;
}
```

whereas scripting languages tend toward compressing these four lines into a one-line thought, like:

```
if (x > 0) return 1;
```

but I have no interest in telling you where to put your curly braces.

Rather, more fundamental features of C that made sense at the time have a real effect on the readability and maintainability of code. In many cases, the textbooks on the market haven't been updated to mention some of the conveniences added to C in 1999, meaning that they do things the hard way.

Don't Bother Explicitly Returning from main

As a warm-up, let's shave a line off of every program you write.

Your program must have a `main` function, and it has to be of return type `int`, so you must absolutely have the following in your program:

```
int main(){ ... }
```

You would think that you therefore have to have a `return` statement that indicates what integer gets returned by `main`. However, the C standard knows how infrequently this is used and lets you not bother: "... reaching the `}` that terminates the main function returns a value of 0" (C99 & C11 §5.1.2.2(3)). That is, if you don't write `return 0;` as the last line of your program, then it will be assumed.

Recall that, after running your program, you can use `echo $?` to see its return value; you can use this to verify that programs that reach the end of `main` do indeed always return zero.

Earlier, I showed you this version of *hello.c*, and you can now see how I got away with a `main` containing only one `#include` plus one line of code:[1]

```
#include <stdio.h>
int main(){ printf("Hello, world.\n"); }
```

Your Turn: Go through your programs and delete the `return 0` line from `main`; see if it makes any difference.

Let Declarations Flow

Think back to the last time you read a play. At the beginning of the text, there was the *Dramatis Personæ*, listing the characters. A list of character names probably didn't have much meaning to you before you started reading, so if you're like me you skipped that page and went straight to the start of the play. When you are in the thick of the plot and you forget who Benvolio is, it's nice to be able to flip back to the head of the play and get a one-line description (he is Romeo's friend and Montague's nephew), but that's because you're reading on paper. If the text were on a screen, you could search for Benvolio's first appearance.

In short, the *Dramatis Personæ* is not very useful to readers. It would be better to introduce characters when they first appear.

1. Readers who were writing code in the 1980s might also be bemused by the header: `int main()`. In what even K& R 2nd ed. called "old style" declarations, having nothing inside the parens indicated no information about parameters, not definite information that there are zero parameters. However, this is wholly deprecated, and since C99, "An empty list in a function declarator that is part of a definition of that function specifies that the function has no parameters." (C99 §6.7.5.3(14) & C11 §6.7.6.3(14))

I see code like this pretty often:

```
#include <stdio.h>

int main(){
    char *head;
    int i;
    double ratio, denom;

    denom=7;
    head = "There is a cycle to things divided by seven.";
    printf("%s\n", head);
    for (i=1; i<= 6; i++){
        ratio = i/denom;
        printf("%g\n", ratio);
    }
}
```

It has three or four lines of introductory material (I'll let you decide how to count the whitespace), followed by the routine.

This is a throwback to ANSI C89, which required all declarations to be at the head of the block, due to technical limitations of early compilers. We still have to declare our variables, but we can minimize burden on the author and the reader by doing so at the first use:

```
#include <stdio.h>

int main(){
    double denom = 7;
    char *head = "There is a cycle to things divided by seven.";
    printf("%s\n", head);
    for (int i=1; i<= 6; i++){
        double ratio = i/denom;
        printf("%g\n", ratio);
    }
}
```

Here, the declarations happen as needed, so the onus of declaration reduces to sticking a type name before the first use. If you have color syntax highlighting, then the declarations are still easy to spot (and if you don't have a text editor that supports color, you are seriously missing out—and there are dozens to hundreds to choose from!).

When reading unfamiliar code, my first instinct when I see a variable is to go back and see where it was declared. If the declaration is at the first use or the line immediately before the first use, I'm saved from a few seconds of skimming back. Also, by the rule that you should keep the scope of a variable as small as possible, we're pushing the active variable count on earlier lines that much lower, which might start to matter for a longer function.

In this example, the declarations are at the beginning of their respective block, followed by nondeclaration lines. This is just how the example turned out, but you can freely intermix declarations and nondeclarations.

I left the declaration of `denom` at the head of the function, but we could move that into the loop as well (because it is only used inside the loop). We can trust that the compiler will know enough not to waste time and energy deallocating and reallocating the variable on every iteration of the loop [although this is what it theoretically does—see C99 & C11 §6.8(3)]. As for the index, it's a disposable convenience for the loop, so it's natural to reduce its scope to exactly the scope of the loop.

Will This New Syntax Slow Down My Program?

No.

The compiler's first step is to parse your code into a language-independent internal representation. This is how the gcc (GNU Compiler Collection) can produce compatible object files for C, C++, ADA, and FORTRAN—by the end of the parsing step, they all look the same. Therefore, the grammatical conveniences provided by C99 to make your text more human-readable are typically abstracted away well before the executable is produced.

Along the same lines, the target device that will run your program will see nothing but postcompilation machine instructions, so it will be indifferent as to whether the original code conformed to C89, C99, or C11.

Set Array Size at Runtime

Dovetailing with putting declarations wherever you want, you can allocate arrays to have a length determined at runtime, based on calculations before the declarations.

Again, this wasn't always true: a quarter-century ago, you either had to know the size of the array at compile time or use `malloc`.

For example, let's say that you'd like to create a set of threads, but the number of threads is set by the user on the command line.[2] The old way of doing this would be to get the size of the array from the user via `atoi(argv[1])` (i.e., convert the first command-line argument to an integer), and then, having established that number at runtime, allocate an array of the right length.

```
pthread_t *threads;
int thread_count;
thread_count = atoi(argv[1]);
threads = malloc(thread_count * sizeof(pthread_t));
...

free(threads);
```

We can write this with less fuss:

2. This example was inspired by *http://www.marco.org/2008/05/31/parallelize-shell-utility-to-execute-command-batches* (found via One Thing Well), though the code here differs from the original.

```
int thread_count = atoi(argv[1]);
pthread_t threads[thread_count];
...
```

There are fewer places for anything to go wrong, and it reads like declaring an array, not initializing memory registers. We had to `free` the manually allocated array, but we can just drop the automatically allocated array on the floor and it'll get cleaned up when the program leaves the given scope.

Cast Less

In the 1970s and 1980s, `malloc` returned a `char*` pointer and had to be cast (unless you were allocating a string), with a form like:

```
//don't bother with this sort of redundancy:
double* list = (double*) malloc(list_length * sizeof(double));
```

You don't have to do this anymore, because `malloc` now gives you a `void` pointer, which the compiler will comfortably autocast to anything. The easiest way to do the cast is to declare a new variable with the right type. For example, functions that have to take in a `void` pointer will typically begin with a form like:

```
int use_parameters(void *params_in){
    param_struct *params = params_in;   //Effectively casting pointer-to-NULL
    ...                                 //to a pointer-to-param_struct.
}
```

More generally, if it's valid to assign an item of one type to an item of another type, then C will do it for you without your having to tell it to with an explicit cast. If it's not valid for the given type, then you'll have to write a function to do the conversion anyway.This isn't true of C++, which depends more on types and therefore requires every cast to be explicit.

There remain two reasons to use C's type-casting syntax to cast a variable from one type to another.

First, when dividing two numbers, an integer divided by an integer will always return an integer, so the following statements will both be true:

```
4/2 == 2;
3/2 == 1;
```

That second one is the source of lots of errors. It's easy to fix: if `i` is an integer, then `i + 0.0` is a floating-point number that matches the integer. Don't forget parentheses as needed, but that solves your problem. If you have a constant, `2` is an integer and `2.0` or even just `2.` is floating point. Thus, all of these variants work:

```
int two=2;
3/(two+0.0) == 1.5;
3/(2+0.0) == 1.5;
3/2.0 == 1.5;
3/2. == 1.5;
```

You can also use the casting form:

```
3/(double)two == 1.5;
3/(double)2 == 1.5;
```

I'm partial to the add-zero form, for æsthetic reasons; you're welcome to prefer the cast-to-double form. But make a habit of one or the other every time you reach for that / key, because this is the source of many, many errors (and not just in C; lots of other languages also like to insist that `int / int` ⇒ `int`—not that that makes it OK).

Second, array indices have to be integers. It's the law [C99 and C11 §6.5.2.1(1)], and gcc will complain if you send a floating-point index. So, you may have to cast to an integer, even if you know that in your situation you will always have an integer-valued expression.

```
4/(double)2 == 2.0;           //This is floating-point, not an int.
mylist[4/(double)2];          //So, an error: floating-point index

mylist[(int)(4/(double)2)]; //Works. Take care with the parens.

int index=4/(double)2;        //This form also works, and is more legible.
mylist[index];
```

You can see that even for the few legitimate reasons to cast, you have options to avoid the casting syntax: adding 0.0 and declaring an integer variable for your array indices. Bear in mind the existence of the casting form `var_type2 = (type2) var_type1`, because it might come in handy some day, and in a few chapters, we'll get to compound literals that mimic this form. But there are always less redundant and easier to read alternatives to explicit type casting.

Enums and Strings

Enums are a good idea that went bad.

The benefit is clear enough: integers are not at all mnemonic, and so wherever you are about to put a short list of integers in your code, you are better off naming them. Here's the even worse means of how we could do it without the `enum` keyword:

```
#define NORTH 0
#define SOUTH 1
#define EAST 2
#define WEST 3
```

With `enum`, we can shrink that down to one line of source code, and our debugger is more likely to know what `EAST` means. Here's the improvement over the sequence of `#define`s:

```
enum directions {NORTH, SOUTH, EAST, WEST};
```

But we now have five new symbols in our namespaces: `directions`, `NORTH`, `SOUTH`, `EAST`, and `WEST`.

For an enum to be useful, it typically has to be global (i.e., declared in a header file intended to be included in many places all over a project). For example, you'll often find enums typedefed in the public header file for a library. To minimize the chance of name clashes, library authors use names like `G_CONVERT_ERROR_NOT_ABSOLUTE_PATH` or the relatively brief `CblasConjTrans`.

At that point, an innocuous and sensible idea has fallen apart. I don't want to type these messes, and I use them so infrequently that I have to look them up every time (especially because many are infrequently used error values or input flags, so there's typically a long gap between each use). Also, all caps reads like yelling.

My own habit is to use single characters, wherein I would mark transposition with `'t'` and a path error with `'p'`. I think this is enough to be mnemonic—in fact, I'm far more likely to remember how to spell `'p'` than how to spell that all-caps mess—and it requires no new entries in the namespace.

I think usability considerations trump efficiency issues at this level, but even so, bear in mind that an enumeration is typically an integer, and `char` is C-speak for a single byte. So when comparing enums, you will likely need to compare the states of 16 bits or more, whereas with a `char`, you need compare only 8. So even if the speed argument were relevant, it would advocate against enums.

We sometimes need to combine flags. When opening a file using the `open` system call, you might need to send `O_RDWR|O_CREAT`, which is the bitwise combination of the two enums. You probably don't use `open` directly all that often; you are probably making more use of `fopen`, which is more user friendly. Instead of using an enum, it uses a one- or two-letter string, like `"r"` or `"r+"`, to indicate whether something is readable, writeable, both, et cetera.

In the context, you know `"r"` stands for *read*, and if you don't have the convention memorized, you can confidently expect that you will after a few more uses of `fopen`, whereas I still have to check whether I need `CblasTrans` or `CBLASTrans` or `CblasTranspose` every time.

On the plus side of enums, you have a small, fixed set of symbols, so if you mistype one, the compiler stops and forces you to fix your typo. With strings, you won't know you had a typo until runtime. Conversely, strings are not a small, fixed set of symbols, so you can more easily extend the set of enums. For example, I once ran into an error handler that offers itself for use by other systems—as long as the errors the new system generates match the handful of errors in the original system's `enum`. If the errors were short strings, extension by others would be trivial.

There are reasons for using enums: sometimes you have an array that makes no sense as a struct but that nonetheless requires named elements, and when doing kernel-level work, giving names to bit patterns is essential. But in cases where enums are used to indicate a short list of options or a short list of error codes, a single character or a short string can serve the purpose without cluttering up the namespace or users' memory.

Labels, gotos, switches, and breaks

In the olden days, assembly code didn't have the modern luxuries of `while` and `for` loops. Instead, there were only conditions, labels, and jumps. Where we would write `while (a[i] < 100) i++;`, our ancestors might have written:

```
label 1
if a[i] >= 100
    go to label 2
increment i
go to label 1
label 2
```

If it took you a minute to follow what was going on in this block, imagine reading this in a real-world situation, where the loop would be interspersed, nested, or half-nested with other jumps. I can attest from my own sad and painful experience that following the flow of such code is basically impossible, which is why `goto` is considered harmful in the present day [Dijkstra 1968].

You can see how welcome C's `while` keyword would have been to somebody stuck writing in assembly code all day. However, there is a subset of C that is still built around labels and jumps, including the syntax for labels, `goto`, `switch`, `case`, `default`, `break`, and `continue`. I personally think of this as the portion of C that is transitional from how authors of assembly code wrote to the more modern style. This segment will present these forms as such, and suggest when they are still useful. However, this entire subset of the language is technically optional, in the sense that you can write equivalent code using the rest of the language.

goto Considered

A line of C code can be labeled by providing a name with a colon after it. You can then jump to that line via `goto`. Example 7-1 is a simple function that presents the basic idea, with a line labeled `outro`. It finds the sum of all the elements in two arrays, provided they are all not NaN (Not a Number; see "Marking Exceptional Numeric Values with NaNs" on page 124). If one of the elements is NaN, this is an error and we need to exit the function. But however we choose to exit, we will free both vectors as cleanup. We could place the cleanup code in the listing three times (once if `vector` has a NaN, once if `vector2` has one, and once on OK exit), but it's cleaner to have one exit segment and jump to it as needed.

Example 7-1. Using goto for a clean getaway in case of errors

```
/* Sum to the first NaN in the vector.
  Sets error to zero on a clean summation, 1 if a NaN is hit.*/
double sum_to_first_nan(double* vector, int vector_size,
                     double* vector2, int vector2_size, int *error){
    double sum=0;
    *error=1;
    for (int i=0; i< vector_size; i++){
```

```
        if (isnan(vector[i])) goto outro;
        sum += vector[i];
    }

    for (int i=0; i< vector2_size; i++){
        if (isnan(vector2[i])) goto outro;
        sum += vector2[i];
    }
    *error=0;

    outro:
    printf("The sum until the first NaN (if any) was %g\n", sum);
    free(vector);
    free(vector2);
    return sum;
}
```

The `goto` will only work within one function. If you need to jump from one function to an entirely different one, have a look at `longjmp` in your C standard library documentation.

A single jump by itself tends to be relatively easy to follow, and can clarify if used appropriately and in moderation. Even Linus Torvalds, the lead author of the Linux kernel, recommends the `goto` for limited uses like cutting out of a function when there's an error or processing is otherwise finished early, as in the example.

So, to revise the common wisdom on `goto`, it is generally harmful but is a common present-day idiom for cleaning up in case of different kinds of errors, and it is often cleaner than the alternatives.

switch

Here is a snippet of code for the textbook norm for using the POSIX-standard `getopt` function to parse command-line arguments:

```
char c;
while ((c = getopt(...))){
    switch(c){
       case 'v':
            verbose++;
            break;
       case 'w':
            weighting_function();
            break;
       case 'f':
            fun_function();
            break;
    }
}
```

So when `c == 'v'`, the verbosity level is increased, when `c == 'w'`, the weighting function is called, et cetera.

Note well the abundance of `break` statements (which cut to the end of the `switch` statement, not the `while` loop, which continues looping). The `switch` function just jumps to the appropriate label (recall that the colon indicates a label), and then the program flow continues along, as it would given any other jump to a label. Thus, if there were no `break` after `verbose++`, then the program would merrily continue on to execute `weighting_function`, and so on. This is called *fall-through*. There are reasons for when fall-through is actually desirable, but to me, it always seemed to be a lemonade-out-of-lemons artifact of how `switch-case` is a smoothed-over syntax for using labels, `goto`, and `break`. [van der Linden 1994, pp 37-38] surveyed a large code base and found that fall-through was appropriate for only 3% of cases.

If the risk of inserting a subtle bug by forgetting a `break` or `default` seems great to you, there is a simple solution: don't use `switch`.

The alternative to the `switch` is a simple series of `if`s and `else`s:

```
char c;
while ((c = getopt(...))){
    if (c == 'v')      verbose++;
    else if (c == 'w') weighting_function();
    else if (c == 'f') fun_function();
}
```

It's redundant because of the repeated reference to `c`, but it's shorter because we don't need a `break` every three lines. Because it isn't a thin wrapper around raw labels and jumps, it's much harder to get wrong.

Marking Exceptional Numeric Values with NaNs

The IEEE floating-point standard gives precise rules for how floating-point numbers are represented, including special forms for infinity, negative infinity, and Not-a-Number—NaN, which indicates a math error like 0/0 or log(-1). IEEE 754 (as the standard is called, because the sort of people who deal with these things are fine with their standards having a number as a name) is not part of the C or POSIX standards, but is supported almost everywhere. If you are working on a Cray or some special-purpose embedded devices, you'll have to ignore the details of this section.

As in Example 10-1, NaN can be useful as a marker to indicate the end of a list, provided we are confident that the list itself will have all not-NaN values.

The other thing everybody needs to know about NaN is that testing for equality *always* fails—even `NaN==NaN` will evaluate to false. Use `isnan(`*x*`)` to test whether *x* is NaN.

Those of you elbow deep in numeric data may be interested in other ways we can use NaNs as markers.

The IEEE standard has a *lot* of forms for NaN: the sign bit can be zero or one, then the exponent is all ones, and the rest is nonzero, so you have a bunch of bits like this: S11111111MMMMMMMMMMMMMMMMMMMMMMM, where S is the sign and M the unspecified mantissa.

A zero mantissa indicates ±infinity, depending on the sign bit, but we can otherwise specify those Ms to be anything we want. Once we have a way to control those free bits, we can add all kinds of distinct semaphores into a cell of a numeric array.

The program in Example 7-2 generates and uses an NA (not available) marker, which is useful in contexts where we need to distinguish between data that is missing and math errors. The trick is primarily in `set_na`, so focus your attention there first.

Example 7-2. Make your own NaN marker to annotate your floating-point data (na.c)

```
#include <stdio.h>
#include <math.h> //isnan

double ref;

double set_na(){
    if (!ref) {
        ref=0/0.;                    ❶
        char *cr = (char *)(&ref);   ❷
        cr[2]='a';                   ❸
    }
    return ref;
}

int is_na(double in){                ❹
    if (!ref) return 0;  //set_na was never called==>no NAs yet.

    char *cc = (char *)(&in);
    char *cr = (char *)(&ref);
    for (int i=0; i< sizeof(double); i++)
        if (cc[i] != cr[i]) return 0;
    return 1;
}

int main(){
    double x = set_na();
    double y = x;
    printf("Is x=set_na() NA? %i\n", is_na(x));
    printf("Is x=set_na() NAN? %i\n", isnan(x));
    printf("Is y=x NA? %i\n", is_na(y));
    printf("Is 0/0 NA? %i\n", is_na(0/0.));
    printf("Is 8 NA? %i\n", is_na(8));
}
```

❶ First produce a plain NaN by calculating `0/0.` (where the dot is important, because we need floating-point division, not integer division—integers have no means of representing NaN, and `0/0` is a plain arithmetic error).

❷ Then, we point a `char` at the bit pattern, where `char` is C's way of saying *byte*.

❸ Now that we can manipulate individual bytes of the floating-point number, we set the third byte, comfortably in the middle of the bit pattern that is this NaN, to match the character `a`. Now we have a bit pattern that is a NaN, but a very specific one, and one that the system didn't generate.

❹ The is_na function checks whether the bit pattern of the number we're testing matches the special bit pattern that set_na made up. It does this by treating both inputs as character strings and performing a character-by-character comparison.

I produced a single semaphore to store in a numeric data point, using the character a as the key element of the marker. Given that the alphabet continues on to b, c, ..., z, and A, B, ..., Z are different bit patterns entirely, we can insert a few dozen other distinct markers directly into our data set using a minor modification of the preceding code.

In fact, some widely used systems (such as WebKit) go much further than just a semaphore and actually insert an entire pointer into the mantissa of their NaNs. This method, *NaN boxing*, is left as an exercise for the reader.

Deprecate Float

Floating-point math is challenging in surprising places. It's easy to write down a reasonable algorithm that introduces 0.01% error on every step, which over 1,000 iterations turns the results into complete slop. You can easily find volumes filled with advice about how to avoid such surprises. Much of it is still valid today, but much of it is easy to handle quickly: use double instead of float, and for intermediate values in calculations, it doesn't hurt to use long double.

For example, *Writing Scientific Software* advises users to avoid what they call the single-pass method of calculating variances ([Oliveira 2006] p. 24). They give an example that is *ill-conditioned*. As you may know, a floating-point number is so named because the decimal floats to the right position in an otherwise scale-independent number. For exposition, let's pretend the computer works in decimal; then this sort of system can store 23,000,000 exactly as easily as it could store .23 or .00023—just let the decimal point float. But 23,000,000.00023 is a challenge, because there are only so many digits available for expressing the prefloat value, as shown in Example 7-3.

Example 7-3. A float can't store this many significant digits (floatfail.c)

```
#include <stdio.h>

int main(){
    printf("%f\n", (float)333334126.98);
    printf("%f\n", (float)333334125.31);
}
```

The output from Example 7-3 on my netbook, with a 32-bit float:

```
333334112.000000
333334112.000000
```

There went our precision. This is why computing books from times past worried so much about writing algorithms to minimize the sort of drift one could have with only seven reliable decimal digits.

That's for a 32-bit float, which is the minimum standard anymore. I even had to explicitly cast to float, because the system will otherwise store these numbers with a 64-bit value.

64 bits is enough to reliably store 15 significant digits: 100,000,000,000,001 is not a problem. (Try it! Hint: `printf(%.20g, val)` prints *`val`* to 20 significant decimal digits).

Example 7-4 presents the code to run Oliveira and Stewart's example, including a single-pass calculation of mean and variance. Once again, this code is only useful as a demonstration, because the GSL already implements means and variance calculators. It does the example twice: once with the ill-conditioned version, which gave our authors from 2006 terrible results, and once after subtracting 34,120 from every number, which thus gives us something that even a plain `float` can handle with full precision. We can be confident that the results using the not-ill-conditioned numbers are accurate.

Example 7-4. Ill-conditioned data: not such a big deal anymore (stddev.c)

```
#include <math.h>
#include <stdio.h> //size_t

typedef struct meanvar {double mean, var;} meanvar;

meanvar mean_and_var(const double *data){
    long double avg = 0,                                        ❶
          avg2 = 0;
    long double ratio;
    size_t cnt= 0;
    for(size_t i=0;  !isnan(data[i]); i++){
        ratio = cnt/(cnt+1.0);
        cnt   ++;
        avg   *= ratio;
        avg2  *= ratio;
        avg   += data[i]/(cnt +0.0);
        avg2  += pow(data[i], 2)/(cnt +0.0);
    }
    return (meanvar){.mean = avg,                               ❷
                    .var = avg2 - pow(avg, 2)}; //E[x^2] - E^2[x]
}

int main(){
    double d[] = { 34124.75, 34124.48,
                   34124.90, 34125.31,
                   34125.05, 34124.98, NAN};

    meanvar mv = mean_and_var(d);
    printf("mean: %.10g var: %.10g\n", mv.mean, mv.var*6/5.);

    double d2[] = { 4.75, 4.48,
                    4.90, 5.31,
                    5.05, 4.98, NAN};

    mv = mean_and_var(d2);
    mv.var *= 6./5;                                             ❸
```

```
    printf("mean: %.10g var: %.10g\n", mv.mean, mv.var);  ❹
}
```

❶ As a rule of thumb, using a higher level of precision for intermediate variables can avoid incremental roundoff problems. That is, if our output is `double`, then `avg`, `avg2`, and `ratio` should be `long double`. Do the results from the example change if we just use `double`s? (Hint: no.)

❷ The function returns a struct generated via designated initializers. If this form is unfamiliar to you, you'll meet it soon.

❸ The function above calculated the population variance; scale to produce the sample variance.

❹ I used `%g` as the format specifier in the `printf`s; that's the `general` form, which accepts both floats and doubles.

Here are the results:

```
mean: 34124.91167 var: 0.07901676614
mean: 4.911666667 var: 0.07901666667
```

The means are off by 34,120, because we set up the calculations that way, but are otherwise precisely identical (the .66666 would continue off the page if we let it), and the ill-conditioned variance is off by 0.000125%. The ill-conditioning had no appreciable effect.

That, dear reader, is technological progress. All we had to do was throw twice as much space at the problem, and suddenly all sorts of considerations are basically irrelevant. *You can still construct realistic cases where numeric drift can create problems*, but it's much harder to do so. Even if there is a perceptible speed difference between a program written with all `double`s and one written with all `float`s, it's worth extra microseconds to be able to ignore so many caveats.

Should we use `long int`s everywhere integers are used? The case isn't quite as open and shut. A `double` representation of π is more precise than a `float` representation of π, even though we're in the ballpark of three; both `int` and `long int` representations of numbers up to a few billion are precisely identical. The only issue is overflow. There was once a time when the limit was scandalously short, like around 32,000. It's good to be living in the present, where the range of integers on a typical system might go up to about ±2.1 billion. But if you think there's even a remote possibility that you have a variable that might multiply its way up to the billions (that's just 200 × 200 × 100 × 500, for example), then you certainly need to use a `long int` or even a `long long int`, or else your answer won't just be imprecise—it'll be entirely wrong, as C suddenly wraps around from +2.1 billion to -2.1 billion. Have a look at your copy of *limits.h* (typically in the usual locations like */include* or */usr/include/*) for details; on my netbook, for example, *limits.h* says that `int` and `long int` are identical.

If you are doing some serious counting, then #include <stdint.h> and use the intmax_t type, which is guaranteed to have a range at least up to 2^{63}-1 = 9,223,372,036,854,775,807 (C99 §7.18.1 & C11 §7.20.1).

If you do switch, remember that you'll need to modify all your printfs to use %li as the format specifier for long int and %ji for intmax_t.

Comparing Unsigned Integers

Here is a simple program that compares an int to a size_t, which is an unsigned integer representing a memory address (formally, it is what sizeof returns):

Example 7-5. Comparing unsigned and signed integers (uint.c)

```
#include <stdio.h>

int main(){
    int neg = -2;
    size_t zero = 0;
    if (neg < zero) printf("Yes, -2 is less than 0.\n");
    else            printf("No, -2 is not less than 0.\n");
}
```

You can run this and verify that it gets the wrong answer. This snippet demonstrates that in most comparisons between signed and an unsigned integers, C will force the signed type to unsigned (C99 & C11 §6.3.1.8(1)), which is the opposite of what we as humans expect. I will admit to having been caught by this a few times, and it is hard to spot the bug because the comparison looks so natural.

C gives you a multitude of ways to represent a number, from unsigned short int up to long double. This section and the last advise against using them all. Micromanaging the types, using float for efficiency and breaking out double for special occasions, or using unsigned int because you are confident the variable will never store a negative number, opens the way to bugs caused by subtle numeric imprecision and C's not-quite-intuitive arithmetic conversions.

CHAPTER 8
Obstacles and Opportunity

There's no C Foundation paying me to advocate the language, and this book is not a sales pitch dressed up as a tutorial, so I can write freely about C's problems. The bits here are too valuable to be in the don't-bother category under which so many of the items in the previous chapter fall, but they also come with cautions about the historic cruft that made sense at the time and is now just a mess.

- C's macro facilities are simple but still pack in a lot of little exceptions.
- The usage of the `static` keyword is at this point painfully confusing, though in the end, it will give us a nice alternative to elaborate macros. Its complement in certain senses, the `extern` keyword, also gives us enough rope with which to hang ourselves.
- The `const` keyword fits this chapter because it is too useful to not use, but it has oddities in its specification in the standard and in its implementation in common compilers.

Cultivate Robust and Flourishing Macros

Chapter 10 will present several options for making the user interface to your library friendlier and less error-inviting, and will rely heavily on macros to do it.

I read a lot of people who say that macros are themselves invitations for errors and should be avoided, but those people don't advise that you shouldn't use `NULL`, `isalpha`, `isfinite`, `assert`, type-generic math like `log`, `sin`, `cos`, `pow`, and so on, or any of the dozens of other facilities defined by the GNU standard library via macros. Those are well-written, robust macros that do what they should every time.

Macros perform text substitions (referred to as *expansions* under the presumption that the substituted text will be longer), and text substitutions require a different mindset from the usual functions, because the input text can interact with the text in the macro and other text in the source code. Macros are best used in cases where we want those interactions, and when we don't we need to take care to prevent them.

Before getting to the rules for making macros robust, of which there are three, let me distinguish between two types of macro. One type expands to an expression, meaning that it makes sense to evaluate these macros, print their values, or in the case of numeric results, use them in the middle of an equation. The other type is a block of instructions, that might appear after an `if` statement or in a `while` loop. That said, here are some rules:

- Parens! It's easy for expectations to be broken when a macro pastes text into place. Here's an easy example:

  ```
  #define double(x) 2*x                    Needs more parens.
  ```

  Now, the user tries `double(1+1)*8`, and the macro expands it to `2*1+1*8`, equals 10, not 32. Parens make it work:

  ```
  #define double(x) (2*(x))
  ```

  Now `(2*(1+1))*8` is what it should be. The general rule is to put all inputs in parens unless you have a specific reason not to. If you have an expression-type macro, put the macro expansion itself in parens.

- Avoid double usage. This textbook example is a little risky:

  ```
  #define max(a, b)   ((a) > (b) ? (a) : (b))
  ```

  If the user tries `int x=1, y=2; int m=max(x, y++)`, the expectation is that `m` will be 2 (the preincrement value of `y`), and then `y` will bump up to 3. But the macro expands to:

  ```
  m = ((x) > (y++) ? (x) : (y++))
  ```

  which will evaluate `y++` twice, causing a double increment where the user expected only a single, and `m=3` where the user expected `m=2`.

  If you have a block-type macro, then you can declare a variable to take on the value of the input at the head of the block, and then use your copy of the input for the rest of the macro.

  This rule is not adhered to as religiously as the parens rule—the `max` macro often appears in the wild—so bear in mind as a macro user that side effects inside calls to unknown macros should be kept to a minimum.

- Curly braces for blocks. Here's a simple block macro:

  ```
  #define doubleincrement(a, b)   \ Needs curly braces.
      (a)++;                      \
      (b)++;
  ```

  We can make it do the wrong thing by putting it after an `if` statement:

  ```
  int x=1, y=0;
  if (x>y)
      doubleincrement(x, y);
  ```

  Adding some indentation to make the error obvious, this expands to:

```
int x=1, y=0;
if (x>y)
    (x)++;
(y)++;
```

Another potential pitfall: what if your macro declares a variable `total`, but the user defined a `total` already? Variables declared in the block can conflict with variables declared outside the block. Example 8-1 has the simple solution to both problems: put curly braces around your macro.

Putting the whole macro in curly braces allows us to have an intermediate variable named `total` that lives only inside the scope of the curly braces around the macro, and it therefore in no way interferes with the `total` declared in `main`.

Example 8-1. We can control the scope of variables with curly braces, just as with typical nonmacro code (curly.c)

```
#include <stdio.h>

#define sum(max, out) {            \
    int total=0;                   \
    for (int i=0; i<= max; i++)    \
        total += i;                \
    out = total;                   \
}

int main(){
    int out;
    int total = 5;
    sum(5, out);
    printf("out= %i original total=%i\n", out, total);
}
```

But there is one small glitch remaining. This code:

```
#define doubleincrement(a, b) { \
    (a)++;                      \
    (b)++;                      \
}

if (a>b) doubleincrement(a, b);
else     return 0;
```

expands to this:

```
if (a>b) {
    (a)++;
    (b)++;
};
else     return 0;
```

The extra semicolon just before the `else` confuses the compiler. The common solution to this is to wrap the macro still further in a run-once `do-while` loop:

```
#define doubleincrement(a, b) do { \
    (a)++;                         \
    (b)++;                         \
} while(0);

if (a>b) doubleincrement(a, b);
else     return 0;
```

For gcc, Clang, and icc, use `-E` to only run the preprocessor, printing the expanded version of everything to stdout. Because that includes the expansion of `#include <stdio.h>` and other voluminous boilerplate, I usually redirect the results to a file or to a pager, with a form like `gcc -E` *`mycode.c`* `|less`, and then search the results for the macro expansion I'm trying to debug.

Using `gcc -E curly.c`, we see that the preprocessor expands the `sum` macro as shown next, and following the curly braces shows us that there's no chance that the `total` in the macro's scope will interfere with the `total` in the `main` scope. So the code would print `total` as 5:

```
int main(){
    int out;
    int total = 5;
    { int total=0; for (int i=0; i<= 5; i++) total += i; out = total; };
    printf("out= %i total=%i\n", out, total);
}
```

Limiting a macro's scope with curly braces doesn't protect us from all name clashes. In the previous example, what would happen if we were to write `int out, i=5; sum(i, out);`?

That's about it for macro caveats. The basic principle of keeping macros simple still makes sense, and you'll find that macros in production code tend to be one-liners that prep the inputs in some way and then call a standard function to do the real work. The debugger and non-C systems that can't parse macro definitions themselves don't have access to your macro, so whatever you write should still have a way of being usable without the macros. "Linkage with static and extern" on page 138 will have one suggestion for reducing the hassle when writing down simple functions.

Macro Arguments Are Optional

Here's a sensible assertion-type macro that returns if an assertion fails:

```
#define Testclaim(assertion, returnval) if (!(assertion))        \
               {fprintf(stderr, #assertion " failed to be true.  \
               Returning " #returnval "\n"); return returnval;}
```

Sample usage:

```
int do_things(){
    int x, y;
    …
    Testclaim(x==y, -1);
    …
    return 0;
}
```

But what if you have a function that has no return value? In this case, you can leave the second argument blank:

```
void do_other_things(){
    int x, y;
    …
    Testclaim(x==y, );
    …
    return;
}
```

Then the last line of the macro expands to `return ;`, which is valid and appropriate for a function that returns `void`. (On the validity of blank macro arguments, see C99 & C11 §6.10.3(4), which explicitly allows "arguments consisting of no preprocessing tokens".)

If so inclined, you could even use this to implement default values:

```
#define Blankcheck(a) {int aval = (strlen(#a)>0) ? (a+0) : 2;  \
        printf("I understand your input to be %i.\n", aval); \
        }

//Usage:

Blankcheck(0);  //will set aval to zero.
Blankcheck( );  //will set aval to two.
```

Preprocessor Tricks

The token reserved for the preprocessor is the octothorp, `#`, and the preprocessor makes three entirely different uses of it.

You know that a preprocessor directive like `#define` begins with a `#` at the head of the line. Whitespace before the `#` is ignored (K&R 2nd ed. §A12, p. 228), so here's your first tip: you can put throwaway macros in the middle of a function, just before they get used, and indent them to flow with the function. According to the old school, putting the macro right where it gets used is against the "correct" organization of a program (which puts all macros at the head of the file), but having it right there makes it easy to refer to and makes the throwaway nature of the macro evident. The preprocessor knows next to nothing of where functions begin and end, so the scope of a macro is from its occurrence in the file to the end of the file.

The next use of the `#` is in a macro: it turns input code into a string. Example 8-2 shows a program demonstrating a point about the use of `sizeof` (see the sidebar), though the main focus is on the use of the preprocessor macro.

Example 8-2. In which text is both printed and evaluated (sizesof.c)

```
#include <stdio.h>

#define Peval(cmd) printf(#cmd ": %g\n", cmd);

int main(){
    double *plist = (double[]){1, 2, 3};        ❶
    double list[] = {1, 2, 3};
    Peval(sizeof(plist)/(sizeof(double)+0.0));
    Peval(sizeof(list)/(sizeof(double)+0.0));
}
```

❶ This is a compound literal. If you're unfamiliar with them, I'll introduce them to you later. When considering how `sizeof` treats `plist`, bear in mind that `plist` is a pointer to an array, not the array itself.

When you try it, you'll see that the input to the macro is printed as plain text, and then its value is printed, because `#cmd` is equivalent to `cmd` as a string. So `Peval(list[0])` would expand to:

```
printf("list[0]" ": %g\n", list[0]);
```

Does that look malformed to you, with the two strings `"list[0]" ": %g\n"` next to each other? The next preprocessor trick is if two literal strings are adjacent, the preprocessor merges them into one: `"list[0]: %g\n"`. And this isn't just in macros:

```
printf("You can use the preprocessor's string "
       "concatenation to break long lines of text "
       "in your program. I think this is easier than "
       "using backslashes, but be careful with spacing.");
```

The Limits of sizeof

Did you try the sample code? It is based on a common trick in which you can get the size of an automatic or static array by dividing its total size by the size of one element (*http://c-faq.com/aryptr/arraynels.html*; see also K&R 1st ed. p. 126, 2nd ed. p 135), e.g.:

```
//This is not reliable:
#define arraysize(list) sizeof(list)/sizeof(list[0])
```

The `sizeof` operator (it's a C keyword, not a plain function) refers to the automatically allocated variable (which might be an array or a pointer), not to the data a pointer might be pointing to. For an automatic array like `double list[100]`, the compiler had to allocate a hundred `double`s, and will have to make sure that much space (probably 800 bytes) is not trampled by the next variable to go on the stack. For manually allocated memory (`double *plist; plist = malloc(sizeof(double *100));`), the pointer on the stack is maybe 8 bytes long (certainly not 100), and `sizeof` will return the length of that pointer, not the length of what it is pointing to.

Some cats, when you point to a toy, will go and inspect the toy; some cats will sniff your finger.

Conversely, you might want to join together two things that are not strings. Here, use two octothorps, which I herein dub the hexadecathorp: `##`. If the value of `name` is `LL`, then when you see `name ## _list`, read it as `LL_list`, which is a valid and usable variable name.

Gee, you comment, *I sure wish every array had an auxiliary variable that gave its length*. OK, Example 8-3 writes a macro that declares a local variable ending in `_len` for each list you tell it to care about. It'll even make sure every list has a terminating marker, so you don't even need the length.

That is, this macro is total overkill, and I don't recommend it for immediate use, but it does demonstrate how you can generate lots of little temp variables that follow a naming pattern that you choose.

Example 8-3. Creating auxiliary variables using the preprocessor (preprocess.c)

```
#include <stdio.h>
#include <math.h> //NAN

#define Setup_list(name, ...)                               \
    double *name ## _list = (double []){__VA_ARGS__, NAN};  \ ❶
    int name ## _len = 0;                                   \
    for (name ## _len =0;                                   \
            !isnan(name ## _list[name ## _len]);            \
            ) name ## _len ++;


int main(){
    Setup_list(items, 1, 2, 4, 8);                         ❷
    double sum=0;
    for (double *ptr= items_list; !isnan(*ptr); ptr++)     ❸
        sum += *ptr;
    printf("total for items list: %g\n", sum);

    #define Length(in) in ## _len                          ❹

    sum=0;
    Setup_list(next_set, -1, 2.2, 4.8, 0.1);
    for (int i=0; i < Length(next_set); i++)               ❺
        sum += next_set_list[i];
    printf("total for next set list: %g\n", sum);
}
```

❶ The right-hand side of the equals sign uses a variadic macro to construct a compound literal. If this jargon is foreign to you, just focus on the macro work on the left-hand side and hold tight until Chapter 10.

❷ Generates `items_len` and `items_list`.

❸ Here is a loop using the `NaN` marker.

❹ Some systems let you query an array for its own length using a form like this.

❺ Here is a loop using the `next_set_len` length variable.

As a stylistic aside, there has historically been a custom to indicate that a function is actually a macro by putting it in all caps, as a warning to be careful to watch for the surprises associated with text substitution. I think this looks like yelling, and prefer to mark macros by capitalizing the first letter. Others don't bother with the capitalization thing at all.

Linkage with static and extern

In this section, we write code that will tell the compiler what kind of advice it should give to the linker. The compiler works one *.c* file at a time, (typically) producing one *.o* file at at a time, then the linker joins those *.o* files together to produce one library or executable.

What happens if there are two declarations in two separate files for the variable `x`? It could be that the author of one file just didn't know that the author of the other file had chosen `x`, so the two `x`es should be broken up and into two separate spaces. Or perhaps the authors were well aware that they are referring to the same variable, and the linker should take all references of `x` to be pointing to the same spot in memory.

External linkage means that symbols that match across files should be treated as the same thing by the linker. For functions and variables declared outside of a function, this is the default, but the `extern` keyword will be useful to indicate external linkage (see later).[1]

Internal linkage indicates that a file's instance of a variable `x` or a function `f()` is its own and matches only other instances of `x` or `f()` in the same scope (which for things declared outside of any functions would be file scope). Use the `static` keyword to indicate internal linkage.

It's funny that external linkage has the `extern` keyword, but instead of something sensible like `intern` for internal linkage, there's `static`. In "Automatic, Static, and Manual Memory" on page 101, I discussed the three types of memory model: static, automatic, and manual. Using the word `static` for both linkage and memory model is joining together two concepts that may at one time have overlapped for technical reasons, but are now distinct.

- For file scope variables, `static` affects only the linkage:
  - The default linkage is external, so use the `static` keyword to change this to internal linkage.
  - Any variable in file scope will be allocated using the static memory model, regardless of whether you used `static int x`, `extern int x`, or just plain `int x`.
- For block scope variables, `static` affects only the memory model:

1. This is from C99 & C11 §6.2.3, which is actually about resolving symbols across different scopes, not just files, but trying crazy linkage tricks across different scopes within one file is generally not done.

- —The default linkage is internal, so the static keyword doesn't affect linkage. You could change the linkage by declaring the variable to be extern, but later, I will advise against this.
- —The default memory model is automatic, so the static keyword changes the memory model to static.

- For functions, static affects only the linkage:
  - —Functions are only defined in file scope (gcc offers nested functions as an extension). As with file-scope variables, the default linkage is external, but use the static keyword for internal linkage.
  - —There's no confusion with memory models, because functions are always static, like file-scope variables.

The norm for declaring a function to be shared across *.c* files is to put the header in a *.h* file to be reincluded all over your project, and put the function itself in one *.c* file (where it will have the default external linkage). This is a good norm, and is worth sticking to, but it is reasonably common for authors to want to put one- or two-line utility functions (like max and min) in a *.h* file to be included everywhere. You can do this by preceding the declaration of your function with the static keyword, for example:

```
//In common_fns.h:
static long double max(long double a, long double b){
    (a > b) ? a : b;
}
```

When you #include "common_fns.h" in each of a dozen files, the compiler will produce a new instance of the max function in each of them. But because you've given the function internal linkage, none of the files has made public the function name max, so all dozen separate instances of the function can live independently with no conflicts. Such redeclaration might add a few bytes to your executable and a few milliseconds to your compilation time, but that's irrelevant in typical environments.

Externally Linked Variables in Header Files

The extern keyword is a simpler issue than static, because it is only about linkage, not memory models. The typical setup for a variable with external linkage:

- In a header to be included anywhere the variable will be used, declare your variable with the extern keyword. E.g., extern *int x*.
- In exactly one .c file, declare the variable as usual, with an optional initializer. E.g., *int x=3*. As with all static-memory variables, if you leave off the initial value (just *int x*), the variable is initialized to zero or NULL.

That's all you have to do to use variables with external linkage.

You may be tempted to put the `extern` declaration not in a header, but just as a loose declaration in your code. In *file1.c*, you have declared `int x`, and you realize that you need access to `x` in *file2.c*, so you throw a quick `extern int x` at the top of the file. This will work—today. Next month, when you change *file1.c* to declare `double x`, the compiler's type checking will still find *file2.c* to be entirely internally consistent. The linker blithely points the routine in *file2.c* to the location where the `double` named `x` is stored, and the routine blithely misreads the data there as an `int`. You can avoid this disaster by leaving all `extern` declarations in a header to `#include` in both *file1.c* and *file2.c*. If any types change anywhere, the compiler will then be able to catch the inconsistency.

Under the hood, the system is doing a lot of work to make it easy for you to declare one variable several times wile allocating memory for it only once. Formally, a declaration marked as `extern` is a declaration (a statement of type information so the compiler can do consistency checking), and not a definition (instructions to allocate and initialize space in memory). But a declaration without the `extern` keyword is a *tentative definition*: if the compiler gets to the end of the unit (defined below) and doesn't see a definition, then the tentative definitions get turned into a single definition, with the usual initialization to zero or `NULL`. The standard defines *unit* in that sentence as a single file, after `#include`s are all pasted in (a translation unit; see C99 & C11 §6.9.2(2)).

Compilers like gcc and Clang typically read *unit* to mean the entire program, meaning that a program with several non-`extern` declarations and no definitions rolls all these tentative definitions up into a single definition. Even with the `--pedantic` flag, gcc doesn't care whether you use the `extern` keyword or leave it off entirely. In practice, that means that the `extern` keyword is largely optional: your compiler will read a dozen declarations like *`int x=3`* as a single definition of a single variable with external linkage. K&R [2nd ed, p 227] describe this behavior as "usual in UNIX systems and recognized as a common extension by the [ANSI] Standard". [Harbison 1991] §4.8 documents four distinct interpretations of the rules for `extern`s.

This means that if you want two variables with the same name in two files to be distinct, but you forget the `static` keyword, your compiler will probably link those variables together as a single variable with external linkage; subtle bugs can easily ensue. So be careful to use `static` for all file-scope variables intended to have internal linkage.

The const Keyword

The `const` keyword is fundamentally useful, but the rules around `const` have several surprises and inconsistencies. This segment will point them out so they won't be surprises anymore, which should make it easier for you to use `const` wherever good style advises that you do.

Early in your life, you learned that *copies* of input data are passed to functions, but you can still have functions that change input data by sending in a *copy of a pointer* to the data. When you see that an input is plain, not-pointer data, then you know that the caller's original version of the variable won't change. When you see a pointer input, it's unclear. Lists and strings are naturally pointers, so the pointer input could be data to be modified, or it could just be a string.

The `const` keyword is a literary device for you, the author, to make your code more readable. It is a *type qualifier* indicating that the data pointed to by the input pointer will not change over the course of the function. It is useful information to know when data shouldn't change, so do use this keyword where possible.

The first caveat: the compiler does not lock down the data being pointed to against all modification. Data that is marked as `const` under one name can be modified using a different name. In Example 8-4, `a` and `b` point to the same data, but because `a` is not `const` in the header for `set_elmt`, it can change an element of the `b` array. See Figure 8-1.

Example 8-4. Data that is marked as const under one name can be modified using a different name (constchange.c)

```
void set_elmt(int *a, int const *b){
    a[0] = 3;
}

int main(){
    int a[10] = {};    ❶
    int const *b = a;
    set_elmt(a, b);
}                      ❷
```

❶ Initialize the array to all zeros.

❷ This is a do-nothing program intended only to compile and run without errors. If you want to verify that `b[0]` did change, you can run this in your debugger, break at the last line, and print the value of `b`.

So `const` is a literary device, not a lock on the data.

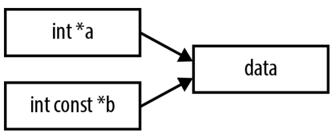


Figure 8-1. We can modify the data via a, even though b is const; this is valid

Noun-Adjective Form

The trick to reading declarations is to read from right to left. Thus:

- `int const` = a constant integer
- `int const *` = a (variable) pointer to a constant integer

- `int * const` = a constant pointer to a (variable) integer
- `int * const *` = a pointer to a constant pointer to an integer
- `int const * *` = a pointer to a pointer to a constant integer
- `int const * const *` = a pointer to a constant pointer to a constant integer

You can see that the `const` always refers to the text to its left, just as the `*` does.

You can switch a type name and `const`, and so write either `int const` or `const int` (though you can't do this switch with `const` and `*`). I prefer the `int const` form because it provides consistency with the more complex constructions and the right-to-left rule. There's a custom to use the `const int` form, perhaps because it reads more easily in English or because that's how it's always been done. Either works.

What About restrict and inline?

I wrote some sample code both using the `restrict` and `inline` keywords and not using them, so that I could demonstrate to you the speed difference that these keywords make.

I had high hopes, and in years past, I found real gains from using `restrict` in numeric routines. But when I wrote up the tests here in the present day, the difference in speed with and without the keywords was minuscule.

As per my recommendations throughout the book, I set `CFLAGS=-g -Wall -O3` when compiling, and that means gcc threw every optimization trick it knew at my sample programs, and those optimizations knew when to treat pointers as `restrict` and when to inline functions without my explicitly instructing the compiler.

Tension

In practice, you will find that `const` sometimes creates tension that needs to be resolved, when you have a pointer that is marked `const`, but want to send it as an input to a function that does not have a `const` marker in the right place. Maybe the function author thought that the keyword was too much trouble, or believed the chatter about how shorter code is always better code, or just forgot.

Before proceeding, you'll have to ask yourself if there is any way in which the pointer could change in the `const`-less function being called. There might be an edge case where something gets changed, or some other odd reason. This is stuff worth knowing anyway.

If you've established that the function does not break the promise of `const`-ness that you made with your pointer, then it is entirely appropriate to cheat and cast your `const` pointer to a non-`const` for the sake of quieting the compiler.

```
//No const in the header this time...
void set_elmt(int *a, int *b){
    a[0] = 3;
}
```

```
int main(){
    int a[10];
    int const *b = a;
    set_elmt(a, (int*)b);     //...so add a type-cast to the call.
}
```

The rule seems reasonable to me. You can override the compiler's const-checking, as long as you are explicit about it and indicate that you know what you are doing.

If you are worried that the function you are calling won't fulfill your promise of `const`-ness, then you can take one step further and make a full copy of the data, not just an alias. Because you don't want any changes in the variable anyway, you can throw out the copy afterward.

Depth

Let us say that we have a struct—name it `counter_s`—and we have a function that takes in one of these structs, of the form `f(counter_s const *in)`. Can the function modify the elements of the structure?

Let's try it: Example 8-5 generates a struct with two pointers, and in `ratio`, that struct becomes `const`, yet when we send one of the pointers held by the structure to the const-less subfunction, the compiler doesn't complain.

Example 8-5. The elements of a const struct are not const (conststruct.c)

```
#include <assert.h>
#include <stdlib.h>  //assert

typedef struct {
    int *counter1, *counter2;
} counter_s;

void check_counter(int *ctr){ assert(*ctr !=0); }

double ratio(counter_s const *in){                      ❶
    check_counter(in->counter2);                        ❷
    return *in->counter1/(*in->counter2+0.0);
}

int main(){
    counter_s cc = {.counter1=malloc(sizeof(int)),      ❸
                    .counter2=malloc(sizeof(int))};
    *cc.counter1 = *cc.counter2 = 1;
    ratio(&cc);
}
```

❶ The incoming struct is marked as `const`.

❷ We send an element of the `const` struct to a function that takes not-`const` inputs. The compiler does not complain.

❸ This is declaration via designated initializers—coming soon.

In the definition of your struct, you can specify that an element be `const`, though this is typically more trouble than it is worth. If you really need to protect only the lowest level in your hierarchy of types, your best bet is to put a note in the documentation.

The char const ** Issue

Example 8-6 is a simple program to check whether the user gave Iggy Pop's name on the command line. Sample usage from the shell (recalling that `$?` is the return value of the just-run program):

```
iggy_pop_detector Iggy Pop; echo $?      #prints 1
iggy_pop_detector Chaim Weitz; echo $?   #prints 0
```

Example 8-6. Ambiguity in the standard causes all sorts of problems for the pointer-to-pointer-to-const (iggy_pop_detector.c)

```
#include <stdbool.h>
#include <strings.h> //strcasecmp

bool check_name(char const **in){  ❶
    return   (!strcasecmp(in[0], "Iggy") && !strcasecmp(in[1], "Pop"))
           ||(!strcasecmp(in[0], "James") && !strcasecmp(in[1], "Osterberg"));
}

int main(int argc, char **argv){
    if (argc < 2) return 0;
    return check_name(&argv[1]);
}
```

❶ If you haven't seen Booleans before, I'll introduce you to them in a sidebar later.

The `check_name` function takes in a pointer to (string that is constant), because there is no need to modify the input strings. But when you compile it, you'll find that you get a warning. Clang says: "passing `char **` to parameter of type `const char **` discards qualifiers in nested pointer types." In a sequence of pointers, all the compilers I could find will convert to `const` what you could call the top-level pointer (casting to `char * const *`), but complain when asked to `const`-ify what that pointer is pointing to (`char const **`, aka `const char **`).

Again, you'll need to make an explicit cast—replace `check_name(&argv[1])` with:

```
check_name((char const**)&argv[1]);
```

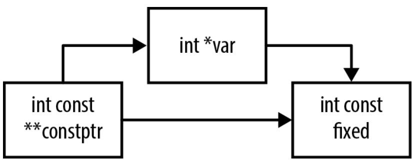
Why doesn't this entirely sensible cast happen automatically? We need some creative setup before a problem arises, and the story is inconsistent with the rules to this point. So the explanation is a slog; I will understand if you skip it.

The code in Example 8-7 creates the three links in the diagram: the direct link from `constptr -> fixed`, and the two steps in the indirect link from `constptr -> var` and `var -> fixed`. In the code, you can see that two of the assignments are made explicitly: `constptr -> var` and `constptr -> -> fixed`. But because `*constptr == var`, that second link implicitly creates the `var -> fixed` link. When we assign `*var=30`, that assigns `fixed = 30`.

Example 8-7. We can modify the data via an alternate name, even though it is const via one name—this is deemed to be illegal (constfusion.c)

```
#include <stdio.h>

int main(){
    int *var;
    int const **constptr = &var; // the line that sets up the failure
    int const fixed = 20;
    *constptr = &fixed;          // 100% valid
    *var = 30;
    printf("x=%i y=%i\n", fixed, *var);
}
```



We would never allow `int *var` to point directly at `int const fixed`. We only managed it via a sleight-of-pointer where `var` winds up implicitly pointing to `fixed` without explicitly stating it.

Your Turn: Is it possible to cause a failure of `const` like this one, but where the disallowed type cast happens over the course of a function call, as per the Iggy Pop detector?

As earlier, data that is marked as `const` under one name can be modified using a different name. So, really, it's little surprise that we were able to modify the `const` data using an alternative name.[2]

I enumerate this list of problems with `const` so that you can surmount them. As literature goes, it isn't all that problematic, and the recommendation that you add `const` to your function declarations as often as appropriate still stands—don't just grumble about how the people who came before you didn't provide the right headers. After all, some day others will use your code, and you don't want them grumbling about how they can't use the `const` keyword because your functions don't have the right headers.

True and False

C originally had no Boolean (true/false) type, instead using the convention that if something is zero or `NULL`, then it is false, and if it is anything else it is true. Thus, `if(`*`ptr`*`!=NULL)` and `if(`*`ptr`*`)` are equivalent, and if you're not used to the second form, get used to it, because your fellow C authors (myself included) expect you to be able to read it without hestiation. (Exception: the custom for program return values is that zero = success and nonzero = failure.)

C99 introduced the `_Bool` type, which is technically unnecessary, because you can always use an integer to represent a true/false value. But to a human reading the code, the Boolean type clarifies that the variable can only take on true/false values, and so gives some indication of its intent.

The string `_Bool` was chosen by the standards committee because it is in the space of strings reserved for additions to the language, but it is certainly awkward. The *stdbool.h* header defines three macros to improve readability: `bool` expands to `_Bool`, so you don't have to use the unappealing underscore in your declarations; `true` expands to `1`; `false` expands to `0`.

Just as the `bool` type is more for the human reader, the `true` and `false` macros can clarify the intent of an assignment: if I forgot that `outcome` was declared as `bool`, `outcome=true` adds a reminder of intent that `outcome=1` does not.

However, there is really no reason to compare any expression to `true` or `false`: we all know to read `if (x)` to mean *if x is true, then…*, without the `==true` explicitly written on the page. Further, given `int x=2`, `if (x)` does what everybody expects and `if (x==true)` doesn't.

2. The code here is a rewrite of the example in C99 & C11 §6.5.16.1(6), where the line analogous to `constptr=&var` is marked as a `constraint violation`. Why do gcc and Clang mark it as a warning, instead of halting? Because it's technically correct: C99 & C11 §6.3.2.3(2), regarding type qualifiers like `const`, explains that, "For any qualifier *q*, a pointer to a non-*q*-qualified type may be converted to a pointer to the *q*-qualified version of the type..."

CHAPTER 9
Text

> I believe that in the end the word will break cement.
>
> —Pussy Riot, paraphrasing Aleksandr Solzhenitsyn in a statement on 8 August 2012.

A string of letters is an array of indeterminate length, and automatically allocated arrays (allocated on the stack) can't be resized, and that in a nutshell is the problem with text in C. Fortunately, many others before us have already faced this problem and produced at least partial solutions. A handful of C-standard and POSIX-standard functions are sufficient to handle many of our string-building needs.

Also, C was designed in the 1970s, before the invention of non-English languages. Again, with the right functions (and the right understanding of how language is encoded), C's original focus on English is not a real problem.

Making String Handling Less Painful with asprintf

The `asprintf` function allocates the amount of string space you will need, and then fills the string. That means you never really have to worry about string-allocing again.

`asprintf` is not part of the C standard, but it's available on systems with the GNU or BSD standard library, which covers a big range of users. Further, the GNU `libiberty` library provides a version of `asprintf` that you can cut and paste into your own code base; see the next section.

The old way made people homicidal (or suicidal, depending on temperament), because they first had to get the length of the string they were about to fill, allocate space, and then actually write to the space. Don't forget the extra slot for the null terminator!

Example 9-1 demonstrates the painful way of setting up a string, for the purpose of using C's `system` command to run an external utility. The thematically appropriate utility, `strings`, searches a binary for printable plain text. The `get_strings` function will receive `argv[0]`, the name of the program itself, so the program searches itself for strings. This is perhaps amusing, which is all we can ask of demo code.

Example 9-1. The tedious way of setting up strings (sadstrings.c)

```
#include <stdio.h>
#include <string.h> //strlen
#include <stdlib.h> //malloc, free, system

void get_strings(char const *in){
    char *cmd;
    int len = strlen("strings ") + strlen(in) + 1;   ❶
    cmd = malloc(len);                                 ❷
    snprintf(cmd, len, "strings %s", in);
    if (system(cmd)) fprintf(stderr, "something went wrong running %s.\n", cmd);
    free(cmd);
}

int main(int argc, char **argv){
    get_strings(argv[0]);
}
```

❶ Premeasuring lengths is such a waste of time.

❷ The C standard says `sizeof(char)==1`, so we at least don't need `malloc(len*sizeof(char))`.

Example 9-2 uses `asprintf`, so `malloc` gets called for you, which means that you also don't need the step where you measure the length of the string.

Example 9-2. This version cuts only two lines from Example 9-1, but they're the most misery-inducing lines (getstrings.c)

```
#define _GNU_SOURCE //cause stdio.h to include asprintf
#include <stdio.h>
#include <stdlib.h> //free

void get_strings(char const *in){
    char *cmd;
    asprintf(&cmd, "strings %s", in);
    if (system(cmd)) fprintf(stderr, "something went wrong running %s.\n", cmd);
    free(cmd);
}

int main(int argc, char **argv){
    get_strings(argv[0]);
}
```

The actual call to `asprintf` looks a lot like the call to `sprintf`, except you need to send the location of the string, not the string itself, because new space will be `malloc`ed and the location written into the `char **` you input.

Security

If you have a string of predetermined length, *`str`*, and write data of unknown length to it using `sprintf`, then you might find that data gets written to whatever is adjacent to *str*—a classic security breach. Thus, `sprintf` is effectively deprecated in favor of `snprintf`, which limits the amount of data written.

Using `asprintf` effectively prevents this problem, because as much memory as is needed will get written. It's not perfect: eventually, whatever mangled and improper input string will hit a `\0` somewhere, but the amount of data could conceivably exceed the amount of free memory, or the additional data written to *str* might be sensitive information like a password.

If memory is exceeded, then `asprintf` will return `-1`, so in a situation involving user inputs, the careful author would use something like the `Stopif` macro (which I introduce in "Variadic Macros" on page 165) with a form like:

```
Stopif(asprintf(&str, "%s", user_input)==-1, return -1, "asprintf failed.")
```

But if you got as far as sending an unchecked string to `asprintf`, you've already lost. Check that strings from untrusted inputs are of a sane length beforehand. The function might also fail on a string of reasonable length because the computer is out of memory or is being eaten by gremlins.

Constant Strings

Here is a program that sets up two strings and prints them to the screen:

```
#include <stdio.h>

int main(){
    char *s1 = "Thread";

    char *s2;
    asprintf(&s2, "Floss");

    printf("%s\n", s1);
    printf("%s\n", s2);
}
```

Both forms will leave a single word in the given string. However, the C compiler treats them in a very different manner, which can trip up the unaware.

Did you try the earlier sample code that showed what strings are embedded into the program binary? In the example here, `Thread` would be such an embedded string, and `s1` could thus point to a location in the executable program itself. How efficient—you don't need to spend runtime having the system count characters or waste memory repeating information already in the binary. I suppose in the 1970s, this mattered.

Both the baked-in `s1` and the allocated-on-demand `s2` behave identically for reading purposes, but you can't modify or free `s1`. Here are some lines you could add to the example, and their effects:

```
s2[0]='f'; //Switch Floss to lowercase.
s1[0]='t'; //Segfault.
```

```
free(s2); //Clean up.
free(s1); //Segfault.
```

Your system may point directly to the string embedded in the executable or it may copy the string to a read-only data segment; the standard never dictates such implementation details, but it does dictate that `s1`'s contents will be absolutely read-only.

The difference between constant and variable strings is subtle and error-prone, and it makes hardcoded strings useful only in limited contexts. I can't think of a scripting language where you would need to care about this distinction.

But here is one simple solution: `strdup`, which is POSIX-standard, and is short for *string duplicate*. It works like this:

```
char *s3 = strdup("Thread");
```

The string `Thread` is still hardcoded into the program, but `s3` is a copy of that constant blob, and so can be freely modified as you wish. With liberal use of `strdup`, you can treat all strings equally, without worrying about which are constant and which are pointers.

If you are unable to use the POSIX standard and are worried that you don't have a copy of `strdup` on your machine, it's easy enough to write a version for yourself. For example, we can once again use `asprintf`:

```
#ifndef HAVE_STRDUP
char *strdup(char const* in){
    if (!in) return NULL;
    char *out;
    asprintf(&out, "%s", in);
    return out;
}
#endif
```

And where does that `HAVE_STRDUP` macro come from? If you are using Autotools, then putting this line:

```
AC_CHECK_FUNCS([asprintf strdup])
```

into *configure.ac* would produce a segment in the `configure` script that generates a *configure.h* with `HAVE_STRDUP` and `HAVE_ASPRINTF` defined or not defined as appropriate.

If `HAVE_ASPRINTF` is undefined, you'll have to provide it. It is provided by the GNU's Libiberty library (which means you will need a `-liberty` flag for the linker). Libiberty ships with some systems with no native `asprintf`, like MSYS for Windows. If you don't want to make users fetch another library, you can easily paste Libiberty's `asprintf`-relevant sections into your own code base.

Extending Strings with asprintf

Here is an example of the basic form for appending another bit of text to a string using `asprintf`, which, as earlier, can be your workhorse for string handling:

```
asprintf(&q, "%s and another clause %s", q, addme);
```

I use this for generating database queries. I would put together a chain, such as this contrived example:

```
int col_number=3, person_number=27;
char *q =strdup("select ");
asprintf(&q, "%scol%i \n", q, col_number);
asprintf(&q, "%sfrom tab \n", q);
asprintf(&q, "%swhere person_id = %i", q, person_number);
```

And in the end I have:

```
select col3
from tab
where person_id = 27
```

This is a rather nice way of putting together a long and painful string, which becomes essential as the subclauses get convoluted.

But it's a memory leak, because the blob at the original address of `q` isn't released when `q` is given a new location by `asprintf`. For one-off string generation, it's not even worth caring about—you can drop a few million query-length strings on the floor before anything noticeable happens.

If you are in a situation where you might produce an unknown number of strings of unknown length, then you will need a form like that in Example 9-3.

Example 9-3. A macro to cleanly extend strings (sasprintf.c)

```
#include <stdio.h>
#include <stdlib.h> //free

//Safer asprintf macro
#define Sasprintf(write_to,  ...) {           \
    char *tmp_string_for_extend = (write_to); \
    asprintf(&(write_to), __VA_ARGS__);       \
    free(tmp_string_for_extend);              \
}

//sample usage:
int main(){
    int i=3;
    char *q = NULL;
    Sasprintf(q, "select * from tab");
    Sasprintf(q, "%s where col%i is not null", q, i);
    printf("%s\n", q);
}
```

The `Sasprintf` macro, plus occasional use of `strdup`, is enough for roughly 100% of your string-handling needs. Except for one glitch and the occasional `free`, you don't have to think about memory issues at all.

The glitch is that if you forget to initialize `q` to `NULL` or via `strdup`, then the first use of the `Sasprintf` macro will be freeing whatever junk happened to be in the uninitialized location `q`—a segfault.

For example, the following fails—wrap that declaration in `strdup` to make it work:

```
char *q = "select * from";  //fails—needs strdup().
Sasprintf(q, "%s %s where col%i is not null", q, tablename, i);
```

In extensive usage, this sort of string concatenation can theoretically cause slowdowns, as the first part of the string gets rewritten over and over. In this case, you can use C as a prototyping language for C: if and only if the technique here proves to be too slow, take the time to replace it with more traditional `snprintf`s.

A Pæan to strtok

Tokenizing is the simplest and most common parsing problem, in which we split a string into parts at delimiters. This definition covers all sorts of tasks:

- Splitting words at whitespace delimiters such as one of `" \t\n\r"`.
- Given a path such as `"/usr/include:/usr/local/include:."`, cutting it at the colons into the individual directories.
- Splitting a string into lines using a simple newline delimiter, `"\n"`.
- You might have a configuration file with lines of the form `value = key`, in which case your delimiter is `"="`.
- Comma-delimited values in a datafile are of course cut at the comma.

Two levels of splitting will get you still further, such as reading a full configuration file by first splitting at newlines, then splitting each line at the `=`.

Tokenizing comes up often enough that there's a standard C library function to do it, `strtok` (string tokenize), which is one of those neat little functions that does its job quietly and well.

The basic working of `strtok` is to step through the string you input until it hits the first delimiter, then overwrite the delimiter with a `'\0'`. Now the first part of the input string is a valid string representing the first token, and `strtok` returns a pointer to the head of that substring for your use. The function holds the original string's information internally, so when you call `strtok` again, it can search for the end of the next token, nullify that end, and return the head of that token as a valid string.

The head of each substring is a pointer to a spot within an already-allocated string, so the tokenizing does a minimum of data writing (just those `\0`s) and no copying. The immediate implication is that the string you input is mangled, and because substrings are pointers to the original string, you can't free the input string until you are done using the substrings (or, you can use `strdup` to copy out the substrings as they come out).

The strtok function holds the rest of the string you first input in a single static internal pointer, meaning that it is limited to tokenizing one string (with one set of delimiters) at a time, and it can't be used while threading. Therefore, consider strtok to be deprecated.

Instead, use strtok_r or strtok_s, which are threading-friendly versions of strtok. The POSIX standard provides strtok_r, and the C11 standard provides strtok_s. The use of either is a little awkward, because the first call is different from the subsequent calls.

- The first time you call the function, send in the string to be parsed as the first argument.
- On subsequent calls, send in NULL as the first argument.
- The last argument is the scratch string. You don't have to initialize it on first use; on subsequent uses it will hold the string as parsed so far.

Here's a line counter for you (actually, a counter of nonblank lines; see warning later on). Tokenizing is often a one-liner in scripting languages, but this is about as brief as it gets with strtok_r. Notice the *if* ? *then* : *else* to send in the original string only on the first use.

```
#include <string.h> //strtok_r

int count_lines(char *instring){
    int counter = 0;
    char *scratch, *txt, *delimiter = "\n";
    while ((txt = strtok_r(!counter ? instring : NULL, delimiter, &scratch)))
        counter++;
    return counter;
}
```

The Unicode section will give a full example, as will the Cetology example of "Count References" on page 219.

The C11-standard strtok_s works just like strtok_r, but has an extra argument (the second) which gives the length of the input string, and is updated to shrink to the length of the remaining string on each call. If the input string is not \0-delimited, this extra element would be useful. We could redo the earlier example with:

```
#include <string.h> //strtok_s

//first use
size_t len = strlen(instring);
txt = strtok_s(instring, &len, delimiter, &scratch);

//subsequent use:
txt = strtok_s(NULL, &len, delimiter, &scratch);
```

Two or more delimiters in a row are treated as a single delimiter, meaning that blank tokens are simply ignored. For example, if your delimiter is `":"` and you are asking `strtok_r` or `strtok_s` to break down `/bin:/usr/bin::/opt/bin`, then you will get the three directories in sequence—the `::` is treated like a `:`. This is also why the preceding line counter is actually a nonblank line counter, as the double newline in a string like `one \n\n three \n four` (indicating that line two is blank) would be treated by `strtok` and its variants as a single newline.

Ignoring double delimiters is often what you want (as in the path example), but sometimes it isn't, in which case you'll need to think about how to detect double delimiters. If the string to be split was written by you, then be sure to generate the string with a marker for intentionally blank tokens. Writing a function to precheck strings for doubled delimiters is not too difficult (or try the BSD/GNU-standard `strsep`). For inputs from users, you can add stern warnings about not allowing delimiters to double up, and warn them of what to expect, like how the line-counter here ignores blank lines.

Example 9-5 presents a small library of string utilities that might be useful to you, including some of the macros from earlier in this book.

There are two key functions: `string_from_file` reads a complete file into a string. This saves us all the hassle of trying to read and process smaller chunks of a file. If you routinely deal with text files larger than a few gigabytes, you won't be able to rely on this, but for situations in which text files never make it past a few megabytes, there's no point screwing around with dealing with incrementally reading a text file one chunk at a time. I'll use this function for several examples over the course of the book.

The second key function is `ok_array_new`, which tokenizes a string and writes the output to a struct, an `ok_array`.

Example 9-4 is the header.

Example 9-4. A header for a small set of string utilities (string_utilities.h)

```
#include <string.h>
#define _GNU_SOURCE //asks stdio.h to include asprintf
#include <stdio.h>

//Safe asprintf macro
#define Sasprintf(write_to,  ...) {           \                    ❶
    char *tmp_string_for_extend = write_to;  \
    asprintf(&(write_to), __VA_ARGS__);      \
    free(tmp_string_for_extend);             \
}

char *string_from_file(char const *filename);

typedef struct ok_array {
    char **elements;
    char *base_string;
```

```
    int length;
} ok_array;                                                    ❷

ok_array *ok_array_new(char *instring, char const *delimiters); ❸

void ok_array_free(ok_array *ok_in);
```

❶ This is the `Sasprintf` macro from earlier, reprinted for your convenience.

❷ This is an array of tokens, which you get when you call `ok_array_new` to tokenize a string.

❸ This is the wrapper to `strtok_r` that will produce the `ok_array`.

Example 9-5 does the work of having GLib read a file into a string and using `strtok_r` to turn a single string into an array of strings. You'll see some examples of usage in Example 9-6, Example 12-3, and Example 12-4.

Example 9-5. Some useful string utilities (string_utilities.c)

```
#include <glib.h>
#include <string.h>
#include "string_utilities.h"
#include <stdio.h>
#include <assert.h>
#include <stdlib.h> //abort

char *string_from_file(char const *filename){
    char *out;
    GError *e = NULL;
    GIOChannel *f = g_io_channel_new_file(filename, "r", &e);      ❶
    if (!f) {
        fprintf(stderr, "failed to open file '%s'.\n", filename);
        return NULL;
    }
    if (g_io_channel_read_to_end(f, &out, NULL, &e) != G_IO_STATUS_NORMAL){
        fprintf(stderr, "found file '%s' but couldn't read it.\n", filename);
        return NULL;
    }
    return out;
}

ok_array *ok_array_new(char *instring, char const *delimiters){      ❷
    ok_array *out= malloc(sizeof(ok_array));
    *out = (ok_array){.base_string=instring};
    char *scratch = NULL;
    char *txt = strtok_r(instring, delimiters, &scratch);
    if (!txt) return NULL;
    while (txt) {
        out->elements = realloc(out->elements, sizeof(char*)*++(out->length));
        out->elements[out->length-1] = txt;
        txt = strtok_r(NULL, delimiters, &scratch);
    }
    return out;
}
```

```
/* Frees the original string, because strtok_r mangled it, so it
   isn't useful for any other purpose. */
void ok_array_free(ok_array *ok_in){
    if (ok_in == NULL) return;
    free(ok_in->base_string);
    free(ok_in->elements);
    free(ok_in);
}

#ifdef test_ok_array
int main (){                                                        ❸
    char *delimiters = " `~!@#$%^&*()_-+={[]}|\\;:\",<>./?\n";
    ok_array *o = ok_array_new(strdup("Hello, reader. This is text."), delimiters);
    assert(o->length==5);
    assert(!strcmp(o->elements[1], "reader"));
    assert(!strcmp(o->elements[4], "text"));
    ok_array_free(o);
    printf("OK.\n");
}
#endif
```

❶ Although it doesn't work in all situations, I've grown enamored of just reading an entire text file into memory at once, which is a fine example of eliminating programmer annoyances by throwing hardware at the problem. If we expect files to be too big for memory, we could use `mmap` (qv) to the same effect.

❷ This is the wrapper to `strtok_r`. If you've read to this point, you are familiar with the `while` loop that is all-but-obligatory in its use, and the function here records the results from it into an `ok_array` struct.

❸ If `test_ok_array` is not set, then this is a library for use elsewhere. If it is set (`CFLAGS=-Dtest_ok_array`), then it is a program that tests that `ok_array_new` works, by splitting the sample string at non-alphanumeric characters.

Unicode

Back when all the computing action was in the United States, ASCII (American Standard Code for Information Interchange) defined a numeric code for all of the usual letters and symbols printed on a standard US QWERTY keyboard, which I will refer to as the naïve English character set. A C `char` is 8 bits (binary digits) = 1 byte = 256 possible values. ASCII defined 128 characters, so it fit into a single `char` with even a bit to spare. That is, the eighth bit of every ASCII character will be zero, which will turn out to be serendipitously useful later.

Unicode follows the same basic premise, assigning a single hexadecimal numeric value, typically between 0000 and FFFF, to every *glyph* used for human communication.[1] By custom, these *code points* are written in the form U+0000. The work is much more ambitious and challenging, because it requires cataloging all the usual Western letters, tens of thousands of Chinese and Japanese characters, all the requisite glyphs for Ugaritic, Deseret, and so on, throughout the world and throughout human history.

The next question is how it is to be encoded, and at this point, things start to fall apart. The primary question is how many bytes to set as the unit of analysis. UTF-32 (UTF stands for UCS Transformation Format; UCS stands for Universal Character Set) specifies 32 bits = 4 bytes as the basic unit, which means that every character can be encoded in a single unit, at the cost of a voluminous amount of empty padding, given that naïve English can be written with only 7 bits. UTF-16 uses 2 bytes as the basic unit, which handles most characters comfortably with a single unit but requires that some characters be written down using two. UTF-8 uses 1 byte as its unit, meaning still more code points written down via multiunit amalgams.

I like to think about the UTF encodings as a sort of trivial encryption. For every code point, there is a single byte sequence in UTF-8, a single byte sequence in UTF-16, and a single byte sequence in UTF-32, none of which are necessarily related. Barring an exception discussed below, there is no reason to expect that the code point and any of the encrypted values are numerically the same, or even related in an obvious way, but I know that a properly programmed decoder can easily and unambiguously translate among the UTF encodings and the correct Unicode code point.

What do the machines of the world choose? On the Web, there is a clear winner: as of this writing over 75% of websites use UTF-8.[2] Also, Mac and Linux boxes default to using UTF-8 for everything, so you have good odds that an unmarked text file on a Mac or Linux box is in UTF-8.

About 12% of the world's websites still aren't using Unicode at all, but are using a relatively archaic format, ISO/IEC 8859 (which has code pages, with names like Latin-1). And Windows, the free-thinking flipping-off-the-POSIX-man operating system, uses UTF-16.

Displaying Unicode is up to your host operating system, and it already has a lot of work to do. For example, when printing the naïve English set, each character gets one spot on the line of text, but the Hebrew ב = *b*, for instance, can be written as a combination

1. The range from 0000 to FFFF is the *basic multilingual plane* (BMP), and includes most but not all of the characters used in modern languages. Later code points (conceivably from 10000 to 10FFFF) are in the *supplementary planes*, including mathematical symbols (like the symbol for the real numbers, ℝ) and a unified set of CJK ideographs. If you are one of the ten million Chinese Miao, or one of the hundreds of thousands of Indian Sora Sompeng or Chakma speakers, your language is here. Yes, the great majority of text can be expressed with the BMP, but rest assured that if you assume that all text is in the Unicode range below FFFF, then you will be wrong on a regular basis.

2. *http://w3techs.com/technologies/overview/character_encoding/all*

of ב (U+05D1) and ּ (U+05BC). Vowels are added to the consonant to further build the character: בָּ = *ba* (U+05D1 + U+05BC + U+05B8). And how many bytes it takes to express these three code points in UTF-8 (in this case, six) is another unrelated layer. Now, when we talk about string length, we could mean number of code points, width on the screen, or the number of bytes required to express the string.

So, as the author of a program that needs to communicate with humans who speak all kinds of languages, what are your responsibilities? You need to:

- Work out what encoding the host system is using, so that you aren't fooled into using the wrong encoding to read inputs and can send back outputs that the host can correctly decode.
- Successfully store text somewhere, unmangled.
- Recognize that one character is not a fixed number of bytes, so any base-plus-offset code you write (given a Unicode string `us`, things like `us++`) may give you fragments of a code point.
- Have on hand utilities to do any sort of comprehension of text: `toupper` and `tolower` work only for naïve English, so we will need replacements.

Meeting these responsibilities will require picking the right internal encoding to prevent mangling, and having on hand a good library to help us when we need to decode.

The Encoding for C Code

The choice of internal coding is especially easy. UTF-8 was designed for you, the C programmer.

- The UTF-8 unit is 8 bits: a `char`.[3] It is entirely valid to write a UTF-8 string to a `char *` string, as with naïve English text.
- The first 128 Unicode code points exactly match ASCII. For example, *A* is 41 (hexadecimal) in ASCII and is Unicode code point U+0041. Therefore, if your Unicode text happens to consist entirely of naïve English, then you can use the usual ASCII-oriented utilities on them, or UTF-8 utilities. The trick is that if the eighth bit of a `char` is zero, then the `char` represents an ASCII character; if it is one, then that `char` is one chunk of a multibyte character. Thus, no part of a UTF-8 non-ASCII Unicode character will ever match an ASCII character.
- U+0000 is a valid code point, which we C authors like to write as `'\0'`. Because `\0` is the ASCII zero as well, this rule is a special case of the last one. This is important because a UTF-8 string with one `\0` at the end is exactly what we need for a valid C `char *` string. Recall how the unit for UTF-16 and UTF-32 is several bytes long, and for naïve English, there will be padding for most of the unit; that means that

3. C89 may have left the size of `char` to be implementation dependent, but there is no longer any ambiguity: C99 & C11 §5.2.4.2.1(1) define `CHAR_BIT==8`; see also §6.2.6.1(4), which defines a byte as `CHAR_BIT` bits.

the first 8 bits have very good odds of being entirely zero, which means that dumping UTF-16 or UTF-32 text to a `char *` variable is likely to give you a string littered with null bytes.

So we C coders have been well taken care of: UTF-8 encoded text can be stored and copied with the `char *` string type we have been using all along. Now that one character may be several bytes long, be careful not to change the order of any of the bytes and to never split a multibyte character. If you aren't doing these things, you're as OK as you are if the string were naïve English. Therefore, here is a partial list of standard library functions that are UTF-8 safe:

- `strdup` and `strndup`
- `strcat` and `strncat`
- `strcpy` and `strncpy`
- The POSIX `basename` and `dirname`
- `strcmp` and `strncmp`, but only if you use them as zero/nonzero functions to determine whether two strings are equal. If you want to meaningfully sort, you will need a collation function; see the next section
- `strstr`
- `printf` and family, including `sprintf`, where `%s` is still the marker to use for a string
- `strtok_r`, `strtok_s` and `strsep`, provided that you are splitting at an ASCII character like one of `" \t\n\r:|;,"`
- `strlen` and `strnlen`, but recognize that you will get the number of bytes, which is not the number of Unicode code points or width on the screen. For these you'll need a new library function, as discussed in the next section.

These are pure byte-slinging functions, but most of what we want to do with text requires decoding it, which brings us to the libraries.

Unicode Libraries

Our first order of business is to convert from whatever the rest of the world dumped on us to UTF-8 so that we can use the data internally. That is, you'll need gatekeeper functions that encode incoming strings to UTF-8, and decode outgoing strings from UTF-8 to whatever the recipient wants on the other end, leaving you safe to do all internal work in one sensible encoding.

This is how Libxml (which we'll meet in "libxml and cURL" on page 247) works: a well-formed XML document states its encoding at the header (and the library has a set of rules for guessing if the encoding declaration is missing), so Libxml knows what translation to do. Libxml parses the document into an internal format, and then you can query and edit that internal format. Barring errors, you are guaranteed that the internal format will be UTF-8, because Libxml doesn't want to deal with alternate encodings either.

If you have to do your own translations at the door, then you have the POSIX-standard `iconv` function. This is going to be an unbelievably complicated function, given that there are so many encodings to deal with. The GNU provides a portable libiconv in case your computer doesn't have the function on hand.

> The POSIX standard also specifies that there be a command-line `iconv` program, a shell-friendly wrapper to the C function.

GLib provides a few wrappers to `iconv`, and the ones you're going to care about are `g_locale_to_utf8` and `g_locale_from_utf8`. And while you're in the GLib manual, you'll see a long section on Unicode manipulation tools. You'll see that there are two types: those that act on UTF-8 and those that act on UTF-32 (which GLib stores via a `gunichar`).

Recall that 8 bytes is not nearly enough to express all characters in one unit, so a single character is between one and six units long. Thus, UTF-8 counts as a *multibyte encoding*, and therefore, the problems you'll have are getting the true length of the string (using a character-count or screen-width definition of *length*), getting the next full character, getting a substring, or getting a comparison for sorting purposes (a.k.a. *collating*).

UTF-32 has enough padding to express any character with the same number of blocks, and so it is called a *wide character*. You'll often see reference to multibyte-to-wide conversions; this is the sort of thing they're talking about.

Once you have a single character in UTF-32 (GLib's `gunichar`), you'll have no problem doing character-content things with it, like getting its type (alpha, numeric, ...), converting it to upper/lower case, et cetera.

If you read the C standard, you no doubt noticed that it includes a wide character type, and all sorts of functions to go with it. The `wchar_t` is from C89, and therefore predates the publication of the first Unicode standard. I'm not sure what it's useful for anymore. The width of a `wchar_t` isn't fixed by the standard, so it could mean 32-bit or 16-bit (or anything else). Compilers on Windows machines like to set it at 16-bit, to accommodate Microsoft's preference for UTF-16, but UTF-16 is still a multibyte encoding, so we need yet another type to guarantee a true fixed-width encoding. C11 fixes this by providing a `char16_t` and `char32_t`, but we don't have much code written around those types yet.

The Sample Code

Example 9-6 presents a program to take in a file and break it into "words," by which I mean use `strtok_r` to break it at spaces and newlines, which are pretty universal. For each word, I use GLib to convert the first character from multibyte UTF-8 to wide character UTF-32, and then comment on whether that first character is a letter, a number, or a CJK-type wide symbol (where CJK stands for Chinese/Japanese/Korean, which are often printed with more space per character).

The `string_from_file` function reads the whole input file to a string, then `localstring_to_utf8` converts it from the locale of your machine to UTF-8. The notable thing about my use of `strtok_r` is that there is nothing notable. If I'm splitting at spaces and newlines, then I can guarantee you that I'm not splitting a multibyte character in half.

I output to HTML, because then I can specify UTF-8 and not worry about the encoding on the output side. If you have a UTF-16 host, open the output file in your browser.

Because this program uses GLib and `string_utilities`, my makefile looks like:

```
CFLAGS==`pkg-config --cflags glib-2.0` -g -Wall -O3
LDADD=`pkg-config --libs glib-2.0`
CC=c99
objects=string_utilities.o

unicode: $(objects)
```

For another example of Unicode character dealings, see Example 10-20, which enumerates every character in every UTF-8-valid file in a directory.

Example 9-6. Take in a text file and print some useful information about its characters (unicode.c)

```
#include <glib.h>
#include <locale.h> //setlocale
#include "string_utilities.h"
#include "stopif.h"

//Frees instring for you—we can't use it for anything else.
char *localstring_to_utf8(char *instring){                              ❶
    GError *e=NULL;
    setlocale(LC_ALL, ""); //get the OS's locale.
    char *out = g_locale_to_utf8(instring, -1, NULL, NULL, &e);
    free(instring); //done with the original
    Stopif(!g_utf8_validate(out, -1, NULL), free(out); return NULL,
            "Trouble: I couldn't convert your file to a valid UTF-8 string.");
    return out;
}

int main(int argc, char **argv){
    Stopif(argc==1, return 1, "Please give a filename as an argument. "
                  "I will print useful info about it to uout.html.");

    char *ucs = localstring_to_utf8(string_from_file(argv[1]));
    Stopif(!ucs, return 1, "Exiting.");
    FILE *out = fopen("uout.html", "w");
    Stopif(!out, return 1, "Couldn't open uout.html for writing.");
    fprintf(out, "<head><meta http-equiv=\"Content-Type\" "
                 "content=\"text/html; charset=UTF-8\" />\n");
    fprintf(out, "This document has %li characters.<br>", g_utf8_strlen(ucs, -1));  ❷
    fprintf(out, "Its Unicode encoding required %zu bytes.<br>", strlen(ucs));
    fprintf(out, "Here it is, with each space-delimited element on a line "
                 "(with commentary on the first character):<br>");
```

```
    ok_array *spaced = ok_array_new(ucs, " \n");                          ❸
    for (int i=0; i< spaced->length; i++, (spaced->elements)++){
        fprintf(out, "%s", *spaced->elements);
        gunichar c = g_utf8_get_char(*spaced->elements);                  ❹
        if (g_unichar_isalpha(c)) fprintf(out, " (a letter)");
        if (g_unichar_isdigit(c)) fprintf(out, " (a digit)");
        if (g_unichar_iswide(c)) fprintf(out, " (wide, CJK)");
        fprintf(out, "<br>");
    }
    fclose(out);
    printf("Info printed to uout.html. Have a look at it in your browser.\n");
}
```

❶ This is the incoming gateway, which converts from whatever it is that your box likes to use to UTF-8. There's no outgoing gateway because I write to an HTML file, and browsers know how to deal with UTF-8. An outgoing gateway would look a lot like this function, but use `g_locale_from_utf8`.

❷ `strlen` is one of those functions that assumes one character equals 1 byte, and so we need a replacement for it.

❸ Use the `ok_array_new` function from earlier in the chapter to split at spaces and newlines.

❹ Here are some per-character operations, which will only work after you convert from the multibyte UTF-8 to a fixed-width (wide character) encoding.

Gettext

Your program probably writes a lot of messages to readers, such as error messages and prompts for user input. Truly user-friendly software has translations of these bits of text in as many human languages as possible. GNU Gettext provides a framework for organizing the translations. The Gettext manual is pretty readable, so I refer you there for details, but here is a rough overview of the procedure to give you a sense of the system:

- Replace every instance of `"Human message"` in your code with `_("Human message")`. The underscore is a macro that will eventually expand to a function call that selects the right string given the user's runtime locale.
- Run `xgettext` to produce an index of strings that need translating, in the form of a portable object template (*.pot*) file.
- Send the *.pot* file to your colleagues around the globe who speak diverse languages, so they can send you *.po* files providing translations of the strings for their language.
- Add `AM_GNU_GETTEXT` to your *configure.ac* (along with any optional macros to specify where to find the *.po* files and other such details).

CHAPTER 10
Better Structures

> Twenty-nine different attributes and only seven that you like.
>
> —The Strokes, "You Only Live Once"

This chapter is about functions that take structured inputs, and just how far they can take us.

- We start by covering three bits of syntax introduced to C in the ISO C99 standard: compound literals, variable-length macros, and designated initializers. The chapter is to a great extent an exploration of all the things that combinations of these elements can do for us.
- With just compound literals, we can more easily send lists to a function. Then, a variable-length macro lets us hide the compound literal syntax from the user, leaving us with a function that can take a list of arbitrary length: `f(1, 2)` or `f(1, 2, 3, 4)` would be equally valid.
- We could do similar tricks to implement the `foreach` keyword as seen in many other languages, or vectorize a one-input function so that it operates on several inputs.
- Designated initializers make working with structs much easier, to the point that I've almost entirely stopped using the old method. Instead of illegible and error-prone junk like `person_struct p = {"Joe", 22, 75, 20}`, we can write self-documenting declarations such as `person_struct p = {.name="Joe", .age=22, .weight_kg=75, .education_years=20}`.
- Now that initializing a struct doesn't hurt, returning a struct from a function is also painless and can go far to clarify our function interfaces.
- Sending structs to functions also becomes a more viable option. By wrapping everything in another variable-length macro, we can now write functions that take a variable number of named arguments, and even assign default values to those the function user doesn't specify.
- The remainder of the chapter gives some examples of situations where input and output structs can be used to make life easier, including when dealing with function

interfaces based on void pointers, and when saddled with legacy code with a horrendous interface that needs to be wrapped into something usable.

Compound Literals

You can send a literal value into a function easily enough: given the declaration `double a_value`, C has no problem understanding `f(a_value)`.

But if you want to send a list of elements—a compound literal value like `{20.38, a_value, 9.8}`—then there's a syntactic caveat: you have to put a type-cast before the compound literal, or else the parser will get confused. The list now looks like `(double[]) {20.38, a_value, 9.8}`, and the call looks like this:

```
f((double[]) {20.38, a_value, 9.8});
```

Compound literals are automatically allocated, meaning that you need neither `malloc` nor `free` to use them. At the end of the scope in which the compound literal appears, it just disappears.

Example 10-1 begins with a rather typical function, `sum`, that takes in an array of `double`, and sums its elements up to the first NaN (Not-a-Number, see "Marking Exceptional Numeric Values with NaNs" on page 124). If the input array has no NaNs, the results will be a disaster; we'll impose some safety below. The example's `main` has two ways to call it: the traditional via a temp variable and the compound literal.

Example 10-1. We can bypass the temp variable by using a compound literal (sum_to_nan.c)

```
#include <math.h> //NAN
#include <stdio.h>

double sum(double in[]){                                  ❶
    double out=0;
    for (int i=0; !isnan(in[i]); i++) out += in[i];
    return out;
}

int main(){
    double list[] = {1.1, 2.2, 3.3, NAN};                 ❷
    printf("sum: %g\n", sum(list));

    printf("sum: %g\n", sum((double[]){1.1, 2.2, 3.3, NAN})); ❸
}
```

❶ This unremarkable function will add the elements of the input array, until it reaches the first NaN marker.

❷ This is a typical use of a function that takes in an array, where we declare the list via a throwaway variable on one line, and then send it to the function on the next.

❸ Here, we do away with the intermediate variable and use a compound literal to create an array and send it directly to the function.

There's the simplest use of compound literals; the rest of this chapter will make use of them to all sorts of benefits. Meanwhile, does the code on your hard drive use any quick throwaway lists whose use could be streamlined by a compound literal?

> This form is setting up an array, not a pointer to an array, so you'll be using the `(double[])` type, not `(double*)`.

Initialization via Compound Literals

Let me delve into a hairsplitting distinction, which might give you a more solid idea of what compound literals are doing.

You are probably used to declaring arrays via a form like:

```
double list[] = {1.1, 2.2, 3.3, NAN};
```

Here we have allocated a named array, `list`. If you called `sizeof(list)`, you would get back whatever `4 * sizeof(double)` is on your machine. That is, `list` *is* the array.

You could also perform the declaration via a compound literal, which you can identify by the `(double[])` type cast:

```
double *list = (double[]){1.1, 2.2, 3.3, NAN};
```

Here, the system first generated an anonymous list, put it into the function's memory frame, and then it declared a pointer, `list`, pointing to the anonymous list. So `list` is an *alias*, and `sizeof(list)` will equal `sizeof(double*)`. Example 8-2 demonstrates this.

Variadic Macros

I broadly consider variable-length functions in C to be broken (more in "Flexible Function Inputs" on page 178). But variable-length macro arguments are easy. The keyword is `__VA_ARGS__`, and it expands to whatever set of elements were given.

In Example 10-2, I revisit Example 2-5, a customized variant of `printf` that prints a message if an assertion fails.

Example 10-2. A macro for dealing with errors, reprinted from Example 2-5 (stopif.h)

```
#include <stdio.h>
#include <stdlib.h> //abort

/** Set this to \c 's' to stop the program on an error.
    Otherwise, functions return a value on failure.*/
char error_mode;

/** To where should I write errors? If this is \c NULL, write to \c stderr. */
FILE *error_log;
```

```
#define Stopif(assertion, error_action, ...) do {                    \
        if (assertion){                                              \
            fprintf(error_log ? error_log : stderr, __VA_ARGS__); \
            fprintf(error_log ? error_log : stderr, "\n");        \
            if (error_mode=='s') abort();                         \
            else                 {error_action;}                  \
        } } while(0)

    //sample usage:
    Stopif(x<0 || x>1, return -1, "x has value %g, "
                    "but it should be between zero and one.", x);
```

You can probably guess how the ellipsis (`...`) and `__VA_ARGS__` work: whatever the user puts down in place of the ellipsis gets plugged in at the `__VA_ARGS__` mark.

As a demonstration of just how much variable-length macros can do for us, Example 10-3 rewrites the syntax of `for` loops. Everything after the second argument—regardless of how many commas are scattered about—will be read as the `...` argument and pasted in to the `__VA_ARGS__` marker.

Example 10-3. The ... of the macro covers the entire body of the `for` loop (varad.c)

```
#include <stdio.h>

#define forloop(i, loopmax, ...) for(int i=0; i< loopmax; i++) \
                                        {__VA_ARGS__}

int main(){
    int sum=0;
    forloop(i, 10,
            sum += i;
            printf("sum to %i: %i\n", i, sum);
    )
}
```

I wouldn't actually use Example 10-3 in real-world code, but chunks of code that are largely repetitive but for a minor difference across repetitions happen often enough, and it sometimes makes sense to use variable-length macros to eliminate the redundancy.

Safely Terminated Lists

Compound literals and variadic macros are the cutest couple, because we can now use macros to build lists and structures. We'll get to the structure building shortly; let's start with lists.

A few pages ago, you saw the function that took in a list and summed until the first NaN. When using this function, you don't need to know the length of the input array, but you do need to make sure that there's a NaN marker at the end; if there isn't, you're in for a segfault. We could guarantee that there is a NaN marker at the end of the list by calling `sum` using a variadic macro, as in Example 10-4.

Example 10-4. Using a variadic macro to produce a compound literal (safe_sum.c)

```
#include <math.h> //NAN
#include <stdio.h>

double sum_array(double in[]){                                  ❶
    double out=0;
    for (int i=0; !isnan(in[i]); i++) out += in[i];
    return out;
}

#define sum(...) sum_array((double[]){__VA_ARGS__, NAN})         ❷

int main(){
    double two_and_two = sum(2, 2);                             ❸
    printf("2+2 = %g\n", two_and_two);
    printf("(2+2)*3 = %g\n", sum(two_and_two, two_and_two, two_and_two));
    printf("sum(asst) = %g\n", sum(3.1415, two_and_two, 3, 8, 98.4));
}
```

❶ The name is changed, but this is otherwise the sum-an-array function from before.

❷ This line is where the action is: the variadic macro dumps its inputs into a compound literal. So the macro takes in a loose list of `double`s but sends to the function a single list, which is guaranteed to end in `NAN`.

❸ Now, `main` can send to `sum` loose lists of numbers of any length, and it can let the macro worry about appending the terminal `NAN`.

Now that's a stylish function. It takes in as many inputs as you have, and you don't have to pack them into an array beforehand, because the macro uses a compound literal to do it for you.

In fact, the macro version only works with loose numbers, not with anything you've already set up as an array. If you already have an array—and if you can guarantee the `NAN` at the end—then call `sum_array` directly.

Foreach

Earlier, you saw that you can use a compound literal anywhere you would put an array or structure. For example, here is an array of strings declared via a compound literal:

```
char **strings = (char*[]){"Yarn", "twine"};
```

Now let's put that in a `for` loop. The first element of the loop declares the array of strings, so we can use the preceding line. Then, we step through until we get to the `NULL` marker at the end. For additional comprehensibility, I'll `typedef` a string type:

```
#include <stdio.h>

typedef char* string;

int main(){
    string str = "thread";
```

```
    for (string *list = (string[]){"yarn", str, "rope", NULL};
                *list; list++)
        printf("%s\n", *list);
}
```

It's still noisy, so let's hide all the syntactic noise in a macro. Then `main` is as clean as can be:

```
#include <stdio.h>
//I'll do it without the typedef this time.

#define Foreach_string(iterator, ...)\
        for (char **iterator = (char*[]){__VA_ARGS__, NULL}; *iterator; iterator++)

int main(){
    char *str = "thread";
    Foreach_string(i, "yarn", str, "rope"){
        printf("%s\n", *i);
    }
}
```

Vectorize a Function

The `free` function takes exactly one argument, so we often have a long cleanup at the end of a function of the form:

```
free(ptr1);
free(ptr2);
free(ptr3);
free(ptr4);
```

How annoying! No self-respecting LISPer would ever allow such redundancy to stand, but would write a vectorized `free` function that would allow:

```
free_all(ptr1, ptr2, ptr3, ptr4);
```

If you've read the chapter to this point, then the following sentence will make complete sense to you: we can write a variadic macro that generates an array (ended by a stopper) via compound literal, then runs a `for` loop that applies the function to each element of the array. Example 10-5 adds it all up.

Example 10-5. The machinery to vectorize any function that takes in any type of pointer (vectorize.c)

```
#include <stdio.h>
#include <stdlib.h> //malloc, free

#define Fn_apply(type, fn, ...) {                                   \  ❶
    void *stopper_for_apply = (int[]){0};                           \  ❷
    type **list_for_apply = (type*[]){__VA_ARGS__, stopper_for_apply}; \
    for (int i=0; list_for_apply[i] != stopper_for_apply; i++)      \
         fn(list_for_apply[i]);                                     \
}

#define Free_all(...) Fn_apply(void, free, __VA_ARGS__);
```

```
int main(){
    double *x= malloc(10);
    double *y= malloc(100);
    double *z= malloc(1000);

    Free_all(x, y, z);
}
```

❶ For added safety, the macro takes in a type name. I put it before the function name, because the type-then-name ordering is reminiscent of a function declaration.

❷ We need a stopper that we can guarantee won't match any in-use pointers, including any `NULL` pointers, so we use the compound literal form to allocate an array holding a single integer and point to that. Notice how the stopping condition of the `for` loop looks at the pointers themselves, not what they are pointing to.

Now that the machinery is in place, we can wrap this vectorizing macro around anything that takes in a pointer. For the GSL, you could define:

```
#define Gsl_vector_free_all(...) \
    Fn_apply(gsl_vector, gsl_vector_free, __VA_ARGS__);
#define Gsl_matrix_free_all(...) \
    Fn_apply(gsl_matrix, gsl_matrix_free, __VA_ARGS__);
```

We still get compile-time type-checking (unless we set the pointer type to `void`), which ensures that the macro inputs are a list of pointers of the same type. To take in a set of heterogeneous elements, we need one more trick—designated initializers.

Designated Initializers

I'm going to define this term by example. Here is a short program that prints a 3-by-3 grid to the screen, with a star in one spot. You get to specify whether you want the star to be in the upper right, left center, or wherever by setting up a `direction_s` structure.

The focus of Example 10-6 is in `main`, where we declare three of these structures using designated initializers—i.e., we designate the name of each structure element in the initializer.

Example 10-6. Using designated initializers to specify a structure (boxes.c)

```
#include <stdio.h>

typedef struct {
    char *name;
    int left, right, up, down;
} direction_s;

void this_row(direction_s d); //these functions are below
void draw_box(direction_s d);

int main(){
    direction_s D = {.name="left", .left=1};           ❶
```

```
    draw_box(D);

    D = (direction_s) {"upper right", .up=1, .right=1};  ❷
    draw_box(D);

    draw_box((direction_s){});                            ❸
}

void this_row(direction_s d){                             ❹
    printf( d.left    ? "*..\n"
          : d.right ? "..*\n"
          : ".*.\n");
}

void draw_box(direction_s d){
    printf("%s:\n", (d.name ? d.name : "a box"));
    d.up                 ? this_row(d) : printf("...\n");
    (!d.up && !d.down)  ? this_row(d) : printf("...\n");
    d.down               ? this_row(d) : printf("...\n");
    printf("\n");
}
```

❶ This is our first designated initializer. Because `.right`, `.up`, and `.down` are not specified, they are initialized to zero.

❷ It seems natural that the name goes first, so we can use it as the first initializer, with no label, without ambiguity.

❸ This is the extreme case, where everything is initialized to zero.

❹ Everything after this line is about printing the box to the screen, so there's nothing novel after this point.

The old school method of filling structs was to memorize the order of struct elements and initialize all of them without any labels, so the `upper right` declaration without a label would be:

```
direction_s upright = {NULL, 0, 1, 1, 0};
```

This is illegible and makes people hate C. Outside of the rare situation where the order is truly natural and obvious, please consider the unlabeled form to be deprecated.

- Did you notice that in the setup of the `upper right` struct, I had designated elements out of order relative to the order in the structure declaration? Life is too short to remember the order of arbitrarily ordered sets—let the compiler sort 'em out.
- The elements not declared are initialized to zero. No elements are left undefined.
- You can mix designated and not-designated initializers. In Example 10-6, it seemed natural enough that the name comes first (and that a string like `"upper right"` isn't an integer), so when the name isn't explicitly tagged as such, the declaration is still legible. The rule is that the compiler picks up where it left off:

```
typedef struct{
    int one;
    double two, three, four;
} n_s;

n_s justone = {10, .three=8};    //10 with no label gets dropped in the first slot: .one=10
n_s threefour = {.two=8, 3, 4}; //By the pick up where you left off rule, 3 gets put in
                                 //the next slot after .two: .three=3 and .four=4
```

- I had introduced compound literals in terms of arrays, but being that structs are more or less arrays with named and oddly sized elements, you can use them for structs, too, as I did in the `upper right` and `center` structs in the sample code. As before, you need to add a cast-like `(typename)` before the curly braces. The first example in `main` is a direct declaration, and so doesn't need a compound initializer syntax, while later assignments set up an anonymous struct via compound literal and then copy that anonymous struct to `D` or send it to a subfunction.

Your Turn: Rewrite every struct declaration in all of your code to use designated initializers. I mean this. The old school way without markers for which initializer went where was terrible. Notice also that you can rewrite junk like

```
direction_s D;
D.left = 1;
D.right = 0;
D.up = 1;
D.down = 0;
```

with

```
direction_s D = {.left=1, .up=1};
```

Initialize Arrays and Structs with Zeros

If you declare a variable inside a function, then C won't zero it out automatically (which is perhaps odd for things called automatic variables). I'm guessing that the rationale here is a speed savings: when setting up the frame for a function, zeroing out bits is extra time spent, which could potentially add up if you call the function a million times and it's 1985.

But here in the present, leaving a variable undefined is asking for trouble.

For simple numeric data, set it to zero on the line where you declare the variable. For pointers, including strings, set it to `NULL`. That's easy enough, as long as you remember (and a good compiler will warn you if you risk using a variable before it is initialized).

For structs and arrays of constant size, I just showed you that if you use designated initializers but leave some elements blank, those blank elements get set to zero. You can therefore set the whole structure to zero by assigning a complete blank. Here's a do-nothing program to demonstrate the idea:

```
typedef struct {
    int la, de, da;
} ladeda_s;

int main(){
    ladeda_s emptystruct = {};
    int ll[20] = {};
}
```

Isn't that easy and sweet?

Now for the sad part: let us say that you have a variable-length array (i.e., one whose length is set by a runtime variable). The only way to zero it out is via `memset`:

```
int main(){
    int length=20;
    int ll[length];
    memset(ll, 0, 20*sizeof(int));
}
```

This is bitter in exact proportion to the sweetness of initializing fixed-length arrays. So it goes.[1]

> **Your Turn:** Write yourself a macro to declare a variable-length array and set all of its elements to zero. You'll need inputs listing the type, name, and size.

For arrays that are sparse but not entirely empty, you can use designated initializers:

```
//Equivalent to {0, 0, 1.1, 0, 0, 2.2, 0}:
double list1[7] = {[2]=1.1, [5]=2.2}

//A form for filling in from the end of an array.  By the pick up
//where you left off rule, this will become {0.1, 0, 0, 0, 0, 1.1, 2.2}:
int len=7;
double list3[len] = {0.1, [len-2]=1.1, 2.2}
```

Typedefs Save the Day

Designated initializers give new life to structs, and the rest of this chapter is largely a reconsideration of what structs can do for us now that they don't hurt so much to use.

But first, you've got to declare the format of your structs. Here's a sample of the format I use:

1. You can blame ISO C standard §6.7.8(3) for this, because it insists that variable length arrays can't be initialized. I say the compiler should be able to work it out.

```
typedef struct newstruct_s {
    int a, b;
    double c, d;
} newstruct_s;
```

This declares a new type (`newstruct_s`) that happens to be a structure of the given form (`struct newstruct_s`). You'll here and there find authors who come up with two different names for the struct tag and the typedef, such as `typedef struct _nst { ... } newstruct_s;`. This is unnecessary: struct tags have a separate namespace from other identifiers (K&R 2nd ed. §A8.3 (p. 213); C99 & C11 §6.2.3(1)), so there is never ambiguity to the compiler. I find that repeating the name doesn't produce any ambiguity for us humans either, and saves the trouble of inventing another naming convention.

The POSIX standard reserves names ending in `_t` for future types that might one day be added to the standard. Formally, the C standard only reserves `int..._t` and `unit..._t`, but each new standard slips in all sorts of new types ending in `_t` via optional headers. A lot of people don't spend a second worrying about potential name clashes their code will face when C22 comes out in a decade, and use the `_t` ending freely. In this book, I end struct names with `_s`.

You can declare a structure of this type in two ways:

```
newstruct_s ns1;
struct newstruct_s ns2;
```

There are only a few reasons for why you would need the `struct newstruct_s` name instead of just `newstruct_s`:

- If you've got a struct that includes one of its own kind as an element (such as how the `next` pointer of a linked list structure is to another linked list structure). For example:

  ```
  typedef struct newstruct_s {
      int a, b;
      double c, d;
      struct newstruct_s *next;
  } newstruct_s;
  ```

- The standard for C11 anonymous structs goes out of its way to require that you use the `struct newstruct_s` form. This will come up in "C, with fewer seams" on page 207.
- Some people just kinda like using the `struct newstruct_s` format, which brings us to a note on style.

A Style Note

I was surprised to see that there are people in the world who think that typedefs are obfuscatory. For example, from the Linux kernel style file: "When you see a `vps_t a;` in the source, what does it mean? In contrast, if it says `struct virtual_container *a;`

you can actually tell what a is." The natural response to this is that it is having a longer name—and even one ending in *container*—that clarifies the code, not the word struct hanging at the beginning.

But this typedef aversion had to come from somewhere. Further research turned up several sources that advise using typedefs to define units. For example:

```
typedef double inches;
typedef double meters;

inches length1;
meters length2;
```

Now you have to look up what inches really is every time it is used (unsigned int? double?), and it doesn't even afford any error protection. A hundred lines down, when you assign:

```
length1 = length2;
```

you have already forgotten about the clever type declaration, and the typical C compiler won't flag this as an error. If you need to take care of units, attach them to the variable name, so the error will be evident:

```
double length1_inches, length2_meters;

//100 lines later:

length1_inches = length2_meters; //this line is self-evidently wrong.
```

It makes sense to use typedefs that are global and the internals of which should be known by the user as sparingly as you would any other global elements, because looking up their declaration is as much a distraction as looking up the declaration of a variable, so they can impose cognitive load at the same time that they impose structure.

That said, it's hard to find a production library that doesn't rely heavily on typdeffed global structures, like the GSL's gsl_vectors and gsl_matrixes; or GLib's hashes, trees, and plethora of other objects. Even the source code for Git, written by Linus Torvalds to be the revision control system for the Linux kernel, has a few carefully placed typedefed structures.

Also, the scope of a typedef is the same as the scope of any other declaration. That means that you can typedef things inside a single file and not worry about them cluttering up the namespace outside of that file, and you might even find reason to have typedefs inside of a single function. You might have noticed that most of the typedefs so far are local, meaning that the reader can look up the definition by scanning back a few lines, and when they are global (i.e., in a header to be included everywhere), they are somehow hidden in a wrapper, meaning that the reader never has to look up the definition at all. So we can write structs that do not impose cognitive load.

Return Multiple Items from a Function

A mathematical function doesn't have to map to one dimension. For example, a function that maps to a 2D point *(x, y)* is nothing at all spectacular.

Python (among other languages) lets you return multiple return values using lists, like this:

```
#Given the standard paper size name, return its width, height
def width_length(papertype):
    if (papertype=="A4"):
        return [210, 297]
    if (papertype=="Letter"):
        return [216, 279]
    if (papertype=="Legal"):
        return [216, 356]

[a, b] = width_length("A4");
print("width= %i, height=%i" %(a, b))
```

In C, you can always return a struct, and thus as many subelements as desired. This is why I was praising the joys of having throwaway structs earlier: generating a function-specific struct is not a big deal.

Let's face it: C is still going to be more verbose than languages that have a special syntax for returning lists. But as demonstrated in Example 10-7, it is not impossible to clearly express that the function is returning a value in $\mathbb{R}^2$.

Example 10-7. If you need to return multiple values from a function, return a struct (papersize.c)

```
#include <stdio.h>
#include <strings.h> //strcasecmp
#include <math.h>    //NaN

typedef struct {
    double width, height;
} size_s;

size_s width_height(char *papertype){
  return
    !strcasecmp(papertype, "A4")     ? (size_s) {.width=210, .height=297}
  : !strcasecmp(papertype, "Letter") ? (size_s) {.width=216, .height=279}
  : !strcasecmp(papertype, "Legal")  ? (size_s) {.width=216, .height=356}
                                     : (size_s) {.width=NAN, .height=NAN};
}

int main(){
    size_s a4size = width_height("a4");
    printf("width= %g, height=%g\n", a4size.width, a4size.height);
}
```

> The code sample uses the *`condition`*`?` *`iftrue`* `:` *`else`* form, which is a single expression, and so can appear after the `return`. Notice how a sequence of these cascade neatly into a sequence of cases (including that last catch-all else clause at the end). I like to format this sort of thing into a nice little table; you can find people who call this terrible style.

The alternative is to use pointers, which is common and not considered bad form, but it certainly obfuscates what is input and what is output, and makes the version with the extra `typedef` look stylistically great:

```
//Return height and width via pointer:
void width_height(char *papertype, double *width, double *height);

//or return width directly and height via pointer:
double width_height(char *papertype, double *height);
```

Reporting Errors

[Goodliffe 2006] discusses the various means of returning an error code from a function and is somewhat pessimistic about the options.

- In some cases, the value returned can have a specific semaphore value, like -1 for integers or NaN for floating-point numbers (but cases where the full range of the variable is valid are common enough).
- You can set a global error flag, but in 2006, Goodliffe was unable to recommend using the C11 `_Thread_local` keyword to allow multiple threads to allow the flag to work properly when running in parallel. Although a global-to-the-program error flag is typically unworkable, a small suite of functions that work closely together could conceivably be written with a `_Thread_local` file-scope variable.
- The third option is to "return a compound data type (or tuple) containing both the return value and an error code. This is rather clumsy in the popular C-like languages and is seldom seen in them."

To this point in the chapter, you have seen that there are many benefits to returning a struct, and modern C provides lots of facilities (typedefs, designated initalizers) that eliminate most of the clumsiness.

> Any time you are writing a new struct, consider adding an `error` or `status` element. Whenever your new struct is returned from a function, you'll then have a built-in means of communicating whether it is valid for use.

Example 10-8 turns a physics 101 equation into an error-checked function to answer the question: given that an ideal object of a given mass has been in freefall to Earth for a given number of seconds, what is its energy?

I tricked it up with a lot of macros, because I find that authors tend to be more comfortable writing error-handling macros in C than for most other problems, perhaps because nobody wants error-checking to overwhelm the central flow of the story.

Example 10-8. If your function returns a value and an error, you can use a struct to do so (errortuple.c)

```
#include <stdio.h>
#include <math.h> //NaN, pow

#define make_err_s(intype, shortname) \              ❶
    typedef struct {                  \
        intype value;                 \
        char const *error;            \              ❷
    } shortname##_err_s;

make_err_s(double, double)
make_err_s(int, int)
make_err_s(char *, string)

double_err_s free_fall_energy(double time, double mass){
    double_err_s out = {};  //initialize to all zeros.
    out.error = time < 0      ? "negative time"      ❸
              : mass < 0      ? "negative mass"
              : isnan(time)   ? "NaN time"
              : isnan(mass)   ? "NaN mass"
                              : NULL;
    if (out.error) return out;                       ❹

    double velocity = 9.8*time;
    out.value = mass*pow(velocity, 2)/2.;
    return out;
}

#define Check_err(checkme, return_val)  \            ❺
    if (checkme.error) {fprintf(stderr, "error: %s\n", checkme.error); return return_val;}

int main(){
    double notime=0, fraction=0;
    double_err_s energy = free_fall_energy(1, 1);    ❻
    Check_err(energy, 1);
    printf("Energy after one second: %g Joules\n", energy.value);
    energy = free_fall_energy(2, 1);
    Check_err(energy, 1);
    printf("Energy after two seconds: %g Joules\n", energy.value);
    energy = free_fall_energy(notime/fraction, 1);
    Check_err(energy, 1);
    printf("Energy after 0/0 seconds: %g Joules\n", energy.value);
}
```

❶ If you like the idea of returning a value/error tuple, then you'll want one for every type. So I thought I'd really trick this up by writing a macro to make it easy to produce one tuple type for every base type. See the usage a few lines down, to generate `double_err_s`, `int_err_s`, and `string_err_s`. If you think this is one trick too many, then you don't have to use it.

❷ Why not let errors be a string instead of an integer? The error messages will typically be constant strings, so there is no messing about with memory management, and nobody needs to look up the translations for obscure enums. See "Enums and Strings" on page 120 for discussion.

❸ Another table of return values. This sort of thing is common in the input-checking preliminaries to a function. Notice that the `out.error` element points to one of the literal strings listed. Because no strings get copied, nothing has to be allocated or freed. To clarify this further, I made `error` a pointer to `char const`.

❹ Or, use the `Stopif` macro from "Error Checking" on page 47: `Stopif(out.error, return out, out.error)`.

❺ Macros to check for errors on return are a common C idiom. Because the error is a string, the macro can print it to `stderr` (or perhaps an error log) directly.

❻ Usage is as expected. Authors often lament how easy it is for users to traipse past the error codes returned from their functions, and in that respect, putting the output value in a tuple is a good reminder that the output includes an error code that the user of the function should take into account.

Flexible Function Inputs

A *variadic function* is one that takes a variable number of inputs. The most famous example is `printf`, where both `printf("Hi.")` and `printf("%f %f %i\n", first, second, third)` are valid, even though the first example has one input and the second has four.

Simply put, C's variadic functions provide exactly enough power to implement `printf`, and nothing more. You must have an initial fixed argument, and it's more or less expected that that first argument provides a catalog to the types of the subsequent elements, or at least a count. In the preceding example, the first argument (`"%f %f %i\n"`) indicates that the next two items are expected to be floating-point variables, and the last an integer.

There is no type safety: if you pass an `int` like 1 when you thought you were passing a `float` like 1.0, results are undefined. If the function expects to have three elements passed in but you sent only two, you're likely to get a segfault. Because of issues like this, CERT, a software security group, considers variadic functions to be a security risk (Severity: high. Likelihood: probable).[2]

Earlier, you met the first way to provide some safety to variable-length function inputs: by writing a wrapper macro that appends a stopper to the end of a list, we can guarantee that the base function will not receive a never-ending list. The compound literal will also check the input types and fail to compile if you send in an input of the wrong type.

2. *http://bit.ly/SAJTl7*

This section covers two more ways to implement variadic functions with some type-checking safety. The last method will let you name your arguments, which can also help to reduce your error rate. I concur with CERT in considering free-form variadic functions too risky, and use only the forms here for variadic functions in my own code.

The first safe format in this segment free-rides on the compiler's checking for `printf`, extending the already-familiar form. The second format in this segment uses a variadic macro to prep the inputs to use the designated initializer syntax in function headers.

Declare Your Function as printf-Style

First, let's go the traditional route, and use C89's variadic function facilities. I mention this because you might be in a situation where macros somehow can't be used. Such situations are typically social, not technical—there are few if any cases where a variadic function can't be replaced by a variadic macro using one of the techniques discussed in this chapter.

To make the C89 variadic function safe, we'll need an addition from gcc, but widely adopted by other compilers: the `__attribute__`, which allows for compiler-specific tricks.[3] It goes on the declaration line of a variable, struct, or function (so if your function isn't declared before use, you'll need to do so).

gcc and Clang will let you set an attribute to declare a function to be in the style of `printf`, meaning that the compiler will type-check and warn you should you have an `int` or a `double*` in a slot reserved for a `double`.

Say that we want a version of `system` that will allow `printf`-style inputs. In Example 10-9, the `system_w_printf` function takes in `printf`-style inputs, writes them to a string, and sends them to the standard `system` command. The function uses `vasprintf`, the `va_list`-friendly analog to `asprintf`. Both of these are BSD/GNU-standard. If you need to stick to C99, replace them with the `snprintf` analog `vsnprintf` (and so, `#include <stdarg.h>`).

The `main` function is a simple sample usage: it takes the first input from the command line and runs `ls` on it.

Example 10-9. The olden way of processing variable-length inputs (olden_varargs.c)

```
#define _GNU_SOURCE //cause stdio.h to include vasprintf
#include <stdio.h>  //printf, vasprintf
```

3. If you are worried that users will have a compiler that does not support `__attribute__`, Autotools can allay your concerns. Get the `AX_C___ATTRIBUTE__` macro from the Autoconf archive and paste it into a file named *aclocal.m4* in your project directory, add the call `AX_C___ATTRIBUTE__` to *configure.ac*, then have the C preprocessor define `__attribute__` to be blank should Autoconf find the user's compiler doesn't support it, via

```
#include "config.h"
#ifndef HAVE___ATTRIBUTE__
#define __attribute__(...)
#endif
```

```
#include <stdarg.h> //va_start, va_end
#include <stdlib.h> //system, free
#include <assert.h>

int system_w_printf(char const *fmt, ...) __attribute__ ((format (printf,1,2))); ❶

int system_w_printf(char const *fmt, ...){
    char *cmd;
    va_list argp;
    va_start(argp, fmt);
    vasprintf(&cmd, fmt, argp);
    va_end(argp);
    int out= system(cmd);
    free(cmd);
    return out;
}

int main(int argc, char **argv){
    assert(argc == 2);                                                          ❷
    return system_w_printf("ls %s", argv[1]);
}
```

❶ Mark this as a `printf`-like function where input one is the format specifier and the list of additional parameters starts at input two.

❷ I confess: I'm being lazy here. Use the raw `assert` macro only to check intermediate values under the author's control, not inputs sent in by the user. See "Error Checking" on page 47 for a macro appropriate for input testing.

The one plus this has over the variadic macro is that it is awkward getting a return value from a macro. However, the macro version in Example 10-10 is shorter and easier, and if your compiler type-checks the inputs to `printf`-family functions, then it'll do so here (without any gcc/Clang-specific attributes).

Example 10-10. The macro version has fewer moving parts (macro_varargs.c)

```
#define _GNU_SOURCE //cause stdio.h to include vasprintf
#include <stdio.h>  //printf, vasprintf
#include <stdlib.h> //system
#include <assert.h>

#define System_w_printf(outval, ...) {          \
    char *string_for_systemf;                   \
    asprintf(&string_for_systemf, __VA_ARGS__); \
    outval = system(string_for_systemf);        \
    free(string_for_systemf);                   \
}

int main(int argc, char **argv){
    assert(argc == 2);
    int out;
    System_w_printf(out, "ls %s", argv[1]);
    return out;
}
```

Optional and Named Arguments

I've already shown you how you can send a list of identical arguments to a function more cleanly via compound literal plus variable-length macro. If you don't remember, go read "Safely Terminated Lists" on page 166 right now.

A struct is in many ways just like an array, but holding not-identical types, so it seems like we could apply the same routine: write a wrapper macro to clean and pack all the elements into a struct, then send the completed struct to the function. Example 10-11 makes it happen.

It puts together a function that takes in a variable number of named arguments. There are three parts to defining the function: the throwaway struct, which the user will never use by name (but that still has to clutter up the global space if the function is going to be global); the macro that inserts its arguments into a struct, which then gets passed to the base function; and the base function.

Example 10-11. A function that takes in a variable number of named arguments—the arguments not set by the user have default values (ideal.c)

```
#include <stdio.h>

typedef struct {                                                              ❶
    double pressure, moles, temp;
} ideal_struct;

/** Find the volume (in cubic meters) via the ideal gas law: V =nRT/P
Inputs:
pressure in atmospheres (default 1)
moles of material (default 1)
temperature in Kelvins (default freezing = 273.15)
  */
#define ideal_pressure(...) ideal_pressure_base((ideal_struct){.pressure=1,   \ ❷
                                        .moles=1, .temp=273.15, __VA_ARGS__})

double ideal_pressure_base(ideal_struct in){                                  ❸
    return 8.314 * in.moles*in.temp/in.pressure;
}

int main(){
    printf("volume given defaults: %g\n", ideal_pressure() );
    printf("volume given boiling temp: %g\n", ideal_pressure(.temp=373.15) );  ❹
    printf("volume given two moles: %g\n", ideal_pressure(.moles=2) );
    printf("volume given two boiling moles: %g\n",
                                ideal_pressure(.moles=2, .temp=373.15) );
}
```

❶ First, we need to declare a struct holding the inputs to the function.

❷ The input to the macro will be plugged into the definition of an anonymous struct, wherein the arguments the user puts in the parens will be used as designated initializers.

❸ The function itself takes in an `ideal_struct`, rather than the usual free list of inputs.

❹ The user inputs a list of designated initializers, the ones not listed get given a default value, and then `ideal_pressure_base` will have an input structure with everything it needs.

Here's how the function call (don't tell the user, but it's actually a macro) on the last line will expand:

```
ideal_pressure_base((ideal_struct){.pressure=1, .moles=1, .temp=273.15,
                                   .moles=2, .temp=373.15})
```

The rule is that if an item is initialized multiple times, then the last initialization takes precedence. So `.pressure` is left at its default of one, while the other two inputs are set to the user-specified value.

Clang flags the repeated initialization of `moles` and `temp` with a warning when using `-Wall`, because the compiler authors expect that the double-initialization is more likely to be an error than a deliberate choice of default values. Turn off this warning by adding `-Wno-initializer-overrides` to your compiler flags. gcc flags this as an error only if you ask for `-Wextra` warnings; use `-Wextra -Woverride-init` if you make use of this option.

Your Turn: In this case, the throwaway struct might not be so throwaway, because it might make sense to run the formula in multiple directions:

- pressure = 8.314 moles * temp/volume
- moles = pressure *volume /(8.314 temp)
- temp = pressure *volume /(8.314 moles)

Rewrite the struct to also have a volume element, and use the same struct to write the functions for these additional equations.

Then, use these functions to produce a unifying function that takes in a struct with three of `pressure`, `moles`, `temp`, and `volume` (the fourth can be `NAN` or you can add a `what_to_solve` element to the struct) and applies the right function to solve for the fourth.

Now that arguments are optional, you can add a new argument six months from now without breaking every program that used your function in the meantime. You are free to start with a simple working function and build up additional features as needed. However, we should learn a lesson from the languages that had this power from day one: it is easy to get carried away and build functions with literally dozens of inputs, each handling only an odd case or two.

Polishing a Dull Function

To this point, the examples have focused on demonstrating simple constructs without too much getting in the way, but short examples can't cover the techniques involved in integrating everything together to form a useful and robust program that solves real-world problems. So the examples from here on in are going to get longer and include more realistic considerations.

Example 10-12 is a dull and unpleasant function. For an amortized loan, the monthly payments are fixed, but the percentage of the loan that is going toward interest is much larger at the outset (when more of the loan is still owed), and diminishes to zero toward the end of the loan. The math is tedious (especially when we add the option to make extra principal payments every month or to sell off the loan early), and you would be forgiven for skipping the guts of the function. Our concern here is with the interface, which takes in 10 inputs in basically arbitrary order. Using this function to do any sort of financial inquiry would be painful and error-prone.

That is, `amortize` looks a lot like many of the legacy functions floating around the C world. It is punk rock only in the sense that it has complete disdain for its audience. So in the style of glossy magazines everywhere, this segment will spruce up this function with a good wrapper. If this were legacy code, we wouldn't be able to change the function's interface (other programs might depend on it), so on top of the procedure that the ideal gas example used to generate named, optional inputs, we will need to add a prep function to bridge between the macro output and the fixed legacy function inputs.

Example 10-12. A difficult-to-use function with too many inputs and no error-checking (amortize.c)

```
#include <math.h> //pow.
#include <stdio.h>
#include "amortize.h"

double amortize(double amt, double rate, double inflation, int months,
                int selloff_month, double extra_payoff, int verbose,
                double *interest_pv, double *duration, double *monthly_payment){
    double total_interest = 0;
    *interest_pv = 0;
    double mrate = rate/1200;

    //The monthly rate is fixed, but the proportion going to interest changes.
    *monthly_payment = amt * mrate/(1-pow(1+mrate, -months)) + extra_payoff;
    if (verbose) printf("Your total monthly payment: %g\n\n", *monthly_payment);
    int end_month = (selloff_month && selloff_month < months )
                            ? selloff_month
                            : months;
    if (verbose) printf("yr/mon\t Princ.\t\tInt.\t|  PV Princ.\t PV Int.\t  Ratio\n");
    int m;
    for (m=0; m < end_month && amt > 0; m++){
        double interest_payment = amt*mrate;
        double principal_payment = *monthly_payment - interest_payment;
        if (amt <= 0)
```

```
            principal_payment =
            interest_payment  = 0;
        amt -= principal_payment;
        double deflator = pow(1+ inflation/100, -m/12.);
        *interest_pv   += interest_payment * deflator;
        total_interest += interest_payment;
        if (verbose) printf("%i/%i\t%7.2f\t\t%7.2f\t| %7.2f\t %7.2f\t%7.2f\n",
                m/12, m-12*(m/12)+1, principal_payment, interest_payment,
                principal_payment*deflator, interest_payment*deflator,
                principal_payment/(principal_payment+interest_payment)*100);
    }
    *duration = m/12.;
    return total_interest;
}
```

Example 10-13 and Example 10-14 set up a user-friendly interface to the function. Most of the header file is Doxygen-style documentation, because with so many inputs, it would be insane not to document them all, and because we now have to tell the user what the defaults will be, should the user omit an input.

Example 10-13. The header file, which is mostly documentation, plus a macro and a header for a prep function (amortize.h)

```
double amortize(double amt, double rate, double inflation, int months,
            int selloff_month, double extra_payoff, int verbose,
            double *interest_pv, double *duration, double *monthly_payment);

typedef struct {
    double amount, years, rate, selloff_year, extra_payoff, inflation;   ❶
    int months, selloff_month;
    _Bool show_table;
    double interest, interest_pv, monthly_payment, years_to_payoff;
    char *error;
} amortization_s;


/** Calculate the inflation-adjusted amount of interest you would pay   ❷
  over the life of an amortized loan, such as a mortgage.

\li \c amount  The dollar value of the loan. No default--if unspecified,
               print an error and return zeros.
\li \c months  The number of months in the loan. Default: zero, but see years.
\li \c years  If you do not specify months, you can specify the number of
              years. E.g., 10.5=ten years, six months.
              Default: 30 (a typical U.S. mortgage).
\li \c rate  The interest rate of the loan, expressed in annual
             percentage rate (APR). Default: 4.5 (i.e., 4.5%), which
             is typical for the current (US 2012) housing market.
\li \c inflation  The inflation rate as an annual percent, for calculating
                  the present value of money. Default: 0, meaning no
                  present-value adjustment. A rate of about 3 has been typical
                  for the last few decades in the US.
\li \c selloff_month  At this month, the loan is paid off (e.g., you resell
                      the house). Default: zero (meaning no selloff).
\li \c selloff_year  If selloff_month==0 and this is positive, the year of
```

```
                    selloff. Default: zero (meaning no selloff).
\li \c extra_payoff  Additional monthly principal payment. Default: zero.
\li \c show_table  If nonzero, display a table of payments. If zero, display
                  nothing (just return the total interest). Default: 1

All inputs but \c extra_payoff and \c inflation must be nonnegative.

\return  an \c amortization_s structure, with all of the above values set as
         per your input, plus:

\li \c interest  Total cash paid in interest.
\li \c interest_pv  Total interest paid, with present-value adjustment for inflation.
\li \c monthly_payment  The fixed monthly payment (for a mortgage, taxes and
                        interest get added to this)
\li \c years_to_payoff  Normally the duration or selloff date, but if you make early
                        payments, the loan is paid off sooner.
\li \c error            If <tt>error != NULL</tt>, something went wrong and the results
                        are invalid.

*/
#define amortization(...) amortize_prep((amortization_s){.show_table=1, \
                                                    __VA_ARGS__})  ❸

amortization_s amortize_prep(amortization_s in);
```

❶ The structure used by the macro to transfer data to the prep function. It has to be part of the same scope as the macro and prep function themselves. Some elements are input elements that are not in the `amortize` function, but can make the user's life easier; some elements are output elements to be filled.

❷ The documentation, in Doxygen format. It's a good thing when the documentation takes up most of the interface file. Notice how each input has a default listed.

❸ This macro stuffs the user's inputs—perhaps something like `amortization (.amount=2e6, .rate=3.0)`—into a designated initializer for an `amortization_s`. We have to set the default to `show_table` here, because without it, there's no way to distinguish between a user who explicitly sets `.show_table=0` and a user who omits `.show_table` entirely. So if we want a default that isn't zero for a variable where the user could sensibly send in zero, we have to use this form.

The three ingredients to the named-argument setup are still apparent: a typedef for a struct, a macro that takes in named elements and fills the struct, and a function that takes in a single struct as input. However, the function being called is a prep function, wedged in between the macro and the base function, the declaration of which is here in the header. Its guts are in Example 10-14.

Example 10-14. The nonpublic part of the interface (amort_interface.c)

```
#include "stopif.h"
#include <stdio.h>
#include "amortize.h"
```

```
amortization_s amortize_prep(amortization_s in){                  ❶
    Stopif(!in.amount || in.amount < 0 || in.rate < 0            ❷
            || in.months < 0 || in.years < 0 || in.selloff_month < 0
            || in.selloff_year < 0,
            return (amortization_s){.error="Invalid input"},
            "Invalid input. Returning zeros.");

    int months = in.months;
    if (!months){
        if (in.years) months = in.years * 12;
        else          months = 12 * 30; //home loan
    }

    int selloff_month = in.selloff_month;
    if (!selloff_month && in.selloff_year)
        selloff_month = in.selloff_year * 12;

    amortization_s out = in;
    out.rate = in.rate ? in.rate : 4.5;                            ❸
    out.interest = amortize(in.amount, out.rate, in.inflation,
            months, selloff_month, in.extra_payoff, in.show_table,
            &(out.interest_pv), &(out.years_to_payoff), &(out.monthly_payment));
    return out;
}
```

❶ This is the prep function that `amortize` should have had: it sets nontrivial, intelligent defaults, and checks for an input errors. Now it's OK that `amortize` goes straight to business, because all the introductory work happened here.

❷ See "Error Checking" on page 47 for discussion of the `Stopif` macro. As per the discussion there, the check on this line is more to prevent segfaults and check sanity than to allow automated testing of error conditions.

❸ Because it's a simple constant, we could also have set the rate in the `amortization` macro, along with the default for `show_table`. You've got options.

The immediate purpose of the prep function is to take in a single struct and call the `amortize` function with the struct's elements, because we can't change the interface to `amortize` directly. But now that we have a function dedicated to preparing function inputs, we can really do error-checking and default-setting right. For example, we can now give users the option of specifying time periods in months or years, and can use this prep function to throw errors if the inputs are out of bounds or insensible.

Defaults are especially important for a function like this one, by the way, because most of us don't know (and have little interest in finding out) what a reasonable inflation rate is. If a computer can offer the user subject-matter knowledge that he or she might not have, and can do so with an unobtrusive default that can be overridden with no effort, then rare will be the user who is ungrateful.

The `amortize` function returns several different values. As per "Return Multiple Items from a Function" on page 175, putting them all in a single struct is a nice alternative to how `amortize` returns one value and then puts the rest into pointers sent as input.

Also, to make the trick about designated initializers via variadic macros work, we had to have another structure intermediating; why not combine the two structures? The result is an output structure that retains all of the input specifications.

After all that interface work, we now have a well-documented, easy-to-use, error-checked function, and the program in Example 10-15 can run lots of what-if scenarios with no hassle. It uses *amortize.c* and *amort_interface.c* from earlier, and the former file uses `pow` from the math library, so your makefile will look like:

```
P=amort_use
objects=amort_interface.o amortize.o
CFLAGS=-g -Wall -O3 #the usual
LDLIBS=-lm
CC=c99

$(P):$(objects)
```

Example 10-15. At this point, we can use the amortization macro/function to write readable what-if scenarios (amort_use.c)

```
#include <stdio.h>
#include "amortize.h"

int main(){
    printf("A typical loan:\n");
    amortization_s nopayments = amortization(.amount=200000, .inflation=3);
    printf("You flushed real $%g down the toilet, or $%g in present value.\n",
            nopayments.interest, nopayments.interest_pv);

    amortization_s a_hundred = amortization(.amount=200000, .inflation=3,
                                .show_table=0, .extra_payoff=100);
    printf("Paying an extra $100/month, you lose only $%g (PV), "
            "and the loan is paid off in %g years.\n",
            a_hundred.interest_pv, a_hundred.years_to_payoff);

    printf("If you sell off in ten years, you pay $%g in interest (PV).\n",
                 amortization(.amount=200000, .inflation=3,
                        .show_table=0, .selloff_year=10).interest_pv);  ❶
}
```

❶ The `amortization` function returns a struct, and in the first two uses, the struct was given a name, and the named struct's elements were used. But if you don't need the intermediate named variable, don't bother. This line pulls the one element of the struct that we need from the function. If the function returned a piece of `malloc`ed memory, you couldn't do this, because you'd need a name to send to the memory-freeing function, but notice how this entire chapter is about passing structs, not pointers-to-structs.

There are a lot of lines of code wrapping the original function, but the boilerplate struct and macros to set up named arguments are only a few of them. The rest is documentation and intelligent input-handling that is well worth adding. As a whole, we've taken a function with an almost unusable interface and made it as user-friendly as an amortization calculator can be.

The Void Pointer and the Structures It Points To

This segment is about the implementation of generic procedures and generic structures. One example in this segment will apply some function to every file in a directory hierarchy, letting the user print the filenames to screen, search for a string, or whatever else comes to mind. Another example will use GLib's hash structure to record a count of every character encountered in a file, which means associating a Unicode character key with an integer value. Of course, GLib provides a hash structure that can take any type of key and any type of value, so the Unicode character counter is an application of the general container.

All this versatility is thanks to the void pointer, which can point to anything. The hash function and directory processing routine are wholly indifferent to what is being pointed to and simply pass the values through as needed. Type safety becomes our responsibility, but structs will help us retain type safety and will make it easier to write and work with generic procedures.

Functions with Generic Inputs

A *callback function* is a function that is passed to another function for the other function's use. Next, I'll present a generic procedure to recurse through a directory and do something to every file found there; the callback is the function handed to the directory-traversal procedure for it to apply to each file.

The problem is depicted in Figure 10-1. With a direct function call, the compiler knows the type of your data, it knows the type the function requires, and if they don't match the compiler will tell you. But a generic procedure should not dictate the format for the function or the data the function uses. "Easy Threading with Pthreads" on page 234 makes use of `pthread_create`, which (omitting the irrelevant parts) might be declared with a form like:

```
typedef void *(*void_ptr_to_void_ptr)(void *in);
int pthread_create(..., void *ptr, void_ptr_to_void_ptr fn);
```

If we make a call like `pthread_create(..., indata, myfunc)`, then the type information for *indata* has been lost, as it was cast to a void pointer. We can expect that somewhere in `pthread_create`, a call of the form `myfunc(indata)` will occur. If `indata` is a `double*`, and `myfunc` takes a `char*`, then this is a disaster the compiler can't prevent.

Example 10-16 is the header file for an implementation of the function that applies functions to every directory and file within a given directory. It includes Doxygen documentation of what the `process_dir` function is expected to do. As it should be, the documentation is roughly as long as the code will be.

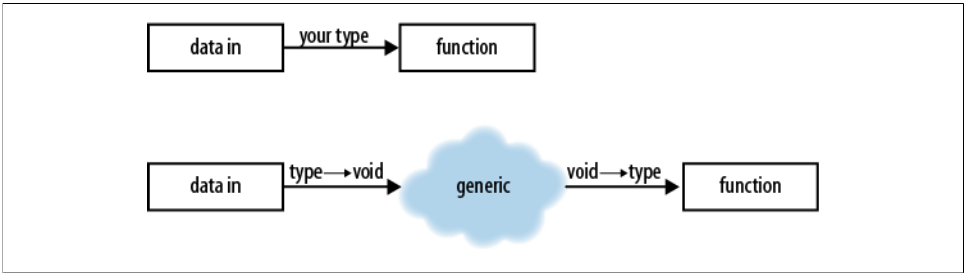


Figure 10-1. Calling a function directly versus having a generic procedure perform the call

Example 10-16. A header file for a generic directory-recursing function (process_dir.h)

```
struct filestruct;
typedef void (*level_fn)(struct filestruct path);

typedef struct filestruct{
    char *name, *fullname;
    level_fn directory_action, file_action;
    int depth, error;
    void *data;
} filestruct;                                                     ❶

/** I get the contents of the given directory, run \c file_action on each
    file, and for each directory run \c dir_action and recurse into the directory.
    Note that this makes the traversal `depth first'.

    Your functions will take in a \c filestruct, qv. Note that there is an \c error
    element, which you can set to one to indicate an error.

    Inputs are designated initializers, and may include:

    \li \c .name The current file or directory name
    \li \c .fullname The path of the current file or directory
    \li \c .directory_action A function that takes in a \c filestruct.
            I will call it with an appropriately-set \c filestruct
            for every directory (just before the files in the directory
            are processed).
    \li \c .file_action Like the \c directory_action, but the function
            I will call for every non-directory file.
    \li \c .data A void pointer to be passed in to your functions.

    \return 0=OK, otherwise the count of directories that failed + errors thrown
            by your scripts.
    Your functions may change the \c data element of the \c filestruct.

    Sample usage:
\code
    void dirp(filestruct in){ printf("Directory: <%s>\n", in.name); }
    void filep(filestruct in){ printf("File: %s\n", in.name); }

    //list files, but not directories, in current dir:
    process_dir(.file_action=filep);
```

```
    //show everything in my home directory:
    process_dir(.name="/home/b", .file_action=filep, .directory_action=dirp);
\endcode
*/
#define process_dir(...) process_dir_r((filestruct){__VA_ARGS__})  ❷

int process_dir_r(filestruct level);                               ❸
```

❶ Here they are again: the three parts of a function that takes in named arguments. But even that trick aside, this struct will be essential to retaining type-safety when passing void pointers.

❷ The macro that stuffs designated initializers from the user into a compound literal struct.

❸ The function that takes in the struct built by the `process_dir` macro. Users won't call it directly.

Comparing this with Figure 10-1, this header already indicates a partial solution to the type-safety problem: defining a definite type, the `filestruct`, and requiring the callback take in a struct of that type. There's still a void pointer buried at the end of the struct. I could have left the void pointer outside of the struct, as in:

```
typedef void (*level_fn)(struct filestruct path, void *indata);
```

But as long as we're defining an ad hoc struct as a helper to the `process_dir` function, we might as well throw the void pointer in there. Further, now that we have a struct associated with the `process_dir` function, we can use it to implement the form where a macro turns designated initializers into a function input, as per "Optional and Named Arguments" on page 181. Structs make everything easier.

Example 10-17 presents a use of `process_dir`—the portions before and after the cloud of Figure 10-1. These callback functions are simple, printing some spacing and the file/directory name. There isn't even any type-unsafety yet, because the input to the callback was defined to be a certain type of struct.

Here's a sample output, for a directory that has two files and a subdirectory named *cfiles*, holding another three files:

```
Tree for sample_dir:
├ cfiles
└───────┐
        │ c.c
        │ a.c
        │ b.c
│ a_file
│ another_file
```

Example 10-17. A program to display a tree of the current directory structure (show_tree.c)

```
#include <stdio.h>
#include "process_dir.h"
```

```
void print_dir(filestruct in){
    for (int i=0; i< in.depth-1; i++) printf("    ");
    printf("├ %s\n", in.name);
    for (int i=0; i< in.depth-1; i++) printf("    ");
    printf("└───┐\n");
}

void print_file(filestruct in){
    for (int i=0; i< in.depth; i++) printf("    ");
    printf("│ %s\n", in.name);
}

int main(int argc, char **argv){
    char *start = (argc>1) ? argv[1] : ".";
    printf("Tree for %s:\n", start ? start: "the current directory");
    process_dir(.name=start, .file_action=print_file, .directory_action=print_dir);
}
```

As you can see, `main` hands the `print_dir` and `print_file` functions to `process_dir`, and trusts that `process_dir` will call them at the right time with the appropriate inputs.

The `process_dir` function itself is in Example 10-18. Most of the work of the function is absorbed in generating an up-to-date struct describing the file or directory currently being handled. The given directory is opened, via `opendir`. Then, each call to `readdir` will pull another entry from the directory, which will describe one file, directory, link, or whatever else in the given directory. The input `filestruct` is updated with the current entry's information. Depending on whether the directory entry describes a directory or a file, the appropriate callback is called with the newly prepared `filestruct`. If it's a directory, then the function is recursively called using the current directory's information.

*Example 10-18. Recurse through a directory, and apply **`file_action`** to every file found and **`directory_action`** to every directory found (process_dir.c)*

```
#include "process_dir.h"
#include <dirent.h> //struct dirent
#include <stdlib.h> //free

int process_dir_r(filestruct level){
    if (!level.fullname){
        if (level.name) level.fullname=level.name;
        else            level.fullname=".";
    }
    int errct=0;

    DIR *current=opendir(level.fullname);                               ❶
    if (!current) return 1;
    struct dirent *entry;
    while((entry=readdir(current))) {
        if (entry->d_name[0]=='.') continue;
        filestruct next_level = level;                                  ❷
        next_level.name = entry->d_name;
        asprintf(&next_level.fullname, "%s/%s", level.fullname, entry->d_name);
```

```
        if (entry->d_type==DT_DIR){
            next_level.depth ++;
            if (level.directory_action) level.directory_action(next_level); ❸
            errct+= process_dir_r(next_level);
        }
        else if (entry->d_type==DT_REG && level.file_action){
             level.file_action(next_level);                                ❹
             errct+= next_level.error;
        }
        free(next_level.fullname);                                         ❺
    }
    closedir(current);
    return errct;
}
```

❶ The `opendir`, `readdir`, and `closedir` functions are POSIX-standard.

❷ For each entry in the directory, make a new copy of the input `filestruct`, then update it as appropriate.

❸ Given the up-to-date `filestruct`, call the per-directory function. Recurse into subdirectory.

❹ Given the up-to-date `filestruct`, call the per-file function.

❺ The `filestruct`s that get made for each step are not pointers and are not `malloc`ed, so they require no memory-management code. However, `asprintf` does implicitly allocate `fullname`, so that has to be freed to keep things clean.

The setup successfully implemented the appropriate encapsulation: the printing functions didn't care about POSIX directory-handling, and *process_dir.c* knew nothing of what the input functions did. And the function-specific struct made the flow relatively seamless.

Generic Structures

Linked lists, hashes, trees, and other such data structures are applicable in all sorts of situations, so it makes sense that they would be provided with hooks for void pointers, and then you as a user would check types on the way in and on the way out.

This segment will present a typical textbook example: a character-frequency hash. A hash is a container that holds key/value pairs, with the intent of allowing users to quickly look up values using a key.

Before getting to the part where we process files in a directory, we need to customize the generic GLib hash to the form that the program will use, with a Unicode key and a value holding a single integer. Once this component (which is already a good example of dealing with callbacks) is in place, it will be easy to implement the callbacks for the file traversal part of the program.

As you will see, the `equal_chars` and `printone` functions are intended as callbacks for use by functions associated with the hash, so the hash will send to these callbacks two void pointers. Thus, the first lines of these functions declare variables of the correct type, effectively casting the void pointer input to a type.

Example 10-19 presents the header, showing what is for public use out of Example 10-20.

Example 10-19. The header for unictr.c (unictr.h)

```
#include <glib.h>

void hash_a_character(gunichar uc, GHashTable *hash);
void printone(void *key_in, void *val_in, void *xx);
GHashTable *new_unicode_counting_hash();
```

Example 10-20. Functions built around a hash with a Unicode character as key and a purpose-built counter value (unictr.c)

```
#include "string_utilities.h"
#include "process_dir.h"
#include "unictr.h"
#include <glib.h>
#include <stdlib.h> //calloc, malloc

typedef struct {                                                    ❶
    int count;
} count_s;

void hash_a_character(gunichar uc, GHashTable *hash){
    count_s *ct = g_hash_table_lookup(hash, &uc);
    if (!ct){
        ct = calloc(1, sizeof(count_s));
        gunichar *newchar = malloc(sizeof(gunichar));
        *newchar = uc;
        g_hash_table_insert(hash, newchar, ct);
    }
    ct->count++;
}

void printone(void *key_in, void *val_in, void *ignored){          ❷
    gunichar const *key= key_in;                                    ❸
    count_s const *val= val_in;
    char utf8[7];                                                   ❹
    utf8[g_unichar_to_utf8(*key, utf8)]='\0';
    printf("%s\t%i\n", utf8, val->count);
}

static gboolean equal_chars(void const * a_in, void const * b_in){  ❺
    const gunichar *a= a_in;                                        ❻
    const gunichar *b= b_in;
    return (*a==*b);
}

GHashTable *new_unicode_counting_hash(){
```

```
    return g_hash_table_new(g_str_hash, equal_chars);
}
```

❶ Yes, this is a struct holding a single integer. One day, it might save your life.

❷ This is going to be a callback for `g_hash_table_foreach`, so it will take in void pointers for the key, value, and an optional void pointer that this function doesn't use.

❸ If a function takes in a void pointer, the first line needs to set up a variable with the correct type, thus casting the void pointer to something usable. Do not put this off to later lines—do it right at the top, where you can verify that you got the type cast correct.

❹ Six `chars` is enough to express any UTF-8 encoding of a Unicode character. Add another byte for the terminating `'\0'`, and 7 bytes is enough to express any one-character string.

❺ Because a hash's keys and values can be any type, GLib asks that you provide the comparison function to determine whether two keys are equal. Later, `new_unicode_counting_hash` will send this function to the hash creation function.

❻ Did I mention that the first line of a function that takes in a void pointer needs to assign the void pointer to a variable of the correct type? Once you do this, you're back to type safety.

Now that we have a set of functions in support of a hash for Unicode characters, Example 10-21 uses them, along with `process_dir` from before, to count all the characters in the UTF-8-readable files in a directory.

It uses the same `process_dir` function defined earlier, so the generic procedure and its use should now be familiar to you. The callback to process a single file, `hash_a_file`, takes in a `filestruct`, but buried within that `filestruct` is a void pointer. The functions here use that void pointer to point to a GLib hash structure. Thus, the first line of `hash_a_file` casts the void pointer to the structure it points to, thus returning us to type safety.

Each component can be debugged in isolation, just knowing what will get input and when. But you can follow the hash from component to component, and verify that it gets sent to `process_dir` via the `.data` element of the input `filestruct`, then `hash_a_file` casts `.data` to a `GHashTable` again, then it gets sent to `hash_a_character`, which will modify it or add to it as you saw earlier. Then, `g_hash_table_foreach` uses the `printone` callback to print each element in the hash.

Example 10-21. A character frequency counter; usage: charct your_dir |sort -k 2 -n (charct.c)

```
#define _GNU_SOURCE            //get stdio.h to define asprintf
#include "string_utilities.h"  //string_from_file
#include "process_dir.h"
#include "unictr.h"
#include <glib.h>
#include <stdlib.h>            //free
```

```
void hash_a_file(filestruct path){
    GHashTable *hash = path.data;                         ❶
    char *sf = string_from_file(path.fullname);
    if (!sf) return;
    char *sf_copy = sf;
    if (g_utf8_validate(sf, -1, NULL)){
        for (gunichar uc; (uc = g_utf8_get_char(sf))!='\0'; ❷
            sf = g_utf8_next_char(sf))
                hash_a_character(uc, hash);
    }
    free(sf_copy);
}

int main(int argc, char **argv){
    GHashTable *hash;
    hash = new_unicode_counting_hash();
    char *start=NULL;
    if (argc>1) asprintf(&start, "%s", argv[1]);
    printf("Hashing %s\n", start ? start: "the current directory");
    process_dir(.name=start, .file_action=hash_a_file, .data=hash);
    g_hash_table_foreach(hash, printone, NULL);
}
```

❶ Recall that the `filestruct` includes a void pointer, `data`. So the first line of the function will of course declare a variable with the correct type for the input void pointer.

❷ UTF-8 characters are variable-length, so you need a special function to get the current character or step to the next character in a string.

I am a klutz who makes every possible error, yet I have rarely (if ever!) put the wrong type of struct in a list, tree, et cetera. Here are my own rules for ensuring type safety:

- If I have a linked list based on void pointers named `active_groups` and another named `persons`, it is obvious to me as a human being that a line like `g_list_append(active_groups, next_person)` is matching the wrong type of struct to the wrong list, without the compiler having to throw up a flag. So the first secret to my success is that I use names that make it very clear when I'm doing something dumb.
- Put the two sides of Figure 10-1 as close together as possible in your code, so when you change one, you can easily change the other.
- I may have mentioned this before, but the first line of a function that takes in a void pointer should declare a variable with the correct type, effectively casting to the correct type, as in `printone` and `equal_chars`. Having it right at the front raises the odds that you do the cast right, and once the cast is done, the type-safety problem is resolved.
- Associating a purpose-built structure with a given use of a generic procedure or structure makes a whole lot of sense.

— Without a purpose-built struct, when you change the input type, you'll have to remember to hunt down every cast from a void pointer to the old type and change it to a cast to the new type, and the compiler won't help you with this. If you are sending a struct holding the data, all you have to do is change the struct definition.

— Along similar lines, when you realize that you need to pass one more piece of information to the callback function—and the odds are good that you will—then all you have to do is add the element to the struct's definition.

— It might seem like passing a single number doesn't merit a whole new structure, but this is actually the riskiest case. Say that we have a generic procedure that takes in a callback and a void pointer to be sent to the callback, and send it a callback function and pointer like so:

```
void callback (void *voidin){
    double *input = voidin;
    ...
}

int i=23;
generic_procedure(callback, &i);
```

Did you notice that this innocuous code is a type disaster? Whatever the bit pattern of an `int` representing 23 might be, rest assured that when it is read as a `double` by `callback`, it won't be anywhere near 23. Declaring a new struct seems like a lot of bureaucracy, but it prevents an easy and natural error:

```
typedef struct {
    int level;
} one_lonely_integer;
```

— I find that there is some cognitive ease in knowing that there is a single type defined for all dealings in some segment of the code. When I cast to a type clearly purpose-built for the current situation, then I know I'm right; there are no lingering doubts that I should double-check that `char *` is the correct type instead of `char **` or `wchar_t *` or whatever else.

This chapter has covered the many ways that sending structs in and out of a function can be easy: with a good macro, the input struct can be filled with defaults and provide named function inputs; the output structure can be built on the fly using a compound literal; if the function has to copy the structure around (as in the recursion), then all you need is an equals sign; returning a blank structure is a trivial case of using designated initializers with nothing set. And associating a purpose-built struct with a function solves many of the problems with using generic procedures or containers, so applying a generic to a given situation is the perfect time to pull out all the struct-related tricks. Having a struct even gave you a place to put error codes, so you don't have to shoehorn them into the arguments to the function. That's a lot of payoff for the investment of writing up a quick type definition.

CHAPTER 11

Object-Oriented Programming in C

> We favor the simple expression of the complex thought.
> ...
> We are for flat forms
> Because they destroy illusion and reveal truth.
>
> —Le Tigre, "Slideshow at Free University"

Here is the common format for the typical library, in C or in any other language:

- A small set of data structures that represent key aspects of the field the library addresses.
- A set of functions (often referred to as *interface functions*) that manipulate those data structures.

An XML library, for example, would have a structure representing an XML document and perhaps views of the document, plus lots of functions for going between the data structure and the XML file on disk, querying the structure for elements, et cetera. A database library would have a structure representing the state of communications with the database, and perhaps structures representing tables, plus lots of functions for talking to the database and dissecting the data it sends.

This is an eminently sensible way to organize a program or a library. It is the means by which an author can represent concepts with nouns and verbs that are appropriate to the problem at hand.

The first fun exercise in object-oriented programming (OOP) is defining the term, and although I won't waste time (and invite flame wars) by giving a precise definition, the preceding description of an object-oriented library should give you a feel for what we are going after: a few central data structures, each with a set of functions that act on those central data structures. Building a structure like this is language-independent, unless you have a serious and firm belief in the *Sapir-Whorf hypothesis*.

Because OOP has so much baggage associated, the first part of this chapter is mostly concerned with what portion of the OOP world is really necessary (or even desirable) for structuring our writing. The discussion will then turn to what an object looks like in C, such as how we can have one structure inherit from another, or when to put struct-related methods inside of the struct itself. The chapter will conclude with a few full-scale examples of some objects with nontrivial problems, like the need for reference counting. Even with the limited syntactic tools we have, the framework works gracefully and is maintainable.

What You Don't Get (and Why You Won't Miss It)

C is great for its simplicity, but with such a simple grammar, how are we to resolve the multiple virtual constructors one can be saddled with when instantiating an instance of a subclass derived via polymorphic inheritance?

And the simple answer, of course, is that we don't.

You will find OOP proponents who insist that it's not OOP without a message-passing infrastructure, object-level scoping constructs, operator overloading, class inheritance rules, et cetera; and for each of these features, you will find an OOP proponent who insists that the feature is an irrelevance to true OOP.[1]

It is so much easier to just stop worrying about it. To develop central structures and build functions that make use of them, C syntax easily provides the 10% of the edifice that creates 90% of the structure.

Scope

The *scope* of a variable is the range of the code over which it exists and can be used. The rule of thumb for sane programming is to keep the scope of a variable as small as practicable, because doing so limits the number of variables you have to keep in mind at any given point, and means lower risk that a variable will be changed by code you didn't bear in mind.

OK, here goes: all of the rules for variable scope in C.

- A variable never has scope in the code before it is declared. That would be silly.
- If a variable is declared somewhere inside a pair of curly braces, then at the closing curly brace, the variable goes out of scope. Semi-exception: `for` loops and functions may have variables declared in a set of parens just before their opening curly brace; variables declared within the parens have scope as if they were declared inside the curly braces.

1. "I once attended a Java user group meeting where James Gosling (Java's inventor) was the featured speaker. During the memorable Q&A session, someone asked him: 'If you could do Java over again, what would you change?' 'I'd leave out classes,' he replied."

—Allen Holub, *Why extends is evil*

- If a variable isn't inside any curly braces, then it has scope from its declaration to the end of the file.

You're done.

There is no class scope, prototype scope, friend scope, namespace scope, runtime environment rebinding, or special scoping keywords or operators (beyond those curly braces, and arguably the linkage specifiers `static` and `extern`). Does dynamic scoping confuse you? Don't worry about it. If you know where the curly braces are, you can determine which variables can be used where.

Everything else is a simple corollary. For example, if *code.c* has a line that will `#include <header.h>`, then the full text of *header.h* is pasted into *code.c*, and variables therein have scope accordingly.

Functions are just another example of curly-brace scope. Here is a sample function to sum all the integers up to the input number:

```
int sum (int max){
    int total=0;
    for (int i=0; i<= max; i++){
        total += i;
    }
    return total;
}
```

Then `max` and `total` have scope inside the function, by the curly-brace rule and the semi-exception about how variables in parens just before the curly brace act as if they are inside the braces. The same holds with the `for` loop, and how `i` is born and dies with the curly braces of the `for` loop. If you have a one-line `for` loop, you don't have to write the curly braces, like `for (int i=0; i <= max; i++) total += i;`, but the scope of `i` is still limited to the loop.

Summary paragraph: C is awesome for having such simple scoping rules, which effectively consist of finding the end of the enclosing curly braces or the end of the file. You can teach the whole scoping system to a novice student in maybe 10 minutes. For the experienced author, the rule is more general than just the curly braces for functions and `for` loops, so you can use them for occasional additional scoping restrictions in exceptional situations, as in the macro tricks in "Cultivate Robust and Flourishing Macros" on page 131.

Private struct elements

So we're cathartically throwing out all the additional rules and keywords that support very fine-grained scope control.

Could we implement private struct elements without the extra keywords? In typical OOP usage, "private" data is not encrypted by the compiler or otherwise seriously hidden: if you have the address of the variable (e.g., if you have its offset in the struct), you can point to it, look at it in the debugger, and modify it. To give the data that level of opacity, we have the technology.

An object will typically be defined via two files: the *.c* file with the details and the *.h* file to be included in other writing that makes use of the object. It is not unreasonable to think of the *.c* file as the private segment and the *.h* file as the public. For example, say we are set on keeping some elements of an object private. The public header might be:

```
typedef struct a_box_s {
    int public_size;
    void *private;
} a_box_s;
```

The `void` pointer is basically useless to other authors, because they don't know what type to cast it to. The private segment, *a_box.c*, would hold the requisite typedef:

```
typedef struct private_box_s {
    long double how_much_i_hate_my_boss;
    char **coworkers_i_have_a_crush_on;
    double fudge_factor;
} private_box_s;

//Given the typedef, we have no problem casting the private pointer to
//its desired type and making use here in a_box.c.

a_box_s *box_new(){
    a_box_s *out = malloc(sizeof(a_box_s));
    private_box_s *outp = malloc(sizeof(private_box_s));
    *out = (a_box_s){.public_size=0, .private=outp};
    return out;
}

void box_edit(a_box_s *in){
    private_box_s *pb = in->private;
    //now work with private variables, e.g.:
    pb->fudge_factor *= 2;
}
```

So it's not all that hard to implement a private segment of a C struct, but I rarely see it used in real-world libraries. Few C authors seem to think that there's serious benefit to doing so.

Here's a sample of the much more common means of putting a private element within a public struct:

```
typedef struct {
    int pub_a, pub_b;
    int private_a, private_b; //Private: please do not use these.
} public_s;
```

That is, document when something should not be used, and trust your users to not cheat. If your colleagues won't follow an instruction as simple as this, then chain the coffee maker to the wall, because you've got problems bigger than a compiler can solve.

Functions are especially easy to make private: don't put their declaration in a header. Optionally, put the `static` keyword in front of the definition so that readers know that the function is private.

Overloaded with Operator Overloading

My impression is that most folks think of integer division—that `3/2==1`—as an annoyance. If I type in `3/2`, I expect `1.5`, darn it, not `1`.

Indeed, this is an annoying gotcha to C and other integer-arithmetic languages, and more broadly, it shows us the dangers of *operator overloading*. O.o. is when an operator, such as `/`, does something different depending on the types involved. For two integer types, the slash effectively does a divide-and-truncate operation, and for anything else, it performs the usual division.

Recall the rule from "Pointers Without malloc" on page 105 that things that behave differently should look different. That's the failure of `3/2`: integer division and floating-point division behave differently, but look identical. Confusion and bugs ensue.

Human language is redundant, which is a good thing, partly because it allows error correction. When Nina Simone says "ne me quitte pas" (which would translate word-for-word as "don't leave me no"), it's OK if you space out at the beginning, because "... me quitte pas" has the *pas* to indicate negation, and it's OK if you space out at the end, because "ne me quitte ..." has the *ne* to indicate negation.

Grammatical gender typically doesn't have much real-world meaning, and sometimes objects will change depending on word choice. My favorite example is in Spanish, where *el pene* and *la polla* both refer to the same object, but the first is masculine and the second feminine. The real value to the gender is that it provides redundancy, forcing parts of the sentence to match, and thus adding clarity.

Programming languages avoid redundancy. We express negation exactly once, typically with only one character (`!`). But programming languages do have genders, where they're called types. Generally, your verbs and your nouns need to agree in type (as in Arabic, Hebrew, and Russian, among other languages). With this added redundancy, you'd need `matrix_multiply(a, b)` when you have two matrices, and `complex_multiply(a, b)` when you have two complex numbers.

Operator overloading is about eliminating redundancy, writing `a * b` whether you have a pair of matrices, complex numbers, natural numbers, or sets. Here's a snippet from an excellent essay on the cost of that reduced redundancy: "When you see the code `i = j * 5;` in C you know, at least, that `j` is being multiplied by five and the results stored in `i`. But if you see that same snippet of code in C++, you don't know anything. Nothing."[2]. The problem is that you don't know what * means until you look up the type for `j`, look through the inheritance tree for `j`'s type to determine *which version* of * you

2. Originally at *http://www.joelonsoftware.com/articles/Wrong.html*; reprinted in [Spolsky 2008].

mean, and then you can start over with identifying i and how that relates to =, given the type of j.

So there's the trade-off to operator overloading: you've saved space on the page, and didn't have to type much of anything, but have lost all redundant hints and checks that b is actually a list and not the vector you thought it was.

The C custom is to closely follow the sort of gender-agreement rules I'd just described, for example:

```
//add two vectors in the GNU Scientific Library
gsl_vector *v1, *v2;
gsl_vector_add(v1, v2);

//Open a GLib I/O channel for reading at a given filename.
GError *e;
GIOChannel *f  = g_io_channel_new_file("indata.csv", "r", &e);
```

It's more typing, and when you have 10 lines acting on the same structure, things start to look repetitive. Later, we'll have some means of slightly reducing this redundancy.

_Generic

C provides limited overloading support via the C11 _Generic keyword. The keyword evaluates to a value based on the type of its input, which lets you write macros that consolidate some types together.

We need type-generic functions when we have a proliferation of types. Some systems provide a voluminous number of precise types, but every new type is another moving part that we have to support. For example, the GNU Scientific Library provides a complex number type, a complex vector type, and a vector type—and then there's the C complex type. One could reasonably multiply any of those four types together, which theoretically means we need sixteen functions. Example 11-1 lists several of these functions; if you are not a complex vector aficionado, it would be entirely reasonable to recognize this example as a hairy mess and move on to the part where we clean it up.

Example 11-1. Where the sausage is made, for those of you with an interest in GSL complex types (complex.c)

```
#include "cplx.h"                //gsl_cplx_from_c99; see below.
#include <gsl/gsl_blas.h>        //gsl_blas_ddot
#include <gsl/gsl_complex_math.h> //gsl_complex_mul(_real)

gsl_vector_complex *cvec_dot_gslcplx(gsl_vector_complex *v, gsl_complex x){
    gsl_vector_complex *out = gsl_vector_complex_alloc(v->size);
    for (int i=0; i< v->size; i++)
        gsl_vector_complex_set(out, i,
                          gsl_complex_mul(x, gsl_vector_complex_get(v, i)));
    return out;
}

gsl_vector_complex *vec_dot_gslcplx(gsl_vector *v, gsl_complex x){
    gsl_vector_complex *out = gsl_vector_complex_alloc(v->size);
```

```
    for (int i=0; i< v->size; i++)
        gsl_vector_complex_set(out, i,
                            gsl_complex_mul_real(x, gsl_vector_get(v, i)));
    return out;
}

gsl_vector_complex *cvec_dot_c(gsl_vector_complex *v, complex double x){
    return cvec_dot_gslcplx(v, gsl_cplx_from_c99(x));
}

gsl_vector_complex *vec_dot_c(gsl_vector *v, complex double x){
    return vec_dot_gslcplx(v, gsl_cplx_from_c99(x));
}

complex double ddot (complex double x, complex double y){return x*y;}    ❶

void gsl_vector_complex_print(gsl_vector_complex *v){
    for (int i=0; i< v->size; i++) {
        gsl_complex x = gsl_vector_complex_get(v, i);
        printf("%4g+%4gi%c", GSL_REAL(x), GSL_IMAG(x), i < v->size-1 ? '\t' : '\n');
    }
}
```

❶ C-native complex numbers are multiplied with a simple *, like real numbers.

The cleanup happens in the header, Example 11-2. It uses `_Generic` to select one of the functions from Example 11-1 based on the input types. The first argument (the "controlling expression") is not evaluated, but is simply checked for its type, and the value of the `_Generic` statement is selected based on that type. We want to select a function based on two types, so the first macro picks which of the second or third macros to use.

Example 11-2. Using `_Generic` to provide a simple front-end to the mess (cplx.h)

```
#include <complex.h> //nice names for C's complex types
#include <gsl/gsl_vector.h> //gsl_vector_complex

gsl_vector_complex *cvec_dot_gslcplx(gsl_vector_complex *v, gsl_complex x);
gsl_vector_complex *vec_dot_gslcplx(gsl_vector *v, gsl_complex x);
gsl_vector_complex *cvec_dot_c(gsl_vector_complex *v, complex double x);
gsl_vector_complex *vec_dot_c(gsl_vector *v, complex double x);
void gsl_vector_complex_print(gsl_vector_complex *v);

#define gsl_cplx_from_c99(x) (gsl_complex){.dat= {creal(x), cimag(x)}} ❶

complex double ddot (complex double x, complex double y);

#define dot(x,y)  _Generic((x),                              \       ❷
                    gsl_vector*: dot_given_vec(y),           \
                    gsl_vector_complex*: dot_given_cplx_vec(y), \
                    default: ddot)((x),(y))

#define dot_given_vec(y) _Generic((y),                       \
                        gsl_complex: vec_dot_gslcplx,        \
                        default: vec_dot_c)
```

```
#define dot_given_cplx_vec(y) _Generic((y),                     \
                        gsl_complex: cvec_dot_gslcplx,          \
                        default: cvec_dot_c)
```

❶ `gsl_complex` and C99 complex double are both a two-element array consisting of real double followed by imaginary double [see the GSL manual and C99 & C11 §6.2.5(13)]. All we have to do is build the appropriate struct—and a compound literal is the perfect way to build a struct on the fly.

❷ The first use of `x` is not actually evaluated, just checked for its type. That means that a call like `dot(x++, y)` would increment `x` only once.

In Example 11-3, life is (mostly) easy again: we can use `dot` to find the product of a `gsl_vector` times a `gsl_complex`, a `gsl_vector_complex` times a C complex, and so on for a great many combinations. Of course, you still need to know the output type, because the return value of a scalar times a scalar is a scalar, not a vector, so the use of the output depends on the input types. The proliferation of types is a fundamental problem, but the `_Generic` facility at least provides a band-aid.

Example 11-3. The payoff: we can use `dot` *(almost) regardless of input types (simple_cplx.c)*

```
#include <stdio.h>
#include "cplx.h"

int main(){
    int complex a = 1+2I;                                                  ❶
    complex double b = 2+I;
    gsl_complex c = gsl_cplx_from_c99(a);

    gsl_vector *v = gsl_vector_alloc(8);
    for (int i=0; i< v->size; i++) gsl_vector_set(v, i, i/8.);

    complex double adotb = dot(a, b);                                      ❷
    printf("(1+2i) dot (2+i): %g + %gi\n", creal(adotb), cimag(adotb));    ❸

    printf("v dot 2:\n");
    double d = 2;
    gsl_vector_complex_print(dot(v, d));

    printf("v dot (1+2i):\n");
    gsl_vector_complex *vc = dot(v, a);
    gsl_vector_complex_print(vc);

    printf("v dot (1+2i) again:\n");
    gsl_vector_complex_print(dot(v, c));
}
```

❶ Declarations with `complex` are a bit like declarations with `const`: both `complex int` and `int complex` are valid.

❷ Finally, the payoff: this function will use the `dot` function four times, each with different input types.

❸ Here are the C-native means of getting the real and imaginary parts of a complex number.

Here's my own rule of thumb for overloading, via `_Generic` or whatever other means: *if users have no idea what the input type is, will they still get the right answer?* Observe that the overloading of absolute value for `int`, `float`, and `double` work just fine with this rule. Following the example, it might also make sense to overload functions using the `gsl_complex` and the native C `complex double`.

Extending Structures and Dictionaries

Moving on from the syntactic tricks, let us get to the core problem of structuring our data.

In 1936, in response to a formal mathematical question (The *Entscheidungsproblem*), Alonso Church developed a *lambda calculus*, a formal means of describing functions and variables. In 1937, in response to the same question, Alan Turing described a formal language in the form of a machine with a tape holding data and a head that can be shifted along the tape to read and write to the tape. Later, Church's lambda calculus and Turing's machine were shown to be equivalent—any calculation you could express in one, you could express in the other. It's been the same divide ever since, and Church's and Turing's constructions continue to be the root of how we structure our data.

The lambda calculus relies heavily on named lists; in lambda-inspired pseudocode, we might express a person's information as:

```
(person (
    (name "Sinead")
    (age 28)
    (height 173)
))
```

With Turing's machine, we would have a block of the tape set aside for the structure. The first few blocks would be a name, the next few would hold the age, and so on. Almost a century later, Turing's tape is still a not-bad description of computer memory: recall from "All the Pointer Arithmetic You Need to Know" on page 111 that this base-plus-offset form is exactly how C treats structures. We would write

```
typedef struct {
    char * name;
    double age, height;
} person;

person sinead = {.name="Sinead", .age=28, .height=173};
```

and `sinead` would point to a block of memory, and `sinead.height` would point to the tape immediately after `name` and `age` (and after any padding for alignment purposes).

Here are some differences between the list approach and the block-of-memory approach:

- Telling the computer to go to a certain offset from a certain address is still among the fastest operations a machine can execute. Your C compiler even does the translation from labels to offsets during compile time. Conversely, finding something in the list requires a lookup: given the label `"age"`, which element in the list corresponds and where is its data in memory? Every system has techniques to make this as fast a lookup as possible, but a lookup will always be more work than a simple base-plus-offset.
- Adding a new element to a list is a much easier process than adding to a struct, which is basically fixed at compile time.
- A C compiler can tell you at compile time that `hieght` is a typo, because it can look in the struct's definition and see that there is no such element. Because a list is extensible, we won't know that there is no `hieght` element until the program runs and checks on the list.

Extending a Structure

Those last two items demonstrate a direct tension: we want extensibility, wherein we can add elements to a structure; we want registration, wherein things that are not in the structure are flagged as errors. That's a balance that has to be struck, and everybody implements controlled extension of an existing list differently.

C++, Java, and their siblings, have a syntax for producing a new type that is an instance of the type to be extended, but that inherits the old type's elements. You still get base-plus-offset speed, and compile-time checking, but at the price of voluminous paperwork; where C has `struct` and its absurdly simple scoping rules from "Scope" on page 198, Java has `implements`, `extends`, `final`, `instanceof`, `class`, `this`, `interface`, `private`, `public`, `protected`.

Perl, Python, and many LISP-inspired languages are based on named lists, so that is a natural means of implementing a structure. Extend the list by just adding elements to it. Pros: fully extensible by just adding a new named item. Cons: as previously, we don't get registration, and although you can improve the name search via various tricks, you're a long way from the speed of a single base-plus-offset step. Many languages in this family have a class definition system, so that you can register a certain set of list items and thus check whether future uses conform to the definition, which, when done right, provides a nice compromise between checking and ease of extension.

Getting back to plain old C, its structs are the fastest way to access a structure's elements, and we get compile-time checking at the price of runtime extensibility. If you want a flexible list that can grow as the runtime need arises, you will need a list structure, such as the GLib's hashes, or the sample dictionary described later.

All the machinery you have in C for extending a structure is to wrap it in another structure. Say that we have a type defined via a form such as:

```
typedef struct {
    ...
} list_element_s;
```

which is already packaged and cannot be changed, but we'd like to add a type marker. Then we'll need a new structure:

```
typedef struct {
    list_element_s elmt;
    char typemarker;
} list_element_w_type_s;
```

Pros: this is so stupid easy, and you still get the speed bonus. Cons: Now, every time you want to refer to the name of the element, you'll need to write out the full path, `your_typed_list->elmt->name`, instead of what you'd get via a C++/Java-like extension: `your_typed_list->name`. Add a few layers to this and it starts to get annoying. You already saw in "Pointers Without malloc" on page 105 how using aliases can help here.

C, with fewer seams

C11 allows us to include anonymous elements of a structure, which make structs within structs easier to use. Although this got added to the standard in December of 2011, it was a Microsoft extension for a long time before then, and gcc already allows it given the `--ms-extensions` flag on the command line.

The syntax: include another struct type somewhere in the declaration of the new structure, as per the `point` struct in Example 11-4, without a name for the element. Example 11-4 uses a bare structure type name, `struct point`, whereas a named declaration would be something like `struct point` *`ptelement`*. All of the elements of the referred-to structure are included in the new structure as if they were declared in place.

Example 11-4 extends a 2D point into a 3D point. So far, it is only notable because the `threepoint` struct extends the `point` seamlessly, to the point where users of the `threepoint` won't even know that its definition is based on another struct.

Example 11-4. An anonymous substructure inside of a wrapping structure merges seamlessly into the wrapper (seamlessone.c)

```
#include <stdio.h>
#include <math.h>

typedef struct point {
   double x, y;
} point;

typedef struct {
    struct point;                                    ❶
    double z;
} threepoint;
```

```
double threelength (threepoint p){
    return sqrt(p.x*p.x + p.y*p.y + p.z*p.z);  ❷
}

int main(){
    threepoint p = {.x=3, .y=0, .z=4};         ❸
    printf("p is %g units from the origin\n", threelength(p));
}
```

❶ This is anonymous. The not-anonymous version would also have a name like `struct point twopt`.

❷ The `x` and `y` elements of the `point` structure look and behave exactly like the additional `z` element of the `threepoint`.

❸ Even the declaration gives no hint that `x` and `y` were inherited from an existing structure.

> It's not in the standard to use a typedef in the nested anonymous declaration. The standards committee explicitly rejected this, thus going out of its way to produce one of the few points in the C language where a typedef for a struct cannot substitute for the struct definition.[3] Though, if you use the naming convention from "Typedefs Save the Day" on page 172, this just means that you need to put the word `struct` in front of the name of the structure type.

Now for the trick that really makes this useful. The original object, the `point`, was probably accompanied by several interface functions that are still potentially useful, like a `length` function measuring the distance between zero and the given point. How are we going to use that function, now that we don't have a name for that subpart of the larger structure?

The solution is to use an anonymous union of a named `point` and an unnamed `point`. Being the union of two identical structures, the two structures share absolutely everything, and the only distinction is in the naming: use the named version when you need to call functions that use the original struct as an input, and use the anonymous version for seamless merging into the larger struct. Example 11-5 rewrites Example 11-4 using this trick.

Example 11-5. The point is seamlessly incorporated into a threepoint, and we still have a name for use with functions that operate on a point (seamlesstwo.c)

```
#include <stdio.h>
#include <math.h>
```

3. The discussion is from David Keaton, "Clarifications to Anonymous Structures and Unions", WG14/N1549, 22 December 2010, voted on and adopted by the Committee in March of 2011.

```
typedef struct point {
   double x, y;
} point;

typedef struct {
    union {
        struct point;                   ❶
        point p2;                       ❷
    };
    double z;
} threepoint;

double length (point p){
    return sqrt(p.x*p.x + p.y*p.y);
}

double threelength (threepoint p){
    return sqrt(p.x*p.x + p.y*p.y + p.z*p.z);
}

int main(){
    threepoint p = {.x=3, .y=0, .z=4};  ❸
    printf("p is %g units from the origin\n", threelength(p));
    double xylength = length(p.p2);     ❹
    printf("Its projection onto the XY plane is %g units from the origin\n", xylength);
}
```

❶ This is an anonymous structure.

❷ This is a named structure. Being part of a union, it is identical to the anonymous structure, differing only in having a name.

❸ The `point` structure is still seamlessly included in the `threepoint` structure, but...

❹ ...the `p2` element is a named element like it always was, so we can use it to call the interface functions written around the original struct.

After the declaration `threepoint p`, we can refer to the *X* coordinate via `p.x` (because of the anonymous struct) or via `p.p2.x` (because of the named struct). The last line of the example shows the length when projecting onto the *XY* plane, and does so using `length(p.p2)`.

From here, the possibilities span $\mathbb{R}^3$. You can extend any structure and still use all of the functions associated with the original.

> Did you notice this is the first time I've used the `union` keyword in this book? Unions are another one of those things where the explanation takes a paragraph—it's like a `struct`, but all of the elements occupy the same space—and then the caveats about how to not hang yourself take up several pages. Memory is cheap, and for writing applications, we don't have to care about memory alignment, so sticking to structs will reduce the possibility of errors, even when only one element is used at a time.

Inheriting from multiple structures with this method is risky. Pick one structure to be the base of the extension using the union trick, and let the others be extended via the plain vanilla substructure. For example, The GNU Scientific Library has matrix and vector types (where `struct _gsl_matrix` is typedeffed as `gsl_matrix`). Let us say that we want to put both into a single structure:

```
typedef struct{  //Alas, this will fail.
    struct _gsl_vector;
    struct _gsl_matrix;
} data_set;

data_set d;
```

This looks innocuous, until you find out that the `_gsl_vector` and the `_gsl_matrix` both have an element named `data`. When we refer to `d.data`, are we referring to the `data` element of the matrix or the vector? We have no syntax for selective inclusion or renaming struct elements, so the best we can do is pick the matrix or vector as primary and the other as secondary, callable only by its subelement name:

```
typedef struct{ //A vector with supporting matrix.
    struct _gsl_vector;           //anonymous and seamless.
    struct _gsl_matrix matrix;    //named
} data_set;

data_set d;
```

Implementing a Dictionary

Earlier, I mentioned differences between a C struct and a LISP-like dictionary of named elements. But a dictionary is an easy structure to generate, given what we have in struct-based C. Doing so is a fine chance to try building some objects. Please note, however, that fleshing this out and making it bulletproof has already been done by other authors; see the GLib's keyed data tables or `GHashTable`, for example. The point here is simply that having compound structs plus simple arrays equals a short hop to a dictionary object.

We're going to start with a simple key/value pair. Its mechanism will be in *keyval.c*. The header in Example 11-6 lists the structure and its interface functions.

Example 11-6. The header, or the public-facing portion of the key/value class (keyval.h)

```
typedef struct keyval{
   char *key;
   void *value;
} keyval;

keyval *keyval_new(char *key, void *value);
keyval *keyval_copy(keyval const *in);
void keyval_free(keyval *in);
int keyval_matches(keyval const *in, char const *key);
```

Those of you with experience in traditional object-oriented programming languages will find this to be very familiar. The first instinct when establishing a new object is to write down new/copy/free functions, and that is what the example does. After that, there are typically a few structure-specific functions, such as the `keyval_matches` function to check whether the key in a `keyval` pair matches the input string.

Having new/copy/free functions mean that your memory management worries are brief: in the new and copy functions, allocate the memory with `malloc`; in the free function, remove the structure with `free`, and having set up these functions, code that uses the object will never use `malloc` or `free` on them, but will trust that `keyval_new`, `keyval_copy`, and `keyval_free` will do all the memory management correctly.

Example 11-7. The typical boilerplate for a key/value object: a structure plus new/copy/free functions (keyval.c)

```
#include <stdlib.h> //malloc
#include <strings.h> //strcasecmp
#include "keyval.h"

keyval *keyval_new(char *key, void *value){
    keyval *out = malloc(sizeof(keyval));
    *out = (keyval){.key = key, .value=value};        ❶
    return out;
}

/** Copy a key/value pair. The new pair has pointers to
  the values in the old pair, not copies of their data.  */
keyval *keyval_copy(keyval const *in){
    keyval *out = malloc(sizeof(keyval));
    *out = *in;                                       ❷
    return out;
}

void keyval_free(keyval *in){ free(in); }

int keyval_matches(keyval const *in, char const *key){
    return !strcasecmp(in->key, key);
}
```

❶ Designated initializers make filling a struct easy.

❷ Remember, you can copy the contents of structs with an equals sign. If we wanted to copy the contents of pointers in the struct (rather than copy the pointers themselves), we would need more lines of code after this one.

Now that we have an object representing a single key/value pair, we can move on to establishing a dictionary as a list of these. Example 11-8 provides the header.

Example 11-8. The public parts of the dictionary structure (dict.h)

```
#include "keyval.h"

extern void *dictionary_not_found;     ❶

typedef struct dictionary{
   keyval **pairs;
   int length;
} dictionary;

dictionary *dictionary_new (void);
dictionary *dictionary_copy(dictionary *in);
void dictionary_free(dictionary *in);
void dictionary_add(dictionary *in, char *key, void *value);
void *dictionary_find(dictionary const *in, char const *key);
```

❶ This will be the marker for when a key is not found in the dictionary. It has to be public.

As you can see, you get the same new/copy/free functions, plus a few other dictionary-specific functions, and a marker to be described later. Example 11-9 provides the private implementation.

Example 11-9. The implementation of the dictionary object (dict.c)

```
#include <stdio.h>
#include <stdlib.h>
#include "dict.h"

void *dictionary_not_found;

dictionary *dictionary_new (void){
    static int dnf;
    if (!dictionary_not_found) dictionary_not_found = &dnf;          ❶
    dictionary *out= malloc(sizeof(dictionary));
    *out= (dictionary){ };
    return out;
}

static void dictionary_add_keyval(dictionary *in, keyval *kv){      ❷
    in->length++;
    in->pairs = realloc(in->pairs, sizeof(keyval*)*in->length);
    in->pairs[in->length-1] = kv;
}

void dictionary_add(dictionary *in, char *key, void *value){
    if (!key){fprintf(stderr, "NULL is not a valid key.\n"); abort();} ❸
    dictionary_add_keyval(in, keyval_new(key, value));
}

void *dictionary_find(dictionary const *in, char const *key){
    for (int i=0; i< in->length; i++)
        if (keyval_matches(in->pairs[i], key))
            return in->pairs[i]->value;
```

```
    return dictionary_not_found;
}

dictionary *dictionary_copy(dictionary *in){
    dictionary *out = dictionary_new();
    for (int i=0; i< in->length; i++)
        dictionary_add_keyval(out, keyval_copy(in->pairs[i]));
    return out;
}

void dictionary_free(dictionary *in){
    for (int i=0; i< in->length; i++)
        keyval_free(in->pairs[i]);
    free(in);
}
```

❶ It is reasonable to have a `NULL` value in the key/value table, so we need a unique marker to indicate a missing value.

❷ Recall that a function marked as `static` cannot be used outside the file, so this is one more reminder that the function is private to the implementation.

❸ I cheated again: using `abort` like this is bad form. It would be better to use a macro like the one in *stopif.h* (Example 10-2). I did it this way to demonstrate a feature of the test harness in "Unit Testing" on page 39.

Now that we have a dictionary, Example 11-10 can use it without thinking about memory management, which the new/copy/free/add functions take care of, and without making reference to key/value pairs, because that is one level too low for our purposes.

Example 11-10. Sample usage of the dictionary object; no need to delve into the guts of the struct, because the interface functions provide all we need (dict_use.c)

```
#include <stdio.h>
#include "dict.h"

int main(){
    int zero = 0;
    float one = 1.0;
    char two[] = "two";
    dictionary *d = dictionary_new();
    dictionary_add(d, "an int", &zero);
    dictionary_add(d, "a float", &one);
    dictionary_add(d, "a string", &two);
    printf("The integer I recorded was: %i\n", *(int*)dictionary_find(d, "an int"));
    printf("The string was: %s\n", (char*)dictionary_find(d, "a string"));
    dictionary_free(d);
}
```

So writing a struct and its new/copy/free and other associated functions was enough to give us the right level of encapsulation: the dictionary didn't have to care about the internals of the key/value pair, and the application didn't have to worry about dictionary internals.

The boilerplate code is not as bad as it is in some languages, but there is certainly some repetition to the new/copy/free functions. And as the examples continue, you'll see this boilerplate several times more.

At some point, I even wrote myself macros to autogenerate these. For example, the copy functions differ only in dealing with internal pointers, so we could write a macro to automate all the boilerplate not about internal pointers:

```
#define def_object_copy(tname, ...)          \
    void * tname##_copy(tname *in) {         \
        tname *out = malloc(sizeof(tname)); \
        *out = *in;                          \
        __VA_ARGS__;                         \
        return out;                          \
    }

def_object_copy(keyval) //Expands to the previous declarations of keyval_copy.
```

But the redundancy is nothing to worry about all that much. Despite our mathematical æsthetic of minimizing repetition and text on the page, sometimes having more code really does make the program more readable and robust.

Base Your Code on Pointers to Objects

Why did I base all of these things on pointers to data structures, instead of just passing around data structures directly? If you use a plain struct, the new/copy/free functions write themselves:

new
: Use designated initializers on the first line where you need a struct. As an added plus, structures can be declared at compile time, so they are immediately available to users without an initial call to a setup function.

copy
: The equals sign does this.

free
: Don't bother; it'll go out of scope soon enough.

So we're making things more difficult for ourselves with pointers. Yet from what I've seen, there's consensus on using pointers to objects as the base of our designs.

Pros to using pointers:

- Copying a single pointer is cheaper than copying a full structure, so you save a microsecond on every function call with a struct as an input. Of course, this only adds up after a few billion function calls.
- Data structure libraries (your trees and linked lists, for example) are all written around hooks for a pointer.
- Now that you're filling a tree or a list, having the system automatically free the struct at the end of the scope in which it was created might not be what you want.
- Many of your functions that take in a struct will modify the struct's contents, meaning that you've got to pass a pointer to the struct anyway. Having some functions that take in the struct itself and some that take in a pointer to struct is confusing (I have written an interface like this and I regret it), so you might as well just send a pointer every time.
- If the contents of the struct include a pointer to data elsewhere, then the convenience bonus from using a plain struct evaporates anyway: if you want a deep copy (wherein the data pointed to is copied, not just the pointer) then you need a copy function, and you will probably want a free function to make sure the internal data is eliminated.

There's no one-size-fits-all set of rules for using structs. As your project gets bigger, and a throwaway struct grows into a core of how your data is organized, the benefits to pointers wax and the benefits to nonpointers wane.

Functions in Your Structs

A struct can include functions among its member elements as easily as it can hold typical variables.

> **Pointer Decay**
>
> Say we have a pointer to a function, *`fn`*, meaning that *`*fn`* is a function and *`fn`* is its address in memory. Then *`(*fn)`*`(x)` makes sense as a function call, but what would *`fn`*`(x)` mean? In this case, C takes a do-what-I-mean approach and interprets calling a pointer-to-function as a simple call to the function. The term for this is *pointer decay*. This is why I treat functions and pointers-to-functions as equivalent in the text.

Given a struct *`object_s`* and a function *`fn`* that is somehow related to it, we can go the usual route of leaving the function outside of the structure but give it a name that indicates a relationship, *`object_fn`*`(...)`, or we could let *`fn`* be an element of an *`object_s`*, so that when we declare *`object_s xo`*, we would call the function via *`xo.fn`*`(...)`.

This is, for the most part, a stylistic choice, affecting how we look up functions in the documentation and how the code looks on the page. The documentation issue, by the way, is why I prefer the *`object_fn`* naming scheme over the *`fn_object`* scheme: with the first form, the documentation's index lists all of *`object_s`*'s associated functions in one place.

The real advantage of the element-of-struct form is that you can more easily change the function associated with every instance of the object: given the declaration *`object_s`* `xo, yo` and a function element of the struct named `add`, then `xo.add` and `yo.add` could be entirely different functions. On the plus side, you can send `xo` and `yo` to a routine with a header `do_math(`*`object_s`* `in)`, and it can call `in.add` somewhere in there without any regard to what `add` actually does. On the minus side, we run risk of once again breaking the rule that things that do different things should look different: if the function `xo.add` has subtly different side effects from `yo.add`, you have no warnings.

This is why I generally prefer the *`object_fn`* form for functions related to objects. If there are two or three similar but distinct types of operation on the same object, I can give them different names (like `dictionary_add` and `dictionary_add_keval` in Example 11-9). I reserve the *`xo.fn`* form for when I expect that almost every instance of *`object_s`* will have a different version of *`fn`*.

It's hard to come by situations where every instance of an object has different methods associated, which is the point where having methods inside of an object really starts to make a difference. I've had the good fortune of running across such a situation, when writing a library of statistical models, named Apophenia (see "The GNU Scientific Library" on page 242). This segment will present a `model_s` object along similar lines, and demonstrate the details of hooking different procedures to every object. I've written this section so that if you read all of the mathematics and statistical jargon as *blahblahblah*, then you should be able to follow along just fine.

Broadly, statistical models are all the same: they have some procedure, like the equation for a bell curve or a story about a line of best fit, and some parameters that fine-tune the procedure to the data. For example, we might specify that the data is from a bell-curve Normal distribution, whose tuning parameters are a mean (μ) and a standard deviation (σ). For the input data [1, 2, 3, 4, 5], the mean is three (because it's symmetric around three), and if you do the math, you'll find that the sample σ is about 1.58. The black box representing the estimation procedure would take in that data and spit out $(\mu, \sigma) = (3, 1.58)$. If I give the black box [100, 100.2, 100.8, 100.7, 100.4], then it will spit out a larger μ and smaller σ: $(\mu, \sigma) = (100.42, 0.33)$.

You might be familiar with *long tail* distributions, like how a handful of books sell millions of copies but thousands of books only sell a few dozen copies. This is hardly a bell curve where everything drifts around an average sales figure, and the calculations for estimating the parameter for a Zipf distribution (one of the more common formalizations of the long tail idea) have nothing to do with the math for a bell curve. The black box has a similar form, though: give it [1, 2, 3, 4, 5], and it spits out β=1.7; give it [100, 100.2, 100.8, 100.7, 100.4] and it spits out β=1.2.

So we've hit heterogeneity: the model struct should have elements named `parameters` and `data`, and there should be an `estimate` function to go from data to parameters, but it will be a different function for every model.

The implementation of this is not much of a stretch from the typical structure implementation. Assume a typedef for `data_s` appropriate to describe a data set; then we have enough to declare Normal and Zipf objects. Here is a mock-up of the key parts of the process:

```
typedef model_s * (*data_to_estimated_model)(model_s *, data_s *);   ❶

typedef struct model_s {
    data_s *parameters, *data;
    data_to_estimated_model estimate;                                  ❷
} model_s;

//Takes in a copy of the input model with NULL parameters.
//Returns a copy of the input model with the parameters calculated.
static model_s* normal_est(model_s *in, data_s *d){
    model_s *outmodel = model_copy(in);                                ❸
    //math goes here to calculate outmodel->parameters;
    return outmodel;
}

static model_s* zipf_est(model_s *in, data_s *d){
    model_s *outmodel = model_copy(in);
    //entirely different math goes here to set outmodel->parameters;
    return outmodel;
}

model_s *normal_model = &(model_s){.estimate = normal_est};            ❹
model_s *zipf_model   = &(model_s){.estimate = zipf_est};

data_s *data = text_to_data("infile");                                 ❺
model_s *norm_est = normal_model->estimate(normal_model, data);
model_s *zipf_est = zipf_model->estimate(zipf_model, data);
```

❶ As per "Typedef as a teaching tool" on page 113, a good typedef makes life with function pointers much more pleasant.

❷ We can put a pointer to a function into a struct as easily as we include any other pointer. Now all that's left to do is establish what function any given function pointer will point to.

❸ I assume that `model_copy` is defined elsewhere. The copy function is the same for every model, so there's no major benefit to putting it inside the structure.

❹ Here, two `model_s` structures are initialized, via designated initializers. The `estimate` pointers in the two models each point to a different function.

❺ An imaginary sample use of the two models to produce versions with parameters estimated.

By the last two lines, we are on our way to having a uniform interface to entirely distinct functions. You could picture a function that takes in data and a `model_s`, names it `m`, and calls `m.estimate(m, data)`.

Note the use of the `static` keyword, which indicates that outside of this file, no code will be able to call `normal_est` or `zipf_est` by those names. They will, however, be able to use the names `normal_mode.estimate` and `zipf_model.estimate` to call them.

There are a few bells and whistles that we'd like to add. First, `zipf_model.estimate(zipf_model, data)` is a redundant form, with a repetition of `zipf_model`. It would be nice to be able to write `zipf_model.estimate(data)` and let the system just know that the first argument should be the object making the call. The function might see a special variable named `this` or `self`, or we could add a special-case rule that ***`object.fn(x)`*** gets reshuffled to ***`fn(object, x)`***.

Sorry, but it's not going to happen in C.

C doesn't define magic variables for you, and it is always honest and transparent about what parameters get sent in to a function. Normally, if we want to futz around with the parameters of a function, we do it with the preprocessor, which will gladly rewrite `f(anything)` to `f(anything else)`. However, all of the transformations happen to what goes on inside of the parens. There's no way to get the preprocessor to transform the text `s.prob(d)` to `s.prob(s, d)`. If you don't want to slavishly imitate C++-type syntax, you can write macros like:

```
#define Estimate(in, ...) (in).estimate((in), __VA_ARGS__)
#define Copy(in, ...) (in).copy((in), __VA_ARGS__)
#define Free(in, ...) (in).free((in), __VA_ARGS__)
```

But now you've cluttered up the global namespace with the `Estimate`, `Copy`, and `Free` symbols. Maybe it's worth it to you (especially given that every function should have associated copy and free functions).

You could keep the namespace organized and prevent name collisions by naming your macros appropriately:

```
#define Model_estimate(in, ...) (in).estimate((in), __VA_ARGS__)
#define Model_copy(in, ...) (in).copy((in), __VA_ARGS__)
```

My preferred alternative is a dispatch function, a thin wrapper function that solves this redundancy annoyance and provides one more benefit over the simple macros shown: defaults. Let us say that we have no estimation routine for a given model. Given a log likelihood function we could use maximum likelihood techniques to estimate the parameters (that is, *blahblahblah*). The default function would look much like the specific estimation routines earlier. Here is a mock-up, making use of a presumed `log_likelihood` method added to the struct:

```
model_s default_estimation(model_s *in, data_s *d){
    model_s *outmodel = _model_copy(in);
    //math making use of additional in->log_likelihood element here
    return outmodel;
}
```

Now for the dispatch function:

```
model_s * model_estimate(model_s *p, data_s *d){
    //Place error checking here.
    if (p->estimate) return p->estimate(p, d);
    else return default_estimation(p, d);
}
```

Usage:

```
model_s normal_model = {.estimate = normal_est};
model_s ad_hoc_model = {.log_likelihood = ad_hoc_ll};

model_s *norm_est = model_estimate(&normal_model, data);
model_s *adhoc_est = model_estimate(&ad_hoc_model, data);
```

We have achieved a homogeneous form out of still more heterogeneous parts—a model structure's `estimate` function could be `NULL` and we can still call the same `model_estimate` function, though the default will need to have a `.log_likelihood` element.

So dispatch functions gave us default routines, solved the annoyance of not having a magic `this` or `self` variable, and did so in a manner that looks similar to the usual interface functions like `model_copy` or `model_free`.

There are other ways to do it. Earlier, I used designated initializers to set up the functions, so unspecified elements are `NULL` and a dispatch function makes sense. If we required that users always use a `model_new` function, then we could set the default functions there. Then eliminating the redundancy of ***`mymodel`***`.estimate(`***`mymodel`***, ***`data`***) can be done by a simple macro, as previously.

Once again, you've got options. We already have more than enough syntactic tools to uniformly call diverse functions for diverse objects. That just leaves the hard part of writing those diverse functions so that calling them in a uniform manner always behaves as expected.

Count References

The remainder of this chapter presents a few more examples of building objects, and how we can modify the boilerplate new/copy/free functions to handle nontrivial situations. As already noted, the examples are going to be more involved, taking into account more real-world considerations and doing something interesting.

The first example presents a small library that has one structure to speak of, which is intended to read an entire file into a single string. Having all of *Moby Dick* in a single string in memory is not a big deal at all, but having a thousand copies of it floating around starts to be wasteful. So instead of copying the potentially very long data string, we'll have views that just mark different start and end points.

Now that we have several views of the string, we need to free the string exactly once, when the string no longer has any views attached. Thanks to the object framework, it's easy to make this happen.

The second example, an agent-based microsimulation of group formation, has a similar problem: the groups should exist as long as they have members, and need to be freed if and when the last member leaves.

Example: A Substring Object

The trick to having a lot of objects pointing to the same string is to add a reference count element to the structure. Modify the four boilerplate elements as follows:

- The type definition includes a pointer-to-integer named `refs`. It will be set up only once (via the `new` function), and all copies (made via the `copy` function) will share the string and this reference counter.
- The `new` function sets up the `refs` pointer and sets `*refs = 1`.
- The `copy` function copies the original struct into the output copy and increments the reference count.
- The `free` function decrements the reference count and, if it has hit zero, frees the shared string.

Example 11-11 provides the header for the string manipulation example, *fstr.h*, which introduces the key structure representing a segment of a string and an auxiliary structure representing a list of these string segments.

Example 11-11. The public tip of the iceberg (fstr.h)

```
#include <stdio.h>
#include <stdlib.h>
#include <glib.h>

typedef struct {          ❶
    char *data;
    size_t start, end;
    int* refs;
} fstr_s;

fstr_s *fstr_new(char const *filename);
fstr_s *fstr_copy(fstr_s const *in, size_t start, size_t len);
void fstr_show(fstr_s const *fstr);
void fstr_free(fstr_s *in);

typedef struct {          ❷
    fstr_s **strings;
    int count;
} fstr_list;
```

```
fstr_list fstr_split (fstr_s const *in, gchar const *start_pattern);
void fstr_list_free(fstr_list in);
```

❶ I hope these headers are starting to get boring for you. It's just the same typdef/new/copy/free over and over again.

❷ The `fstr_list` struct had originally been intended to be a throwaway, not quite a full object, but I found myself using it to organize much of the code. Such accidental falling upon structure is a good thing, and we should encourage it. Notice that the `fstr_split` function returns the list, not a pointer to the list.

Example 11-12 shows the library, *fstr.c*. It uses GLib to read in the text file and for Perl-compatible regular expression parsing. The numbered callouts focus on the steps at the head of this section, so you can follow them to trace the use of the `refs` element to implement reference counting.

Example 11-12. An object representing a substring (fstr.c)

```
#include "fstr.h"
#include "string_utilities.h"

fstr_s *fstr_new(char const *filename){
    fstr_s *out = malloc(sizeof(fstr_s));
    *out = (fstr_s){.start=0, .refs=malloc(sizeof(int))};          ❶
    out->data = string_from_file(filename);
    out->end = out->data ? strlen(out->data) : 0;
    *out->refs = 1;
    return out;
}

/** Make a new fstr_s that is a substring of the input fstr_s.
\param in    The parent string.
\param start The offset in the original string where the substring starts.
\param len   The length of the substring. If longer than the available text,
                 the substring will only go to the end of the parent string.
*/
fstr_s *fstr_copy(fstr_s const *in, size_t start, size_t len){     ❷
    fstr_s *out = malloc(sizeof(fstr_s));
    *out=*in;
    out->start += start;
    if (in->end > out->start + len)
        out->end = out->start + len;
    (*out->refs)++;                                                ❸
    return out;
}

void fstr_free(fstr_s *in){                                        ❹
    (*in->refs)--;
    if (!*in->refs) {
        free(in->data);
        free(in->refs);
    }
```

```
    free(in);
}

/** Split an input string into a sequence of substrings
\param in             The input string to split.
\param start_pattern  The regex marking the beginning of a new substring.
\return               A list of substrings.
*/
fstr_list fstr_split (fstr_s const *in, gchar const *start_pattern){
    fstr_s **out=malloc(sizeof(fstr_s*));
    int outlen = 1;
    out[0] = fstr_copy(in, 0, in->end);
    GRegex *start_regex = g_regex_new (start_pattern, 0, 0, NULL);
    gint mstart=0, mend=0;
    fstr_s *remaining = fstr_copy(in, 0, in->end);
    do {
        GMatchInfo *start_info;
        g_regex_match(start_regex, &remaining->data[remaining->start],
                                    0, &start_info);
        g_match_info_fetch_pos(start_info, 0, &mstart, &mend);
        g_match_info_free(start_info);
        if (mend > 0 && mend < remaining->end - remaining->start){ ❺
            out = realloc(out, ++outlen * sizeof(fstr_s*));
            out[outlen-1] = fstr_copy(remaining, mend, remaining->end-mend);
            out[outlen-2]->end = remaining->start + mstart;
            remaining->start += mend;
        } else break;
    } while (1);
    fstr_free(remaining);
    g_regex_unref(start_regex);
    return (fstr_list){.strings=out, .count=outlen};
}

void fstr_list_free(fstr_list in){
    for (int i=0; i < in.count; i++) fstr_free(in.strings[i]);
    free(in.strings);
}

void fstr_show(fstr_s const *fstr){
    printf("%.*s", (int)fstr->end-fstr->start, &fstr->data[fstr->start]);
}
```

❶ For a new `fstr_s`, the reference count is set to one. Otherwise, this function is a boilerplate new object function.

❷ The copy function copies the `fstr_s` sent in, and sets the start and endpoints to the substring given (making sure that the endpoint doesn't go past the endpoint of the input `fstr_s`).

❸ Here's where the reference count gets incremented.

❹ Here's where the reference count gets used, to determine whether the base data should be freed or not.

❺ Else, no match or out of bounds.

And finally, an application. To make this work, you'll need a copy of *Moby Dick, or the Whale*, by Herman Melville. If you don't have a copy on your drive, try Example 11-13 to download one from Project Gutenberg.

Example 11-13. Use curl to get the Project Gutenberg edition of Moby Dick, then use sed to cut the Gutenberg header and footer; you might have to ask your package manger to install curl (find.moby)

```
if [ ! -e moby ] ; then
 curl -A "Mozilla/4.0" http://www.gutenberg.org/cache/epub/2701/pg2701.txt  \
     | sed -e '1,/START OF THIS PROJECT GUTENBERG/d'       \
     | sed -e '/End of Project Gutenberg/,$d'              \
     > moby
fi
```

Now that you have a copy of the book, Example 11-15 splits it into chapters and uses the same splitting function to count the uses of the words *whale(s)* and *I* in each chapter. Notice that the `fstr` structs can be used as opaque objects at this point, using only the new, copy, free, show, and split functions.

The program requires GLib, *fstr.c*, and the string utilities from earlier in the book, so the basic makefile is now as in Example 11-14.

Example 11-14. A sample make file for the cetology program (cetology.make)

```
P=cetology
CFLAGS=`pkg-config --cflags glib-2.0` -g -Wall -std=gnu99 -O3
LDLIBS=`pkg-config --libs glib-2.0`
objects=fstr.o string_utilities.o

$(P): $(objects)
```

Example 11-15. An example, in which a book is split into chapters and characteristics of each chapter counted (cetology.c)

```
#include "fstr.h"

int main(){
    fstr_s *fstr = fstr_new("moby");
    fstr_list chapters = fstr_split(fstr, "\nCHAPTER");
    for (int i=0; i< chapters.count; i++){
        fstr_list for_the_title=fstr_split(chapters.strings[i],"\\.");
        fstr_show(for_the_title.strings[1]);
        fstr_list me     = fstr_split(chapters.strings[i], "\\WI\\W");
        fstr_list whales = fstr_split(chapters.strings[i], "whale(s|)");
        fstr_list words  = fstr_split(chapters.strings[i], "\\W");
        printf("\nch %i, words: %i.\t Is: %i\twhales: %i\n", i, words.count-1,
                me.count-1, whales.count-1);

        fstr_list_free(for_the_title);
        fstr_list_free(me);
        fstr_list_free(whales);
        fstr_list_free(words);
    }
    fstr_list_free(chapters);
```

```
    fstr_free(fstr);
}
```

To give you incentive to try the program, I won't reprint the results in detail. But I will give some notes, which generally point to how hard it would be for Mr. Melville to publish or even blog the book here in the modern day:

- Chapter lengths range by an order of magnitude.
- Whales don't get discussed all that much until around Chapter 30.
- The narrator decidedly has a voice. Even in the famed cetology chapter, he uses the first person singular 60 times, personalizing what would otherwise be an encyclopedia chapter.
- GLib's regex parser is a little slower than I'd hoped it'd be.

An Agent-Based Model of Group Formation

This example is an agent-based model of group membership. Agents are on a two-dimensional preference space (because we'll plot the groups) in the square between (-1, -1) and (1, 1). At each round, agents will join the group with the best utility to the agent. An agent's utility from a group is -(distance to group's mean position + *M**number of members). The group's mean position is the mean of the positions of the group's members (excluding the agent querying the group), and *M* is a constant that scales how much the agents care about being in a large group relative to how much they care about the group's mean position: if *M* is near zero, then size of group is basically irrelevant, and agents care only about proximity; as *M* goes to infinity, position becomes irrelevant, and only group size matters.

With some random odds, the agent will originate a new group. However, because agents are picking a new group every period, the agent may abandon that newly originated group in the next period.

The problem of reference counting is similar, and the process is roughly similar for this case:

- The type definition includes an integer named `counter`.
- The `new` function sets `counter = 1`.
- The `copy` function sets `counter++`.
- The free function queries `if(--counter==0)`, and if yes, then `free` all shared data; or else, just leave everything as is, because we know there are still references to the structure.

Again, as long as your changes to the structure are entirely via its interface functions, you don't have to think about memory allocation when using the object at all.

The simulation takes almost 125 lines of code, and because I used CWEB to document it, the code files total almost double that length (where I gave some tips on reading and writing CWEB in "Literate Code with CWEB" on page 45). Given the literate coding style, this should be very readable; even if you're in the habit of skipping big blocks of code, maybe give it a skim. If you have CWEB on hand, you can generate the PDF documentation and try reading it in that format.

The output from this program is intended to be piped to Gnuplot, a plotting program that stands out for being easy to automate. Here is a command-line script that uses a here document to pipe the given text to Gnuplot, including a series of data points (with an `e` to mark the end of the series).

```
cat << "------" | gnuplot --persist
set xlabel "Year"
set ylabel "U.S. Presidential elections"
set yrange [0:5]
set key off
plot '-' with boxes
2000, 1
2001, 0
2002, 0
2003, 0
2004, 1
2005, 0
e
------
```

You can probably already picture producing commands to Gnuplot programmatically, via a `printf` or two for the plot settings, and a `for` loop to output the data set. Further, sending a series of plots to Gnuplot generates an animation sequence.

The simulation below produces an animation like this, so you can run the simulation via `./groups | gnuplot` to display the animation on-screen. It's hard to print an animation, so you'll have to run it yourself. You will see that, even though such behavior was not programmed into the simulation, new groups cause nearby groups to shift, producing an evenly-spaced, uniform distribution of group positions. Political scientists have often observed similar behavior in the space of political party positions: when new parties enter, existing parties adjust their positions accordingly.

Now for the header. What I call the join and exit functions might more commonly be read as the copy and free functions. The `group_s` structure has a `size` element, which is the number of group members—the reference count. You can see that I use Apophenia and GLib. Notably, the groups are held in a linked list, private to the *groups.c* file; maintaining that list will require fully two lines of code, including a call to `g_list_append` and `g_list_remove` (Example 11-16).

Example 11-16. The public portion of the `group_s` *object. (groups.h)*

```
#include <apop.h>
#include <glib.h>

typedef struct {
    gsl_vector *position;
```

```
    int id, size;
} group_s;

group_s* group_new(gsl_vector *position);
group_s* group_join(group_s *joinme, gsl_vector *position);
void group_exit(group_s *leaveme, gsl_vector *position);
group_s* group_closest(gsl_vector *position, double mb);
void print_groups();
```

Now for the file defining the details of the group object (shown in Example 11-17).

Example 11-17. The **group_s** *object. (groups.w)*

```
@ Here in the introductory material, we include the header and specify
the global list of groups that the program makes use of. We'll need
new/copy/free functions for each group.

@c
#include "groups.h"

GList *group_list;
@<new group@>
@<copy group@>
@<free group@>

@ The new group method is boilerplate: we |malloc| some space,
fill the struct using designated initializers, and append the newly-formed
group to the list.

@<new group@>=
group_s *group_new(gsl_vector *position){
    static int id=0;
    group_s *out = malloc(sizeof(group_s));
    *out = (group_s) {.position=apop_vector_copy(position), .id=id++, .size=1};
    group_list = g_list_append(group_list, out);
    return out;
}

@ When an agent joins a group, the group is `copied' to the agent, but
there isn't any memory being copied: the group is simply modified to
accommodate the new person. We have to increment the reference count, which
is easy enough, and then modify the mean position.  If the mean position
without the $n$th person is $P_{n-1}$, and the $n$th person is at position
$p$, then the new mean position with the person, $P_n$ is the weighted sum.

$$P_n = \left( (n-1)P_{n-1}/n \right) + p/n.$$

We calculate that for each dimension.

@<copy group@>=
group_s *group_join(group_s *joinme, gsl_vector *position){
   int n = ++joinme->size;  //increment the reference count
   for (int i=0; i< joinme->position->size; i++){
       joinme->position->data[i] *= (n-1.)/n;
       joinme->position->data[i] += position->data[i]/n;
```

```
    }
    return joinme;
}

@ The `free' function really only frees the group when the reference count
is zero. When it isn't, then we need to run the data-augmenting formula
for the mean in reverse to remove a person.

@<free group@>=
void group_exit(group_s *leaveme, gsl_vector *position){
    int n = leaveme->size--;  //lower the reference count
    for (int i=0; i< leaveme->position->size; i++){
        leaveme->position->data[i] -= position->data[i]/n;
        leaveme->position->data[i] *= n/(n-1.);
    }
    if (leaveme->size == 0){ //garbage collect?
        gsl_vector_free(leaveme->position);
        group_list= g_list_remove(group_list, leaveme);
        free(leaveme);
    }
}

@ I played around a lot with different rules for how exactly people
evaluate the distance to the groups. In the end, I wound up using the $L_3$
norm. The standard distance is the $L_2$ norm, aka Euclidian distance,
meaning that the distance between $(x_1, y_1)$ and $(x_2, y_2)$ is
$\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}$. This is $L_3$,
$\sqrt[3]{(x_1-x_2)^3+(y_1-y_2)^3}$.
This and the call to |apop_copy| above are the only calls to the Apophenia
library; you could write around them if you don't have that library on hand.

@<distance@>=
apop_vector_distance(g->position, position, .metric='L', .norm=3)

@ By `closest', I mean the group that provides the greatest benefit,
by having the smallest distance minus weighted size. Given the utility
function represented by the |dist| line, this is just a simple |for|
loop to find the smallest distance.

@c
group_s *group_closest(gsl_vector *position, double mass_benefit){
    group_s *fave=NULL;
    double smallest_dist=GSL_POSINF;
    for (GList *gl=group_list; gl!= NULL; gl = gl->next){
        group_s *g = gl->data;
        double dist= @<distance@> - mass_benefit*g->size;
        if(dist < smallest_dist){
            smallest_dist = dist;
            fave = g;
        }
    }
    return fave;
}
```

```
@ Gnuplot is automation-friendly. Here we get an animated simulation with
four lines of plotting code. The header |plot '-'| tells the system to plot
the data to follow, then we print the $(X, Y)$ positions, one to a line. The
final |e| indicates the end of the data set. The main program will set some
initial Gnuplot settings.

@c
void print_groups(){
    printf("plot '-' with points pointtype 6\n");
    for (GList *gl=group_list; gl!= NULL; gl = gl->next)
        apop_vector_print(((group_s*)gl->data)->position);
    printf("e\n");
}
```

Now that we have a group object and interface functions to add, join, and leave groups, the program file can focus on the simulation procedure: defining the array of persons followed by the main loop of rechecking memberships and printing out (Example 11-18).

Example 11-18. The agent-based model, making use of the **`group_s`** *object (groupabm.w)*

```
@* Initializations.

@ This is the part of the agent-based model with the handlers for the
|people| structures and the procedure itself.

At this point all interface with the groups happens via the
new/join/exit/print functions from |groups.cweb.c|. Thus, there is zero
memory management code in this file--the reference counting guarantees us
that when the last member exits a group, the group will be freed.

@c
#include "groups.h"

int pop=2000,
    periods=200,
    dimension=2;

@ In |main|, we'll initialize a few constants that we can't have as static
variables because they require math.

@<set up more constants@>=
    double  new_group_odds = 1./pop,
            mass_benefit = .7/pop;
    gsl_rng *r = apop_rng_alloc(1234);

@* The |person_s| structure.

@ The people in this simulation are pretty boring: they do not die, and do
not move. So the struct that represents them is simple, with just |position|
and a pointer to the group of which the agent is currently a member.

@c
typedef struct {
```

```
    gsl_vector *position;
    group_s *group;
} person_s;

@ The setup routine is also boring, and consists of allocating a uniform
random vector in two dimensions.

@c
person_s person_setup(gsl_rng *r){
    gsl_vector *posn = gsl_vector_alloc(dimension);
    for (int i=0; i< dimension; i++)
        gsl_vector_set(posn, i, 2*gsl_rng_uniform(r)-1);
    return (person_s){.position=posn};
}

@* Group membership.

@ At the outset of this function, the person leaves its group.
Then, the decision is only whether to form a new group or join an existing one.

@c
void check_membership(person_s *p, gsl_rng *r,
                        double mass_benefit, double new_group_odds){
    group_exit(p->group, p->position);
    p->group = (gsl_rng_uniform(r) < new_group_odds)
             ? @<form a new group@>
             : @<join the closest group@>;
}

@
@<form a new group@>=
group_new(p->position)

@
@<join the closest group@>=
group_join(group_closest(p->position, mass_benefit), p->position)

@* Setting up.

@ The initialization of the population. Using CWEB's macros, it is at this point
self-documenting.

@c
void init(person_s *people, int pop, gsl_rng *r){
    @<position everybody@>
    @<start with ten groups@>
    @<everybody joins a group@>
}

@
@<position everybody@>=
    for (int i=0; i< pop; i++)
        people[i] = person_setup(r);
```

```
@ The first ten people in our list form new groups, but because everybody's
position is random, this is assigning the ten groups at random.

@<start with ten groups@>=
    for (int i=0; i< 10; i++)
        people[i].group = group_new(people[i].position);

@
@<everybody joins a group@>=
    for (int i=10; i< pop; i++)
        people[i].group = group_join(people[i%10].group, people[i].position);

@* Plotting with Gnuplot.

@ This is the header for Gnuplot. I arrived at it by playing around on
Gnuplot's command line, then writing down my final picks for settings here.

@<print the Gnuplot header@>=
printf("unset key;set xrange [-1:1]\nset yrange [-1:1]\n");

@ Gnuplot animation simply consists of sending a sequence of plot statements.
@<plot one animation frame@>=
print_groups();

@* |main|.

@ The |main| routine consists of a few setup steps, and a simple loop:
calculate a new state, then plot it.

@c
int main(){
    @<set up more constants@>
    person_s people[pop];
    init(people, pop, r);

    @<print the Gnuplot header@>
    for (int t=0; t< periods; t++){
        for (int i=0; i< pop; i++)
            check_membership(&people[i], r, mass_benefit, new_group_odds);
        @<plot one animation frame@>
    }
}
```

CHAPTER 12
Libraries

> And if I really wanted to learn something I'd listen to more records.
> And I do, we do, you do.
>
> —The Hives, "Untutored Youth"

This chapter will cover a few libraries that will make your life easier.

My impression is that C libraries have grown less pedantic over the years. Ten years ago, the typical library provided the minimal set of tools necessary for work, and expected you to build convenient and programmer-friendly versions from those basics. The typical library would require you to perform all memory allocation, because it's not the place of a library to grab memory without asking. Conversely, the libraries presented in this chapter all provide an "easy" interface, like `curl_easy_...` functions for cURL, Sqlite's single function to execute all the gory steps of a database transaction, or the three lines of code we need to set up a mutex via GLib. If they need intermediate workspaces to get the work done, they just do it. They are fun to use.

I'll start with somewhat standard and very general libraries, and move on to a few of my favorite libraries for more specific purposes, including SQLite, the GNU Scientific Library, libxml2, and libcURL. I can't guess what you are using C for, but these are friendly, reliable systems for doing broadly applicable tasks.

GLib

Given that the standard library left so much to be filled in, it is only natural that a library would eventually evolve to fill in the gaps. GLib implements enough basic computing needs that it will pass the first year of CompSci for you, is ported to just about everywhere (even POSIX-less editions of Windows), and is at this point stable enough to be relied on.

I'm not going to give you sample code for the GLib, because I've already given you several samples:

- The lighting-quick intro to linked lists in Example 2-2.
- A test harness, in "Unit Testing" on page 39.
- Unicode tools, in "Unicode" on page 156.
- Hashes, in "Generic Structures" on page 192.
- Reading a text file into memory, in "Count References" on page 219.
- Perl-compatible regular expression parsing, also in the section "Count References" on page 219.

And over the next few pages, I'll mention GLib's contributions for:

- Wrapping `mmap` for both POSIX and Windows, in "Using mmap for Gigantic Data Sets" on page 232.
- Mutexes, in "Easy Threading with Pthreads" on page 234.

There's more: if you are writing a mouse-and-window program, then you will need an event loop to catch and dispatch mouse and keyboard events; GLib provides this. There are file utilities that do the right thing on POSIX and non-POSIX (i.e., Windows) systems. There's a simple parser for configuration files, and a lightweight lexical scanner for more complex processes. Et cetera.

POSIX

The POSIX standard adds several useful functions to the standard C library. Given how prevalent POSIX is, they are worth getting to know.

Using mmap for Gigantic Data Sets

I've mentioned the three types of memory (static, manual, and automatic), and here's a fourth: disk based. With this type, we take a file on the hard drive and map it to a location in memory using `mmap`.

This is often how shared libraries work: the system finds *libwhatever.so*, assigns a memory address to the segment of the file representing a needed function, and there you go: you've loaded a function into memory.

Or, we could share data across processes by having them both `mmap` the same file.

Or, we could use this to save data structures to memory. `mmap` a file to memory, use `memmove` to copy your in-memory data structure to the mapped memory, and it's stored for next time. Problems come up when your data structure has a pointer to another data structure; converting a series of pointed-to data structures to something savable is the *serialization* problem, which I won't cover here.

And, of course, there's dealing with data sets too large to fit in memory. The size of an `mmap`ed array is constrained by the size of your disk, not memory.

Example 12-1 presents sample code. The `load_mmap` routine does most of the work. If used as a `malloc`, then it needs to create the file and stretch it to the right size; if you are opening an already-existing file, it just has to be opened and `mmap`ed.

Example 12-1. A file on disk can be mapped transparently to memory (mmap.c)

```
#include <stdio.h>
#include <unistd.h> //lseek, write, close
#include <stdlib.h> //exit
#include <fcntl.h>  //open
#include <sys/mman.h>
#include "stopif.h"

#define Mapmalloc(number, type, filename, fd) \                        ❶
            load_mmap((filename), &(fd), (number)*sizeof(type), 'y')
#define Mapload(number, type, filename, fd)   \
            load_mmap((filename), &(fd), (number)*sizeof(type), 'n')
#define Mapfree(number, type, fd, pointer)    \
            releasemmap((pointer), (number)*sizeof(type), (fd))

void *load_mmap(char const *filename, int *fd, size_t size, char make_room){ ❷
    *fd=open(filename,
            make_room=='y' ?  O_RDWR | O_CREAT | O_TRUNC : O_RDWR,
            (mode_t)0600);
    Stopif(*fd==-1, return NULL, "Error opening file");

    if (make_room=='y'){ // Stretch the file size to the size of the (mmapped) array
        int result=lseek(*fd, size-1, SEEK_SET);
        Stopif(result==-1, close(*fd); return NULL, "Error stretching file with lseek");
        result=write(*fd, "", 1);
        Stopif(result!=1, close(*fd); return NULL, "Error writing last byte of the file");
    }

    void *map=mmap(0, size, PROT_READ | PROT_WRITE, MAP_SHARED, *fd, 0);
    Stopif(map==MAP_FAILED, return NULL, "Error mmapping the file");
    return map;
}

int releasemmap(void *map, size_t size, int fd){                         ❸
    Stopif(munmap(map, size) == -1, return -1, "Error un-mmapping the file");
    close(fd);
    return 0;
}

int main(int argc, char *argv[]) {
    int fd;
    long int N=1e5+6;
    int *map = Mapmalloc(N, int, "mmapped.bin", fd);

    for (long int i = 0; i <N; ++i) map[i] = i;                          ❹

    Mapfree(N, int, fd, map);

    //Now reopen and do some counting.
    int *readme = Mapload(N, int, "mmapped.bin", fd);
```

```
    long long int oddsum=0;
    for (long int i = 0; i <N; ++i) if (readme[i]%2) oddsum += i;
    printf("The sum of odd numbers up to %li: %lli\n", N, oddsum);

    Mapfree(N, int, fd, readme);
}
```

❶ I wrapped the functions that follow in macros so you don't have to type `sizeof` every time, and won't have to remember how to call `load_mmap` when allocating versus when loading.

❷ The macros hide that this function gets called two different ways. If only reopening existing data, the file gets opened, `mmap` gets called, the results are checked, and that's all. If called as an allocate function, we need to stretch the file to the right length.

❸ Releasing the mapping requires using `munmap`, which is akin to `malloc`'s friend `free`, and closing the file handle. The data is left on the hard drive, so when you come back tomorrow you can reopen it and continue where you left off. If you want to remove the file entirely, use `unlink("`*`filename`*`")`.

❹ The payoff: you can't tell `map` is on disk and not in the usual memory.

Final details: the `mmap` function is POSIX-standard, so it is available everywhere but Windows boxes and some embedded devices. In Windows, you can do the identical thing but with different function names and flags; see `CreateFileMapping` and `MapViewOfFile`. GLib wraps both `mmap` and the Windows functions in an *if POSIX … else if Windows …* construct and names the whole thing `g_mapped_file_new`.

Easy Threading with Pthreads

If your computer is less than about five years old and is not a telephone, then it has several *cores*, which are independent pipelines for processing. How many cores do you have? To find out, run the following:

- Linux: `grep cores /proc/cpuinfo`.
- Mac: `sysctl hw.logicalcpu`.
- Cygwin: `env | grep NUMBER_OF_PROCESSORS`.

Threading is billed as a complex and arcane topic, but when I first implemented threads in a program, I was delighted by how easy it is to get a serial loop to become a set of parallel threads. It's not the syntax; the hard part is in dealing with the details of how threads interact.

The simplest case, sometimes called a process that is *embarrassingly parallel*, is when you are applying the same task to every element of an array, and each is independent of the other. Any shared data is used read-only. As per the nickname for this kind of thing, this is the easy case, and I'll show you the syntax for making it work next.

Variant Threads

POSIX threads work for the multiple cores on a single machine. If you need to cross computers (such as multiple blades on a server), then you need the Message Passing Interface (MPI) library.

C11 adds a C-standard thread library and atomic variables.

If the new thread doesn't share a great deal of data with the main part of the program, then it might be easier to use the POSIX-standard `fork` to split off a subprocess rather than use threads. For example, you might want to use `fork` to write a file to disk, so the main program isn't waiting for the disk to do its thing.

The first complication is when there is some resource that is writable and is shared across threads. Let us say that we have two threads doing some simple arithmetic:

```
int a=0;

//Thread 1:
a++;
a*=2;
printf("T1: %i\n", a);

//Thread 2:
printf("T2: %i\n", a);
a++;
```

It's anybody's guess what this might print. Maybe thread two will run first, so we'll get:

```
T2: 0
T1: 4
```

It is not impossible for the commands in the threads to alternate, like so:

```
a++;                    //T1
printf("T2: %i\n", a);  //T2, prints T2: 1
a*=2;                   //T1
a++;                    //T2
printf("T1: %i\n", a);  //T1, prints T1: 3
```

It gets worse, because a single line of C like `a++` can consist of several machine instructions, and we have no idea what `a` looks like halfway through an increment.

A *mutex* locks a resource (here, `a`) while in use by one thread, and tells the other threads that want to use the resource to hold on until the prior thread is done and releases the lock.

When you have multiple mutexes that may interact, then you're up to rocket science. It's easy for threads to get into states where both are waiting for the other to release a mutex or some other odd case occurs that causes the threads to trample each other, and debugging this sort of thing is now a question of the luck of replicating the surprising order of execution when the debugger is running. But the simple stuff here will already be enough for you to safely speed up your code.

The pthreads checklist

You have a `for` loop over elements, such as an operation on every element of an array. As earlier, no one iteration of the loop has any bearing on any other. If the iterations were somehow run in random order, you wouldn't care, as long as every array element gets hit once and only once.

We're going to turn that serial `for` loop into parallel threads. We are going to convert the body of the loop (one iteration) into a function that will be applied to each element of the array, using `pthread_create`, and then use `pthread_join` to wait for each thread to return. At the end of that disperse/gather procedure, the program can continue as if nothing special had happened.

- For gcc, Clang, or Intel, add `-pthread` to the compiler line.
- `#include <pthreads.h>`.
- Write a wrapper function, which will be called by every thread. It has to have a signature of the form `void * your_function (void *)`. That is, it takes one void pointer in and spits one void pointer out. If you started with a `for` loop, paste the body of the loop into this wrapper, and do the appropriate surgery so that you are acting on the function input instead of element *i* of the array.
- Disperse the threads: your `for` loop now applies `pthread_create` to each array element. See the following example.
- Gather the threads: Write a second `for` loop to call `pthread_join` to gather all of the threads and check their return values.

Example 12-3 presents an example. I am sorry to say that it is a word counter, which is such a typical example. However, it's at least a zippy one, which runs about 3x faster than `wc`. (The definitions of a word also differ, so it'll be hard to seriously compare, though.) The focus is on the implementation of the preceding gather/disperse procedure.

I use the string utilities from Example 9-5, and that will need GLib. At this point, the makefile is as in Example 12-2.

*Example 12-2. A makefile for pthreads and GLib; the **`gthread-2.0`** part is necessary only if you are using GLib's mutexes (pthreads.make)*

```
P=pthreads
objects=string_utilities.o
# To use Glib mutexes, some systems will require both glib-2.0 and gthread-2.0.
CFLAGS=`pkg-config --cflags glib-2.0` -g -Wall -std=gnu99 -O3 -pthread
LDLIBS=`pkg-config --libs glib-2.0` -lpthread

$(P): $(objects)
```

Example 12-3. Given a list of filenames on the command line, simultaneously count words in each (pthreads.c)

```
#include "stopif.h"
#include "string_utilities.h"
#include <pthread.h>

typedef struct{
    int wc;
    char *docname;
} wc_struct;

void *wc(void *voidin){
    wc_struct *in = voidin;                                          ❶
    char *doc = string_from_file(in->docname);                       ❷
    if (!doc) return NULL;   // in->wc remains zero.
    char *delimiters = " `~!@#$%^&*()_-+={[]}|\\;:\",<>./?\n";
    ok_array *words = ok_array_new(doc, delimiters);                 ❸
    if (!words) return NULL;
    in->wc = words->length;
    ok_array_free(words);
    return NULL;
}

int main(int argc, char **argv){
    argc--;
    argv++;                                                          ❹
    Stopif(!argc, return 0, "Please give some file names on the command line.");
    pthread_t threads[argc];
    wc_struct s[argc];
    for (int i=0; i< argc; i++){
        s[i] = (wc_struct){.docname=argv[i]};
        pthread_create(&threads[i], NULL, wc, &s[i]);                ❺
    }

    for (int i=0; i< argc; i++) pthread_join(threads[i], NULL);     ❻

    for (int i=0; i< argc; i++) printf("%s:\t%i\n",argv[i], s[i].wc);
}
```

❶ As discussed in "The Void Pointer and the Structures It Points To" on page 188, the throwaway typedef, `wc_struct`, adds immense safety. I still have to be careful to write the inputs and outputs to the pthread system correctly, but the internals of the struct get type-checked, both in `main` and here in the wrapper function. Next week, when I change `wc` to a `long int`, the compiler will warn me if I don't do the change correctly.

❷ `string_from_file` reads the given document into a string, and is borrowed from the string utilities in Example 9-5.

❸ Also borrowed from the string utility library, this function divides a string at the given delimiters. We just want the count from it.

❹ `argv[0]` is the name of the program, so we step the `argv` pointer past it. The rest of the arguments on the command line are files to be word-counted.

❺ This is the thread creation step. We set up a list of thread info pointers, and then we send to `pthread_create` one of those, the wrapper function, and an item to send in to the wrapper function. Don't worry about the second argument, which controls some threading attributes.

❻ This second loop gathers outputs. The second argument to `pthread_join` is an address where we could write the output from the threaded function (`wc`). I cheat and just write the output to the input structure, which saves some `malloc`ing; if you think the program would be more readable if there were a separate output struct, I would not bicker with you.

At the end of this loop, the threads have all been gathered, and the program is once again single-threaded.

> **Your Turn:** Now that you have the form down (or at least, you have a template you can cut and paste), check your code for embarrassingly parallel loops, and thread 'em.
>
> Earlier, I gave each row of an array one thread; how would you split something into a more sensible number, like two or three threads? Hint: you've got a struct, so you can send in extra info, like start/endpoints for each thread.

Protect threaded resources with mutexes

What about the case where some resource may be modified by some of the threads? We can retain consistency via the *mutex*, which provides mutual exclusion. We will provide one mutex for each resource to be shared, such as a read/write variable *`i`*. Any thread may lock the mutex, so that when other threads try to claim the mutex, they are locked out and have to wait. So, for example:

- The write thread claims the mutex for *`i`* and begins writing.
- The read thread tries to claim the mutex, is locked out.
- The write thread keeps writing.
- The read thread pings the mutex—Can I come in now? It is rejected.
- The write thread is done and releases the mutex.
- The read thread pings the mutex, and is allowed to continue. It locks the mutex.
- The write thread is back to write more data. It pings the mutex, but is locked out, and so has to wait.

Et cetera. The read thread is guaranteed that there won't be shenanigans about transistors in memory changing state mid-read, and the write thread is similarly guaranteed that things will be clean.

So any time we have a resource, like stdout or a variable, at least one thread that wants to modify the resource, and one or more threads that will read or write the resource, we will attach a mutex to the resource. At the head of each thread's code to use the resource, we lock the mutex; at the end of that block of code, we release the mutex.

What if one thread never gives up a mutex? Maybe it's caught in an infinite loop. Then all the threads that want to use that mutex are stuck at the step where they are pinging the mutex over and over, so if one thread is stuck, they all are. In fact, *stuck pinging a mutex that is never released* sounds a lot like an infinite loop. If thread *A* has locked mutex 1 and is waiting for mutex 2, and thread *B* has locked mutex 2 and is waiting for mutex 1, you've got a deadlock.

If you are starting out with threading, I recommend that any given block of code lock one mutex at a time. You can often make this work by just associating a mutex with a larger block of code that you might have thought deserved multiple mutexes.

The example

Let us rewrite the `wc` function from earlier to increment a global counter along with the counters for each thread. If you throw a lot of threads at the program, you'll be able to see if they all get equal time or run in serial despite our best efforts. The natural way to maintain a global count is by tallying everything at the end, but this is a simple and somewhat contrived example, so we can focus on wiring up the mutex.

If you comment the mutex lines, you'll be able to watch the threads walking all over each other. To facilitate this, I wrote:

```
for (int i=0; i< out->wc; i++) global_wc++;
```

which is entirely equivalent to:

```
global_wc += out->wc;
```

but takes up more processor time.

You may need to add `gthread-2.0` to the makefile above to get this running.

All of the mutex-oriented changes were inside the function itself. By allocating a mutex to be a static variable, all threads see it. Then, each thread by itself tries the lock before changing the global word count, and unlocks when finished with the shared variable.

Example 12-4 presents the code.

Example 12-4. All the word counts run at once (mutex_wc.c)

```
#include "string_utilities.h"
#include <pthread.h>
#include <glib.h> //mutexes

long int global_wc;

typedef struct{
    int wc;
    char *docname;
} wc_struct;
```

```
void *wc(void *voidin){
    wc_struct *in = voidin;
    char *doc = string_from_file(in->docname);
    if (!doc) return NULL;
    static GMutex count_lock;      ❶

    char *delimiters = " `~!@#$%^&*()_-+={[]}|\\;:\",<>./?\n\t";
    ok_array *words = ok_array_new(doc, delimiters);
    if (!words) return NULL;
    in->wc = words->length;
    ok_array_free(words);
    g_mutex_lock(&count_lock);     ❷
    for (int i=0; i< in->wc; i++)
        global_wc++; //a slow global_wc += in->wc;
    g_mutex_unlock(&count_lock);   ❸
    return NULL;
}

int main(int argc, char **argv){
    argc--;
    argv++; //step past the name of the program.

    pthread_t threads[argc];
    wc_struct s[argc];
    for (int i=0; i< argc; i++){
        s[i] = (wc_struct){.docname=argv[i]};
        pthread_create(&threads[i], NULL, wc, &s[i]);
    }

    for (int i=0; i< argc; i++) pthread_join(threads[i], NULL);

    for (int i=0; i< argc; i++) printf("%s:\t%i\n",argv[i], s[i].wc);
    printf("The total: %li\n", global_wc);
}
```

❶ Because the declaration is static, it is shared across all instances of the function. Also, it is initialized to zero.

❷ The next few lines use a variable shared across threads, so this is the appropriate place to set a checkpoint.

❸ Here, we are done with the shared resource, so release the lock. These three marked lines (declare/init, lock, unlock) are all we need for the mutex.

Your Turn: Try this on a few dozen files. I used the complete works of Shakespeare, because I have Gutenberg's Shakespeare broken up by play; I'm sure you've got some files on hand to try out. After you run it as is, comment out the lock/unlock lines, and rerun. Do you get the same counts?

GDB users, add this line to your `.gdbinit` to turn off those annoying notices about new threads:

```
set print thread-events off
```

_Thread_local and static variables

All of the `static` variables in a program, meaning those declared outside of a function plus those inside a function with the `static` keyword, are shared across all threads. Same with anything `malloc`ed (that is, each thread may call `malloc` to produce a pocket of memory for its own use, but any thread that has the address could conceivably use the data there). Automatic variables are specific to each thread.

As promised, here's your fifth type of memory. C11 provides a keyword, `_Thread_local`, that splits off a static variable (either in the file scope or in a function via the `static` keyword) so that each thread has its own version, but the variable still behaves like a static variable when determining scope and not erasing it at the end of a function. The variable is initialized when the threads start and is removed when the threads exit.

C11's new keyword seems to be an emulation of the gcc-specific `__thread` keyword. If this is useful to you, within a function, you can use either of:

```
static __thread int i;      //GCC-specific; works today.
   // or
static _Thread_local int i; //C11, when your compiler implements it.1
```

You can check for which to use via a block of preprocessor conditions, like this one, which sets the string `threadlocal` to the right thing for the given situation.

```
#undef threadlocal
        #ifdef _ISOC11_SOURCE
            #define threadlocal _Thread_local
        #elif defined(__APPLE__)
            #define threadlocal
        #elif defined(__GNUC__) && !defined(threadlocal)
            #define threadlocal __thread
        #else
            #define threadlocal
        #endif

/* The globalstate variable is thread-safe if you are using a C11-compliant
            compiler or the GCC (but not on Macs). Otherwise, good luck. */
        static threadlocal int globalstate;
```

Outside of a function, the `static` keyword is optional, as always.

1. The standard requires a *<threads.h>* header that defines `thread_local`, so you don't need the annoying underscore-capital combination (much like *<bool.h>* defines `bool=_Bool`). But this header isn't yet implemented in any standard libraries I could find.

The GNU Scientific Library

If you ever read somebody asking a question that starts *I'm trying to implement something from Numerical Recipes in C…* [Press 1992], the correct response is almost certainly *download the The GNU Scientific Library (GSL), because they already did it for you* [Gough 2003].

Some means of numerically integrating a function are just better than others, and as hinted in "Deprecate Float" on page 126, some seemingly sensible numeric algorithms will give you answers that are too imprecise to be considered anywhere near correct. So especially in this range of computing, it pays to use existing libraries where possible.

At the least, the GSL provides a reliable random number generator (the C-standard RNG may be different on different machines, which makes it inappropriate for reproducible inquiry), and vector and matrix structures that are easy to subset and otherwise manipulate. The standard linear algebra routines, function minimizers, basic statistics (means and variances), and permutation structure may be of use to you even if you aren't spending all day crunching numbers.

And if you know what an Eigenvector, Bessel function, or Fast Fourier Transform are, then here's where you can get them.

I give an example of the GSL's use in Example 12-5, though you'll notice that the string `gsl_` only appears once or twice in the example. The GSL is a fine example of an old-school library that provides the minimal tools needed and then expects you to build the rest from there. For example, the GSL manual will show you the page of boilerplate you will need to use the provided optimization routines to productive effect. It felt like something the library should do for us, and so I wrote a set of wrapper functions for portions of the GSL, which became *Apophenia*, a library aimed at modeling with data. For example, the `apop_data` struct binds together raw GSL matrices and GSL vectors with row/column names and an array of text data, which brings the basic numeric-processing structs closer to what real-world data looks like. The library's calling conventions look like the modernized forms in Chapter 10.

An optimizer has a setup much like the routines in "The Void Pointer and the Structures It Points To" on page 188, where routines took in any function and used the provided function as a black box. The optimizer tries an input to the given function and uses the output value to improve its next guess for an input that will produce a larger output; with a sufficiently intelligent search algorithm, the sequence of guesses will converge to the function-maximizing input. The procedure is relatively complex (over how many dimensions is the optimizer searching? Is the optimization relative to some reference data set? Which search procedure should the optimizer use?), so the `apop_estimate` function takes in an `apop_model` struct with hooks for the function and the relevant additional information.

In typical use, the reference data set comes from a text file (read via `apop_text_to_data`), and the model struct is a standard model that ships with the library, such as ordinary least squares regression. Example 12-5 sets up an optimization in greater detail. It first presents a `distance` function that calculates the total distance from the parameters in the input model struct and the list of input data points, then declares a model struct holding that function and advice on the input vector's size (and a slot for the optimizer to put its guesses for parameter values), then attaches optimization settings to that model. The data set is prepared in `main`. When all that setup is done, the optimization is a one-line call to `apop_estimate`, which spits out a model struct with its parameters set to the point that minimizes total distance to the input data points.

Example 12-5. Finding the point that minimizes the sum of distances to a set of input points (gsl_distance.c)

```
#include <apop.h>

double one_dist(gsl_vector *v1, void *v2){
    return apop_vector_distance(v1, v2);
}

double distance(apop_data *data, apop_model *model){
    gsl_vector *target = model->parameters->vector;
    return -apop_map_sum(data, .fn_vp=one_dist, .param=target, .part='r');    ❶
}

apop_model min_distance={.name="Minimum distance to a set of input points.",  ❷
    .p=distance, .vbase=-1};                                                  ❸

int main(){
    apop_data *locations = apop_data_fill(                                    ❹
                            apop_data_alloc(5, 2),
                            1.1, 2.2,
                            4.8, 7.4,
                            2.9, 8.6,
                            -1.3, 3.7,
                            2.9, 1.1);
    Apop_model_add_group(&min_distance, apop_mle, .method= APOP_SIMPLEX_NM,   ❺
                                                  .tolerance=1e-5);
    Apop_model_add_group(&min_distance, apop_parts_wanted);                   ❻
    apop_model *est = apop_estimate(locations, min_distance);                 ❼
    apop_model_show(est);
}
```

❶ Map the input function `one_dist` to every row (`.part='r'`) of the input data set, thus calculating the distance between that row and the `target` vector (sent as the `void *` input to the function), then sum the distances to find total distance. It is a common trick to turn a maximizer into a minimizer by negating the objective function; we seek the minimum total distance, so the function returns the negation of the sum.

❷ The `apop_model` struct includes over a dozen elements, but designated initializers save the day yet again, and we need only declare the elements we use.

❸ The `.vbase` is normally set to the number of elements in the vector the optimizer is searching for. As a special case that is common in modeling settings, setting `.vbase=-1` indicates that the parameter count should equal the number of columns in the data set.

❹ The first argument to `apop_data_fill` is an already-allocated data set; here, we allocate one just in time, then fill the grid just allocated with five 2D points.

❺ This line adds notes to the model about the maximum likelihood estimation (MLE): use the Nelder-Mead simplex algorithm, and keep trying until the algorithm's error measure is less than 1e-5. Add `.verbose=1` for some information about each iteration of the optimization search.

❻ Being a stats library, Apophenia finds the covariance and other statistical measures of the parameters. We don't need that information here, so a blank `apop_parts_wanted` group tells the optimizer that none of the auxiliary information should be calculated.

❼ This line will prep the `apop_model` struct by allocating a `parameters` set and an `info` set (which will mostly be NaNs in this case). It will then fill the parameters set with test points, evaluate the distance to that test point using the `min_distance.p` function, and use the test evaluations to refine later test points, until the convergence criterion is met and the search declares that it has reached a minimum.

SQLite

Structured Query Language (SQL) is a roughly human-readable means of interacting with a database. Because the database is typically on disk, it can be as large as desired. An SQL database has two especial strengths for these large data sets: taking subsets of a data set and joining together data sets.

I won't go into great detail about SQL, because there are voluminous tutorials available. If I may cite myself, [Klemens 2008] has a chapter on SQL and using it from C, or just type ***`sql tutorial`*** into your favorite search engine. The basics are pretty simple. Here, I will focus on getting you started with the SQLite library itself.

SQLite provides a database via a single C file plus a single header. That file includes the parser for SQL queries, the various internal structures and functions to talk to a file on disk, and a few dozen interface functions for our use in interacting with the database. Download the file, unzip it into your project directory, add `sqlite3.o` to the `objects` line of your makefile, and you've got a complete SQL database engine on hand.

There are only a few functions that you will need to interact with, to open the database, close the database, send a query, and get rows of data from the database.

Here are some serviceable database-opening and -closing functions:

```
sqlite3 *db=NULL; //The global database handle.
```

```
int db_open(char *filename){
    if (filename)  sqlite3_open(filename, &db);
    else           sqlite3_open(":memory:", &db);
    if (!db) {printf("The database didn't open.\n"); return 1;}
    return 0;
}

//The database closing function is easy:
sqlite3_close(db);
```

I prefer to have a single global database handle. If I need to open multiple databases, then I use the SQL `attach` command to open another database. The SQL to use a table in such an attached database might look like:

```
attach "diskdata.db" as diskdb;
create index diskdb.index1 on diskdb.tab1(col1);
select * from diskdb.tab1 where col1=27;
```

If the first database handle is in memory, and all on-disk databases are attached, then you will need to be explicit about which new tables or indices are being written to disk; anything you don't specify will be taken to be a temporary table in faster, throwaway memory. If you forget and write a table to memory, you can always write it to disk later using a form like `create table` *`diskdb.saved_table`* `as select * from` *`table_in_memory`*.

The Queries

Here is a macro for sending SQL that doesn't return a value to the database engine. For example, the `attach` and `create index` queries tell the database to take an action, but return no data.

```
#define ERRCHECK {if (err!=NULL) {printf("%s\n",err);  return 0;}}

#define query(...){char *query; asprintf(&query, __VA_ARGS__);  \
                   char *err=NULL;                               \
                   sqlite3_exec(db, query, NULL,NULL, &err);    \
                   ERRCHECK                                      \
                   free(query); free(err);}
```

The `ERRCHECK` macro is straight out of the SQLite manual. I wrap the call to `sqlite3_exec` in a macro so that you can write things like:

```
for (int i=0; i< col_ct; i++)
    query("create index idx%i on data(col%i)", i, i);
```

Building queries via `printf`-style string construction is the norm for SQL-via-C, and you can expect that more of your queries will be built on the fly than will be verbatim from the source code. This format has one pitfall: SQL `like` clauses and `printf` bicker over the `%` sign, so `query("select * from data where col1 like 'p%%nts'")` will fail, as `printf` thinks the `%%` was meant for it. Instead, `query("%s", "select * from data where col1 like 'p%%nts'")` works. Nonetheless, building queries on the fly is so common that it's worth the inconvenience of an extra `%s` for fixed queries.

Getting data back from SQLite requires a callback function, as per “Functions with Generic Inputs” on page 188. Here is an example that prints to the screen.

```
int the_callback(void *ignore_this, int argc, char **argv, char **column){
    for (int i=0; i< argc; i++)
        printf("%s,\t", argv[i]);
    printf("\n");
    return 0;
}

#define query_to_screen(...){                           \
    char *query; asprintf(&query, __VA_ARGS__);         \
    char *err=NULL;                                     \
    sqlite3_exec(db, query, the_callback, NULL, &err);  \
    ERRCHECK                                            \
    free(query); free(err);}
```

The inputs to the callback look a lot like the inputs to `main`: you get an `argv`, which is a list of text elements of length `argc`. The column names (also a text list of length `argc`) are in `column`. Printing to screen means that I treat all of the strings as such, which is easy enough. So is a function that fills an array, for example:

```
typedef {
    double *data;
    int rows, cols;
} array_w_size;

int the_callback(void *array_in, int argc, char **argv, char **column){
    array_w_size *array = array_in;
    *array = realloc(&array->data,  sizeof(double)*(++(array->rows))*argc);
    array->cols=argc;
    for (int i=0; i< argc; i++)
        array->data[(array->rows-1)*argc + i] = atof(argv[i]);
}

#define query_to_array(a, ...){\
    char *query; asprintf(&query, __VA_ARGS__);     \
    char *err=NULL;                                 \
    sqlite3_exec(db, query, the_callback, a, &err); \
    ERRCHECK                                        \
    free(query); free(err);}

//sample usage:
array_w_size untrustworthy;
query_to_array(&untrustworthy, "select * from people where age > %i", 30);
```

The trouble comes in when we have mixed numeric and string data. Implementing something to handle a case of mixed numeric and text data took me about page or two in the previously mentioned Apophenia library.

Nonetheless, let us delight in how the given snippets of code, along with the two SQLite files themselves and a tweak to the `objects` line of the makefile, are enough to provide full SQL database functionality to your program.

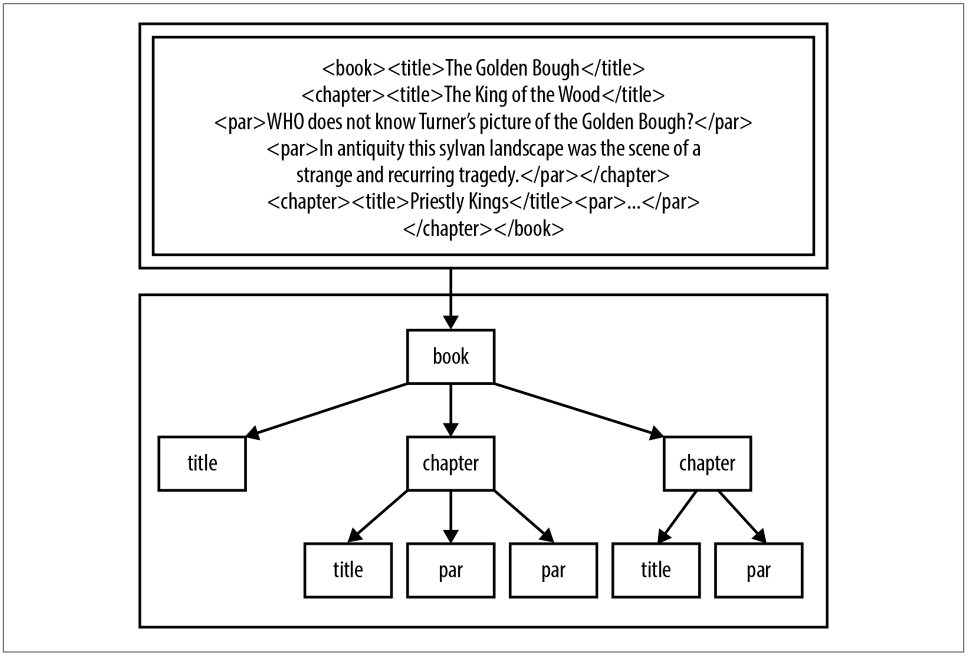


Figure 12-1. An XML document and the tree structure encoded therein

libxml and cURL

The cURL library is a C library that handles a long list of Internet protocols, including HTTP, HTTPS, POP3, Telnet, SCP, and of course Gopher. If you need to talk to a server, you can probably use libcURL to do it. As you will see in the following example, the library provides an easy interface that requires only that you specify a few variables, and then run the connection.

While we're on the Internet, where markup languages like XML and HTML are so common, it makes sense to introduce libxml2 at the same time.

Extensible Markup Language (XML) is used to describe the formatting for plain text files, but it is really the definition of a tree structure. The first half of Figure 12-1 is a typical barely readable slurry of XML data; the second half displays the tree structure formed by the text. Handling a well-tagged tree is a relatively easy affair: we could start at the root node (via `xmlDocGetRootElement`) and do a recursive traversal to check all elements, or we could get all elements with the tag `par`, or we could get all elements with the tag `title` that are children of the second chapter, and so on. In the following sample code, `//item/title` indicates all `title` elements whose parent is an `item`, anywhere in the tree.

libxml2 therefore speaks the language of tagged trees, with its focal objects being representations of the document, nodes, and lists of nodes.

Example 12-6 presents a full example. I documented it via Doxygen (see "Interweaving Documentation" on page 43), which is why it looks so long, but the code explains itself. Again, if you're in the habit of skipping long blocks of code, do try it out and see if it's readable. If you have Doxygen on hand, you can try generating the documentation and viewing it in your browser.

Example 12-6. Parse the NYT Headline feed to a simpler format (nyt_feed.c)

```
/** \file

 A program to read in the NYT's headline feed and produce a simple
 HTML page from the headlines. */
#include <stdio.h>
#include <curl/curl.h>
#include <libxml2/libxml/xpath.h>
#include "stopif.h"

/** \mainpage
The front page of the Grey Lady's web site is as gaudy as can be, including
several headlines and sections trying to get your attention, various formatting
schemes, and even photographs--in <em>color</em>.

This program reads in the NYT Headlines RSS feed, and writes a simple list in
plain HTML. You can then click through to the headline that modestly piques
your attention.

For notes on compilation, see the \ref compilation page.
*/

/** \page compilation Compiling the program

Save the following code to \c makefile.

Notice that cURL has a program, \c curl-config, that behaves like \c pkg-config,
but is cURL-specific.

\code
CFLAGS =-g -Wall -O3  `curl-config --cflags` -I/usr/include/libxml2
LDLIBS=`curl-config --libs ` -lxml2 -lpthread
CC=c99

nyt_feed:
\endcode

Having saved your makefile, use <tt>make nyt_feed</tt> to compile.

Of course, you have to have the development packages for libcurl and libxml2
installed for this to work.
*/

//These have in-line Doxygen documentation. The < points to the prior text
//being documented.
char *rss_url = "http://rss.nytimes.com/services/xml/rss/nyt/HomePage.xml";
                                      /**< The URL for an NYT RSS feed. */
```

```
char *rssfile = "nytimes_feeds.rss";  /**< A local file to write the RSS to.*/
char *outfile = "now.html";       /**< The output file to open in your browser.*/

/** Print a list of headlines in HTML format to the outfile, which is overwritten.

\param urls The list of urls. This should have been tested for non-NULLness
\param titles The list of titles, also pre-tested to be non-NULL. If the length
      of the \c urls list or the \c titles list is \c NULL, this will crash.
*/
void print_to_html(xmlXPathObjectPtr urls, xmlXPathObjectPtr titles){
    FILE *f = fopen(outfile, "w");
    for (int i=0; i< titles->nodesetval->nodeNr; i++)
        fprintf(f, "<a href=\"%s\">%s</a><br>\n"
                 , xmlNodeGetContent(urls->nodesetval->nodeTab[i])
                 , xmlNodeGetContent(titles->nodesetval->nodeTab[i]));
    fclose(f);
}

/** Parse an RSS feed on the hard drive. This will parse the XML, then find
all nodes matching the XPath for the title elements and all nodes matching
the XPath for the links. Then, it will write those to the outfile.

  \param infile The RSS file in.
*/
int parse(char const *infile){
    const xmlChar *titlepath= (xmlChar*)"//item/title";
    const xmlChar *linkpath= (xmlChar*)"//item/link";

    xmlDocPtr doc = xmlParseFile(infile);
    Stopif(!doc, return -1, "Error: unable to parse file \"%s\"\n", infile);

    xmlXPathContextPtr context = xmlXPathNewContext(doc);
    Stopif(!context, return -2, "Error: unable to create new XPath context\n");

    xmlXPathObjectPtr titles = xmlXPathEvalExpression(titlepath, context);
    xmlXPathObjectPtr urls = xmlXPathEvalExpression(linkpath, context);
    Stopif(!titles || !urls, return -3, "either the Xpath '//item/title' "
                              "or '//item/link' failed.");

    print_to_html(urls, titles);

    xmlXPathFreeObject(titles);
    xmlXPathFreeObject(urls);
    xmlXPathFreeContext(context);
    xmlFreeDoc(doc);
    return 0;
}
```

```
/** Use cURL's easy interface to download the current RSS feed.

\param url The URL of the NY Times RSS feed. Any of the ones listed at
            \url http://www.nytimes.com/services/xml/rss/nyt/ should work.

\param outfile The headline file to write to your hard drive. First save
the RSS feed to this location, then overwrite it with the short list of links.

 \return 1==OK, 0==failure.
 */
int get_rss(char const *url, char const *outfile){
    FILE *feedfile = fopen(outfile, "w");
    if (!feedfile) return -1;

    CURL *curl = curl_easy_init();
    if(!curl) return -1;
    curl_easy_setopt(curl, CURLOPT_URL, url);
    curl_easy_setopt(curl, CURLOPT_WRITEDATA, feedfile);
    CURLcode res = curl_easy_perform(curl);
    if (res) return -1;

    curl_easy_cleanup(curl);
    fclose(feedfile);
    return 0;
}

int main(void) {
    Stopif(get_rss(rss_url, rssfile), return 1, "failed to download %s to %s.\n",
                                                                rss_url, rssfile);
    parse(rssfile);
    printf("Wrote headlines to %s. Have a look at it in your browser.\n", outfile);
}
```

Epilogue

> Strike another match, go start anew—
>
> —Bob Dylan, closing out his 1965 Newport Folk Festival set,
> "It's All Over Now Baby Blue"

Wait!, you exclaim. *You said that I can use libraries to make my work easier, but I'm an expert in my field, I've searched everywhere, and I still can't find a library to suit my needs!*

If that's you, then it's time for me to reveal my secret agenda in writing this book: as a C user, I want more people writing good libraries that I can use. If you've read this far, you know how to write modern code based on other libraries, how to write a suite of functions around a few simple objects, how to make the interface user-friendly, how to document it so others can use it, what tools are available so you can test it, how to use a Git repository so that others can contribute, and how to package it for use by the general public using Autotools. C is the foundation of modern computing, so when you solve your problem in C, then the solution is available for all sorts of platforms everywhere.

Punk rock is a do-it-yourself art form. It is the collective realization that music is made by people like us, and that you don't need permission from a corporate review committee to write something new and distribute it to the world. In fact, we already have all the tools we need to make it happen.

Glossary

alignment
: A requirement that data elements begin at certain boundaries in memory. For example, given an 8-bit alignment requirement, a struct holding a 1-bit `char` followed by an 8-bit `int` might need 7 bits of padding after the `char` so that the `int` starts on an 8-bit boundary.

ASCII
: American Standard Code for Information Interchange. A standard mapping from the naïve English character set to the numbers 0–127. Tip: on many systems, `man ascii` will print the table of codes.

automatic allocation
: For an automatically allocated variable, its space in memory is allocated by the system at the point of the variable's declaration, then removed at the end of the given scope.

Autotools
: A set of programs from the GNU that simplify automatic compilation on any system, including Autoconf, Automake, and Libtool.

Benford's law
: Leading digits in a wide range of data sets tend to have a log-like distribution: *1* has about 30% frequency, *2* about 17.5%, ..., *9* about 4.5%.

Boolean
: True/false. Named after George Boole, an English mathematician living in the early-to-mid 1800s.

BSD
: Berkeley Software Distribution. An implementation of POSIX.

callback function
: A function (A) that is sent as an input to another function (B) so that function B can call function A over the course of its operation. For example, generalized sort functions typically take as input a function to compare two elements.

call graph
: A box-and-arrow diagram showing which functions call and are called by which other functions.

cetology
: The study of whales.

compiler
: Formally, the program that converts the (human-readable) text of a program into (human-illegible) machine instructions. Often used to refer to the preprocessor + compiler + linker.

debugger
: A program for interactive execution of a compiled program, allowing users to pause the program, check and modify variable values, et cetera. Often useful for understanding bugs.

deep copy
: A copy of a structure containing pointers, that follows all pointers and makes copies of the pointed-to data.

encoding
The means by which human-language characters are converted into numeric codes for processing by the computer. See also *ASCII*, *multibyte encoding*, and *wide-character encoding*.

environment variable
A variable present in the environment of a program, set by the parent program (typically the shell).

external pointer
See *opaque pointer*.

floating point
A representation of a number akin to scientific notation, like `2.3×10^4`, with an exponent part (in this example, 4) and a mantissa (here, 2.3). After writing down the mantissa, think of the exponent allowing the decimal point to float to its correct position.

frame
The space in the stack in which function information (such as inputs and automatic variables) is stored.

gdb
GNU debugger.

global
A variable is global when its scope is the entire program. C doesn't really have global scope, but if a variable is in a header that can reasonably be expected to be included in every code file in a program, then it is reasonable to call it a global variable.

glyph
A symbol used for written communication

GNU
Gnu's Not Unix.

GSL
GNU Scientific Library.

heap
The space of memory from which manually allocated memory is taken. Compare with the *stack*.

IDE
Integrated Development Environment. Typically a program with a graphical interface based around a text editor, with facilities for compilation, debugging, and other programmer-friendly features.

integration test
A test that executes a sequence of steps that involve several segments of a code base (each of which should have its own unit test).

library
Basically, a program that has no `main` function, and is therefore a set of functions, typedefs, and variables available for use by other programs.

linker
The program that joins together disparate portions of a program (such as separate object files and libraries) and thus reconciles references to external-to-one-object-file functions or variables.

Linux
Technically, an operating system kernel, but generally used to refer to a full suite of BSD/GNU/Internet Systems Consortium/Linux/Xorg/... utilities bundled as a unified package.

macro
A (typically) short blob of text for which a (typically) longer blob is substituted.

manual allocation
Allocation of a variable on the heap at the programmer's request, using `malloc` or `calloc`, and freed at the user's request via `free`.

multibyte encoding
An encoding of text that uses a variable number of `char`s to represent a single human-language character. Contrast with *wide-character encoding*.

mutex
Short for mutual exclusion, a structure that can be used to ensure that only one thread is using a resource at a time.

NaN
: Not-a-Number. The IEEE 754 (floating-point) standard defines this as the outcome of mathematical impossibilities like 0/0 or log(-1). Often used as a flag for missing or bad data.

object
: A data structure and the associated functions that act on the data structure. Ideally, the object encapsulates a concept, providing a limited set of entry points for other code to interact with the object.

object file
: A file containing machine-readable instructions. Typically the result of running a compiler on a source code file.

opaque pointer
: A pointer to data in a format that can't be read by the function handling the pointer, but that can be passed on to other functions that can read the data. A function in a scripting language might call one C function that returns an opaque pointer to C-side data, and then a later function in the scripting language would use that pointer to act on the same C-side data.

POSIX
: The Portable Operating System Interface. An IEEE standard to which UNIX-like operating systems conform, describing a set of C functions, the shell, and some basic utilities.

preprocessor
: Conceptually, a program that runs just before the compiler, executing directives such as `#include` and `#define`. In practice, typically a part of the compiler.

process
: A running program.

profiler
: A program that reports where your program is spending its time, so you know where to focus your efforts at speedup.

pthread
: POSIX thread. A thread generated using the C threading interface defined in the POSIX standard.

RNG
: Random Number Generator, where *random* basically means that one can reasonably expect that a sequence of random numbers is not systematically related to any other sequence.

RTFM
: Read the manual.

Sapir-Whorf Hypothesis
: The claim that the language we speak determines the thoughts we are capable of having. Its weakest form, that we often think in words, is obvious; its strongest form, that we are incapable of thoughts that our language lacks words or constructions for, is clearly false.

scope
: The portion of the code base over which a variable is declared and accessible. Good coding style depends on keeping the scope of variables small.

script
: A program in an interpreted language, such as the shell.

segfault
: Segmentation fault.

segmentation fault
: Touching an incorrect segment of memory. Causes the operating system to halt the program immediately, and so often used metonymically to refer to any program-halting error.

SHA
: Secure Hash Algorithm.

shell
: A program that allows users to interact with an operating system, either at a command line or via scripts.

SQL
: Structured Query Language. A standardized means of interacting with databases.

stack
: The space in memory where function execution occurs. Notably, automatic variables are placed here. Each function gets a frame, and every time a subfunction is called, its frame is conceptually stacked on top of the calling function's frame.

static allocation
: The method by which variables with file scope and variables inside functions declared as `static` are allocated. Allocation occurs before the program starts, and the variable continues to exist until the end of the program.

test harness
: A system for running a sequence of unit tests and integration tests. Provides easy setup/teardown of auxiliary structures, and allows for checking of failures that may (correctly) halt the main program.

thread
: A sequence of instructions that a computer executes independently of any other thread.

token
: A set of characters to be treated as a semantic unit, such as a variable name, a keyword, or an operator like `*` or `+`. The first step in parsing text is to break it down into tokens; `strtok_r` and `strtok_n` are designed for this.

type punning
: Casting a variable of one type to a second type, thus forcing the compiler to treat the variable as data of the second type. For example, given `struct {int a; char *b:} astruct`, then `(int) astruct` is an integer (but for a safer alternative, see "C, with fewer seams" on page 207). Frequently not portable; always bad form.

type qualifier
: A descriptor of how the compiler may handle a variable. Is unrelated to the type of the variable (`int`, `float`, et cetera). C's only type qualifiers are `const`, `restrict`, `volatile`, and `_Atomic`.

union
: A single block of memory that can be interpreted as one of several types.

unit test
: A block of code to test a small piece of a code base. Compare with *integration test*.

UTF
: Unicode Transformation Format.

variadic function
: A function that takes in a variable number of inputs (e.g., `printf`).

wide-character encoding
: An encoding of text where each human-language character is given a fixed number of `char`s. For example, UTF-32 guarantees that each Unicode character is expressed in exactly 4 bytes. Uses multiple bytes for each human-language character, but contrast this definition with *multibyte encoding*.

XML
: Extensible Markup Language.

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Index

Symbols

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We'd like to hear your suggestions for improving our indexes. Send email to *index@oreilly.com*.

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About the Author

Ben Klemens has been doing statistical analysis and computationally intensive modeling of populations ever since getting his Ph.D. in Social Sciences from Caltech. He is of the opinion that writing code should be fun, and has had a grand time writing analyses and models (mostly in C) for the Brookings Institution, the World Bank, National Institute of Mental Health, et al. As a nonresident fellow at Brookings and with the Free Software Foundation, he has done work on ensuring that creative authors retain the right to use the software they write. He currently works for the United States Federal Government.

Colophon

The animal on the cover of *21st Century C* is the common spotted cuscus (*Spilocuscus maculatus*), a marsupial that lives in the rainforests and mangroves of Australia, New Guinea, and nearby smaller islands. It has a round head, small hidden ears, thick fur, and a prehensile tail to aid in climbing. The curled tail is a distinctive characteristic; the upper part of the tail closest to the body is covered in fur, while the lower half is covered in rough scales on the inside surface to grip branches. Its eyes range in color from yellows and oranges to reds, and are slit much like a snake's.

The common spotted cuscus is typically very shy, so it is rarely seen by humans. It is nocturnal, hunting and feeding at night and sleeping during the day on self-made platforms in tree branches. It is slow moving and somewhat sluggish—sometimes mistaken for sloths, other possums, or even monkeys.

Cuscuses are typically solitary creatures, feeding and nesting alone. Interactions with others, especially between competing males, can be aggressive and confrontational. Male cuscuses scent-mark their territory to warn off other males, emitting a penetrating musk odor both from their bodies and scent gland excretions. They distribute saliva on branches and twigs of trees to inform others of their territory and mediate social interactions. If they encounter another male in their area, they make barking, snarling, and hissing noises, and stand upright to defend their territory.

The common spotted cuscus has an unspecialized dentition, allowing it to eat a wide variety of plant products. It is also known to eat flowers, small animals, and occasionally eggs. Predators of the common spotted cuscus include pythons and some birds of prey.

The cover image is from *Wood's Animate Creation*. The cover font is Adobe ITC Garamond. The text font is Linotype Birka; the heading font is Adobe Myriad Condensed; and the code font is LucasFont's TheSansMonoCondensed.